CAETS ENERGY PROJECT

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INTERNATIONAL COUNCIL OF ACADEMIES OF ENGINEERING AND TECHNOLOGICAL SCIENCES, INC. (CAETS)

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OPPORTUNITIES FOR LOW-CARBON ENERGY TECHNOLOGIES FOR ELECTRICITY GENERATION TO 2050
CAETS Working Group Report

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Executive Summary

The International Council of Academies of Engineering and Technological Sciences (CAETS)[1] Working Group[2, 3] (WG) on Low-Carbon Energy undertook a project entitled 'Opportunities for Low-Carbon Energy Technologies for Electricity Generation to 2050'. The report of the WG is focused on identifying promising initiatives to accelerate the commercial deployment of low-carbon energy (LCE) technologies for electricity generation and to highlight the engineering and financial risks to be overcome to facilitate the deployment of such technologies. It is recognised that there are many additional factors that influence the development and deployment of electrical generation that are beyond the scope of this report (such as the need to obtain a social licence to implement LCE technologies). The WG report takes a global perspective on LCE technologies and the observations contained in the report are not necessarily applicable to any one nation. The key findings of the Working Group's investigation are given below.

KEY POINTS

Achieving a transition to a lower-carbon electricity generating system is technically feasible provided:

1. *Significant investments are made to scale-up the development and deployment of LCE technologies (including carbon capture and storage (CCS)) for electric power generation by the end of this decade.*
2. *Consistent and significant government policy action is taken immediately.*

The following conclusions are relevant:

- *There is no single preferred LCE technology. Rather, the costs of different LCE technologies are expected to broadly converge over time. Hence, a portfolio of technologies can be expected to be deployed.*
- *Promising initiatives in prospect for each LCE technology are identified, but significant technical and financial risks must be overcome for their widespread commercial deployment.*
- *Opportunities are identified where a number of LCE technologies may be integrated with either other LCE technologies or with fossil-fuel technologies to expedite their possible commercial deployment, including the lowering of greenhouse gas emissions of those fossil fuel technologies and delivering increased generating efficiency.*
- *Currently, most emerging LCE technologies do not have intrinsic commercial advantage over those technologies used today, so they will need sustained government support for research, development and deployment (RD&D).*
- *First-of-a-kind technologies have high risk and financial support is not readily available to support commercial deployment. There are opportunities for government support and this may include some form of subsidy (for example, cash or tax benefit).*
- *Even with support, major engineering challenges must be overcome to achieve a low-carbon electricity generating system.*

1 CAETS is the International Council of Academies of Engineering and Technological Sciences Inc. It consists of those national academies of engineering and technological sciences that have satisfied an agreed set of criteria for membership. It was established in 1978 and was incorporated as a charitable, non-profit corporation in the District of Columbia (US) in 2000. Its Articles of Incorporation, Bylaws and Operating Procedures set down its objectives and governance arrangements. These documents and its membership and achievements are posted on the CAETS website (www.caets.org). A list of CAETS member Academies is given on the final page of this document.
2 The views contained in the Working Group report are not necessarily endorsed by each member Academy of CAETS.
3 Details of the Member Academies comprising the Working Group are given in the Acknowledgements section of this report.

- *Substantial investments are required in new electricity generating plant. For example, it is estimated that $6.4 trillion[4] is required to be invested over a 10-year period for electric power generation technologies.*
- *Successful deployment of LCE technologies normally requires partnerships between research, industry and government. Appropriate public policy settings can make a clear difference in inducing innovation and the international diffusion of LCE technologies.*

It is not within the scope of this report to recommend either particular technology development strategies or electricity generation technology mixes; these subjects are clearly the province of individual nations. Recommendations for possible consideration include:

- *GHG reduction is a global issue – hence international RD&D collaboration should be supported with adequate resources, particularly in critical areas such as CCS.*
- *Governments and industry should work closely to ensure the strategic development and the acquisition of skills and resources for research, development, manufacture, deployment and possible international diffusion of LCE technologies.*

This report has been prepared as a resource for use by:

- *Those CAETS academies that may wish to engage with key stakeholders (including governments) in their respective countries about strategies that might be adopted to deploy LCE technologies for electric power generation as a means to achieve progress towards a low carbon environment.*
- *CAETS when it wishes to engage with relevant International organisations and inform them on:*
  - *the technical and financial feasibility of particular LCE technologies;*
  - *what are the promising initiatives that could be undertaken to accelerate their deployment; and*
  - *what are the risks to be addressed.*

This is an overview report and as such it contains general observations and technology assessments; it does not contain detailed technical appraisal of each of the LCE technologies.

The report considers nine LCE technologies that can be used for electric power generation; namely:

- Hydroelectric
- Solar Energy
- Geothermal
- Marine and Tidal Energy
- Wind
- Biomass
- Gas
- Coal
- Nuclear
- Carbon Sequestration

(Carbon Sequestration is an enabling technology to achieve lower carbon emissions for fossil fuels.)

Each of the low-carbon technologies is evaluated in the report under a common set of headings in the Technology Assessment section. In addition, the issues identified for each technology are then synthesised into general observations in a Technology Overview – Broad Findings section. Some of these observations are given below.

4 All $ symbols refer to US dollars unless otherwise specified.

Many of the LCE energy technologies considered in this report have been in existence for years. They have formed a component of the electricity generation portfolio, but the majority of the world's electricity generation capacity is still provided by fossil fuels. While the proportion of electricity generated by LCE technologies is expected to increase significantly, it is expected also that fossil fuels will continue to be significant in the electricity generation in the short to medium term.

Further, as most renewable technologies transform an energy source (for example, solar) into electricity and, as the proportion of electricity generated by renewable technologies increases, it can be expected that this will facilitate the substitution of a number of current energy sources by electricity as an energy source (for example, for transportation, heating and industrial processes) and thus increase the importance of electricity and electricity generation in the energy mix.

This report is concerned with electricity generation which forms part of a power system along with transmission, distribution and use. Traditional power systems are being challenged by the introduction of new LCE generation technologies including issues associated with integration, intermittency and storage. Further, locally distributed electricity grids are being developed and these pose separate challenges. These challenges are outside the scope of this report.

It is recognised that increased energy efficiency is perhaps the most cost-effective mechanism in the near term for achieving lower greenhouse gas emissions and lowering the need for new electricity generation capacity. The reason that such a strategy of increased energy efficiency is important for LCE power generation technologies is that it provides a window of additional time and opportunity for emerging technologies to mature and become more cost competitive. Nevertheless, energy efficiency is outside the scope of this report.

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Acknowledgements

Acknowledgements for the preparation of this report are given to the CAETS Working Group representatives for their commitment to the authorship of the report, and their host Academies, for the support given and involvement in the report. In particular, the following principal authors are acknowledged for their significant contributions:

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A biography of each of the contributing authors is given at the end of this report.

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* Working Group representative

Overview

BACKGROUND

To achieve targets for Greenhouse Gases (GHG) reduction there must be significant changes to energy sources and their production, distribution and use. As noted in a previous CAETS WG report on LCE for electric power generation: *There are massive technological and financial challenges involved in reducing greenhouse gas emissions from electricity generation while, at the same time, ensuring that sufficient electric power is available to meet the growing needs of the world* (CAETS, 2010).

There is a strong correlation between GDP and energy consumption and this means that increased economic growth in many large and rapidly developing countries will inevitably result in a significant increase in total world energy consumption in the decades to come. While a low-carbon world may be desirable, it cannot be achieved overnight, as over 85 per cent of all the energy we use is derived from fossil fuels. Accordingly, the world faces a long period of heavy investment in low-carbon energy technologies, especially for electric power generation to meet the increasing demand for electricity and respond to climate change by reducing greenhouse gas emissions. As an indication of the massive task ahead it has been estimated that, over the next decade, investments in the power sector are estimated at US$6.4 trillion (IEA 2012a). The power generation sector is expected to contribute more than one-third of potential CO_2 emission reductions worldwide by 2020 and almost 40 per cent of emission reductions savings by 2050. It is noted in the IEA Energy Technology Perspectives (IEA 2012b) report that enhanced power generation efficiency, a switch to lower-carbon fossil fuels, increased use of renewables and nuclear power, and the introduction of carbon capture and storage (CCS) will all be required to achieve this objective. Over the past decade, however, close to 50 per cent of new global electricity demand was met by coal. This trend must be reversed quickly to successfully reduce power sector carbon emissions. Further as most renewable technologies transform an energy source (e.g. solar) into electricity, and as the proportion of renewable technologies increase, it can be expected that this will facilitate the transformation of energy sources to electricity (e.g. for cars) and thus increase the importance of electricity and electricity generation in the energy mix.

Given this environment, there is a need for access to impartial and informed information on low-carbon technologies to help facilitate improved investment decision-making associated with these technologies for both the electricity generation sector and public policy makers in supporting investment decision making. This report is intended to provide such impartial and informed information on low-carbon technologies.

SCOPE AND PURPOSE

While the first CAETS WG report on Low Emissions Technologies concentrated on broad global issues, this second CAETS WG Report focuses on promising initiatives to accelerate deployment and to identify the technological and financial risks that may hinder such deployment. The CAETS WG report focuses on the engineering aspects and identifies the broad technical and financial risks for commercial deployment of technologies for electricity generation. It is recognised that there are many other factors that influence the development and deployment of electrical generating technologies but such factors are beyond the scope of this report.

LOW-CARBON ENERGY TECHNOLOGIES

The report considers nine LCE technologies that can be used for electric power generation. The following low-carbon technologies for electric power generation are considered:

- Hydroelectric
- Solar Energy
- Geothermal
- Marine and Tidal Energy
- Wind
- Biomass
- Gas
- Coal
- Nuclear
- Carbon Sequestration*

* NOTE: Carbon sequestration is not a LCE electricity generating technology. Rather, it is an enabling technology for gas and coal electricity generation technologies to be considered as low-carbon energy technologies.

Each of the low-carbon energy technologies is evaluated in the report under the following headings:

- Current state of the technology;
- Technological and other risks to overcome;
- Initiatives to accelerate investment;
- Viability of investment;
- Integration with other technologies; and
- Timescale for deployment.

* NOTE: At the end of the Technology Assessments section, a summary table is provided that captures some of the issues listed above. Further, the issues identified for each technology are then synthesised into general observations in the Technology Overview – Broad Findings section (section 4); a condensed version of that section is provided immediately below.

This report is intended to be an overview and as a consequence, each technology is considered in broad qualitative terms and not in depth. While outside the scope of this report, it is most important to recognise that increasing energy efficiency can dramatically lower the rate of demand growth for electricity supply and hence both the need for and they type of technology most suitable for generation expansion.

This CAETS WG report is intended to be a resource for those CAETS academies that wish to engage with key stakeholders (including governments) in their countries about strategies that might be adopted to deploy technologies to progress a successful low-carbon strategy for electric power generation. In addition, CAETS can use this report to engage with relevant international organisations on the technical and financial feasibility that particular technologies can contribute to the reduction of greenhouse gases, what are the promising initiatives that could be undertaken to accelerate deployment and what are the risks to be addressed.

TECHNOLOGY OVERVIEW – BROAD FINDINGS (CONDENSED)

Based on considerations in this report (in particular, see section 4), the following broad observations are relevant.

Financial considerations

Based on the use of discounted cashflow techniques, it is found that currently there is substantial uncertainty in the cost estimates of producing electricity for each technology considered and further there is currently a wide cost variation between the different technologies. Further there are several fossil fuel, nuclear and wind technologies that are currently commercially viable. It is recognised that as a technology moves along the continuum of research, development and deployment the type of risk tends to change. The first-of-a-kind commercial plant will normally have relatively high costs associated with it. As further commercial plants are installed, the level of learning results in increased understanding and improvements in the technology and reductions in the cost of delivery. This leads to a downward pressure on both the capital and operating costs. These technology learnings (in conjunction with a price on carbon) are expected to result in broadly similar costs for different LCE electricity generating technologies over time, typically 25 to 40 years. As such it is expected that a mix of technologies will be deployed to generate the required future electricity demand.

Emerging technology costs typically change much more rapidly than those of mature technologies as learning curves develop for newer technologies. For example, even among renewable power technologies, the costs of photovoltaic (PV) installed systems in the US fell by 22 per cent between 2007 and 2010 whereas the costs of other renewable options declined more gradually.

What are the most promising initiatives for individual technologies that might accelerate their investment and deployment?

Virtually all of the power generation technologies will require some kind of substantial initiative – fundamental innovation, technology development, demonstration at market scale, market incentive, or other action – to change the course of deployment of these technologies throughout much of the world. These substantial initiatives must be undertaken urgently if they are to make a significant difference in reduction of emissions by 2050.

A number of the most promising possible initiatives that could have a profound influence on development and rate of adoption of LCE technologies are common to all such technologies, such as various mechanisms that place an actual or de facto price on carbon; expansion, improved control and efficiency of electric power transmission and distribution; and development and deployment of electricity storage or other mechanisms for dealing with generation variability common to many of the relevant emerging technologies. In addition, each technology has its own features that limit the rate of commercial deployment. Some technologies require substantial continued development or fundamental innovation, despite being on a fast development track already, to reduce cost or mitigate performance risks and compete with traditional options. Many have geographic constraints that limit their potential in many parts of the world. Tragic or costly experiences with some quite mature technologies have led to deployments at much lower rates than expected. Promising initiatives that will facilitate the development of each technology considered are identified in the report.

For example given that fossil fuels represent about 67 per cent of the current world electricity generation, then CCS is important for the future viability of fossil fuels. While the individual components of the CCS chain are well known there are few commercial-scale operations that demonstrate the integrated process. A key technological challenge is to have demonstration plants that show the technology is operable at commercial-size scale and which can be used to help define the risks to deployment in other installations. An increasing carbon price trajectory over a 10 to 20-year period will assist the commercial viability of such plants.

What integration and combinations of technologies will accelerate investment and deployment?

There are many possible combinations of technologies that can lead to improved efficiencies and/or cost, but not all of them achieve the purpose of reducing emissions for a given quantity of energy produced. The report identifies those combinations of technologies where the power is greater than the output of the individual technologies where, for instance, the one technology may reduce a constraint on the deployment of the other; alternatively, where there is an overall reduction in the carbon emissions by the utilisation of the combination (such as the use of CCS in conjunction with fossil-fuel-based power generation plants).

An example of system integration is the use of pumped water storage. In periods where there is excess in electricity generation (e.g. from intermittent renewable sources) this excess can be used to pump water into storage and use this to generate electricity when there is insufficient generation from intermittent renewable sources. Similarly, solar thermal (e.g. linear Fresnel Reflectors) can be used to heat the feed water to a fossil-fuel boiler and this can reduce the carbon emissions from the generation of electricity.

A range of opportunities for each generation technology are identified where integration and combinations of technologies can accelerate investment and deployment.

Risks to deployment of LCE technologies at scale

The risks and barriers associated with the commercial deployment of low-carbon energy (LCE) technologies are many and varied and include the following:

Engineering and technology risks: As LCE technologies move along the RD&D continuum, they will have lower engineering/technology risks. The technological risks of early stage LCE options arise from the difficulties in demonstrating that they are cost-effective.

Environmental risks of LCE technologies can arise during energy generation as well as utilisation phases: Sometimes, they can be resource or location specific. For example, large land requirements in the case of solar thermal power systems may have negative impact on native vegetation, wildlife habitat loss and water drainage problems in heavy rainfall areas. Similarly, high temperatures associated with concentrating solar thermal systems can pose risks to the avian population in the vicinity.

Social risks: LCE systems can give rise to social risks. For instance, they can interfere with the existing land use patterns, soil compaction, water access, drainage channel alterations and increased runoff/soil erosion in special designated areas. During the construction and operation phases of major LCE projects, disruption of public services, high influx of working personnel and equipment from other areas and social justice related issues in case of those sections of the population that receive little or no benefits from the LCE developments can pose high social risks.

Financial risks: Major financial risks can occur in LCE plants due to their initial lack of market competitiveness without government subsidies. There may be other economic barriers that need to be overcome to attract private sector investments on a larger scale, such as achieving an adequate rate of return on investment. Several LCE projects suffer from high financial risks since bank finances are difficult to access, initial investment is high enough for small and medium scale entrepreneurs to hesitate before venturing into this area, and to cause difficulties in meeting high collateral requirements of lenders for capital assets. Further, many LCE technologies are yet to demonstrate routinely sound business models with minimum financial risks.

Legal risks: Some LCE technologies can also present legal risks which act as barriers for their commercial deployment. A typical example is CO_2 transportation and storage after its capture from thermal power plants. In the event of significant leakage of CO_2 into the atmosphere, long-term liability issues may arise. Government regulations need to address such issues with adequate institutional framework for their monitoring and reporting and the need to consider appropriate mitigation strategies.

The existence of these risks implies that private sector is likely to under-invest in the initial phases of LCE technology deployment without government intervention and/or support. To help resolve this impasse, governments need to judiciously employ a set of policy instruments to encourage the adoption of LCE technologies despite the perceived risks.

Engineering challenges to deploy LCE technologies at scale

Many of the LCE technologies proposed for future use have been demonstrated in functioning test facilities, whether in laboratories or pilot plants; some are even at commercial scale. However, the transition from those early demonstrations to equipment at production scale, whether in terms of plant size or in large numbers of devices operating at smaller unit scale, can pose engineering or economic barriers as challenging as the development of the basic technology.

It is considered that for most of the technologies evaluated here the engineering challenges can be overcome to realise deployment at scale. However, marine and tidal energy technologies face probably the greatest engineering challenges for deployment at scale. Apart from the technical and development barriers still to be overcome, the reliable installation, connection to the network, operation and maintenance will require a large engineering effort and an associated infrastructure including both ships and ports. Manufacture and delivery in volume of what are likely to be large heavy devices, up to 10 tonnes per kilowatt, implies a substantial and sophisticated industry with heavy delivery capabilities.

Challenges facing industry and governments to introduce LCE technologies

Deployment of LCE technologies presents enormous challenges to both government and industry because of the short time frame for deployment, the high cost involved, the high risk and large uncertainties and the absence of simple technological solutions.

Challenges for government: LCE technologies, in general, require long-term development and large- scale investment. Government, in collaboration with industry, needs to establish consistent and stable policy settings and also direction and support for research, development and deployment of these technologies. Government also needs to provide supporting initiatives, policies and direct financial incentives and investments, and to ensure that the implementation plans gain societal acceptance. It has been noted that perhaps the most important determinant of innovation outcomes for LCE technologies is the general innovative capacity of a nation. Clearly, public policy also makes a difference in inducing innovation and the international diffusion of technology.

Challenges facing industry: Industry is challenged by market uncertainties, rapidly changing technologies, or large-scale investment in some cases. Industry needs to develop its own investment strategies, including investment timing, financing options, technology selection, and market penetration. Technology selection for investment is also crucial. For a system that requires large investment, once a technology is selected, it may not possible to change for several decades. For technology developers to compete in the market, it is necessary to build credibility in the industry through long term demonstrations and installations. A technology that requires a large-scale demonstration can be implemented through international cooperation.

Public acceptance: Another important factor for successful implementation of LCE technologies is to establish 'social acceptance' or a 'licence to operate'. Appropriate information must be provided to prevent misunderstandings. It is also necessary to provide continuous environmental monitoring, education and training, and public participation in decision-making processes. A better understanding is also needed of the dynamics of public views through rigorous social research to look into factors that contribute to shape public acceptance.

OTHER ISSUES

This report is focused on the issues relevant to the development and commercial deployment of electrical generation technologies that contribute to greenhouse gas reductions. Further, as most renewable technologies transform an energy source (e.g. solar) into electricity, and as the proportion of renewable technologies increase, it can be expected that this will facilitate the substitution of current energy sources to the use of electricity as an energy source (e.g. for transportation, heating and industrial processes) and thus lead to increased demand for electricity.

This report does not consider related issues such as electricity transmission and distribution. Further, it is acknowledged that there are many factors beyond the direct consideration of the generating technologies that influence the development and deployment of electrical energy technologies. These include matters such as: technical progress, economical factors, financial markets, market development, institutional, regulatory and legal frameworks, political processes and social acceptance.

Significant reductions in greenhouse gases can be achieved by strategies such as improved energy efficiency in the built environment and industry, the deployment of CCS in industrial processing and reduced emissions in the transport industry (such as improved efficiency and fuel substitution). It is most important to recognise the importance of increasing energy efficiency and the dramatic affect this can have on the rate of demand growth and hence both the need for and the type of technology most suitable for generation expansion. For example, the IEA report (IEA 2011) observes that the potential for energy efficiency improvements in Russia alone could save nearly a third of its annual primary energy use, an amount equivalent to the total energy used in one year by the UK. Similarly, a US National Academies 2009 report (National Academies 2009) concluded that by 2030, using currently available or emerging efficiency technologies in buildings, which account for 73 per cent of electricity and 40 per cent of all US energy consumed, could lower energy use by 25 to 30 per cent compared to predictions reflected in the US Energy Information Administration's 'business as usual' scenario, even with expected growth in consumer demand. This reduction in energy use in buildings alone would eliminate the need to build any new electric power generating plants before 2030 except to address regional supply imbalances, replace obsolete generating assets, or substitute more environmentally benign electricity sources.

The reason that such a strategy of increased energy efficiency is important for LCE power generation technologies is that it provides a window of additional time and opportunity for emerging technologies to mature and become more cost competitive. This might reduce the necessity or at least the intensity of other kinds of policy initiatives to encourage deployment. In short, by far the most promising options for both reducing carbon emissions and profoundly affecting the prospects of most if not all power generation technologies to reduce emissions are efforts to develop and deploy technologies and other means of promoting improved energy efficiency.

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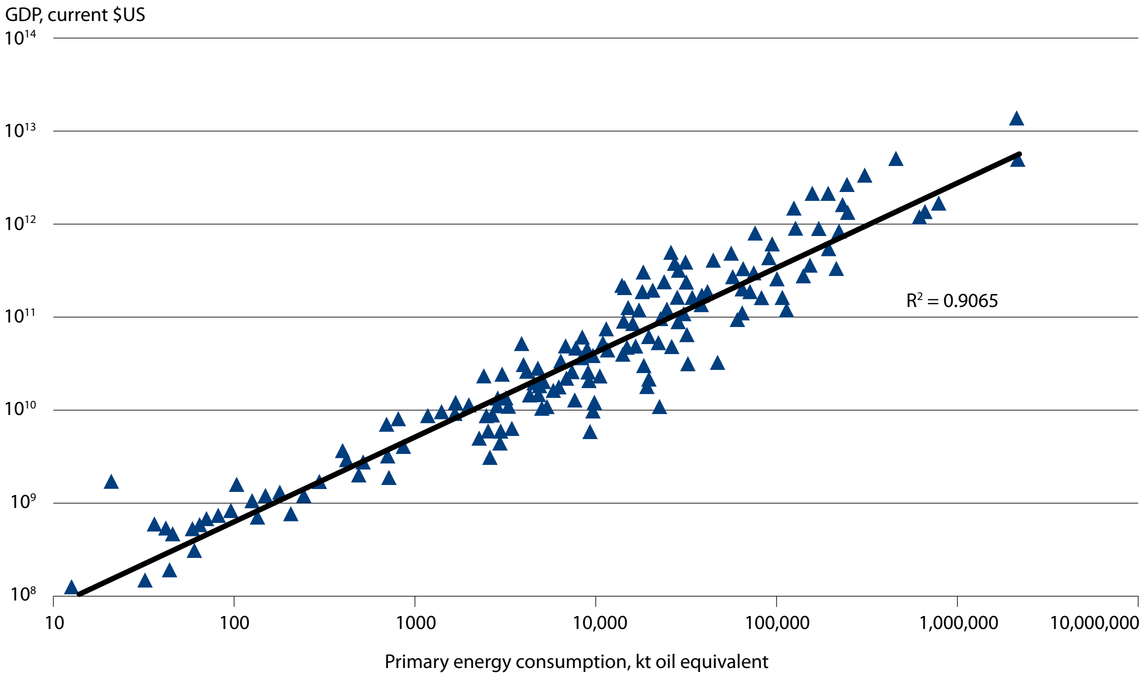
1 Introduction

Energy use, and its impact on the environment, is one of the most important technical, social and public-policy issues that face mankind today. There is a very strong correlation between GDP and energy consumption, as shown in Figure 1. This means that increased economic growth in many large and rapidly developing countries will inevitably result in a significant increase in total world energy consumption in the decades to come. Today, more than 85 per cent of all the energy we use is derived from fossil fuels which ultimately results in high levels of carbon emissions. While a low-carbon world may be desirable, it cannot be achieved overnight, since there is so much invested in the existing predominantly carbon-based energy systems. In order to make progress towards a low-carbon future, however, we need to be aware of the impacts of our energy use, all the way from the primary energy source through to the final end-use.

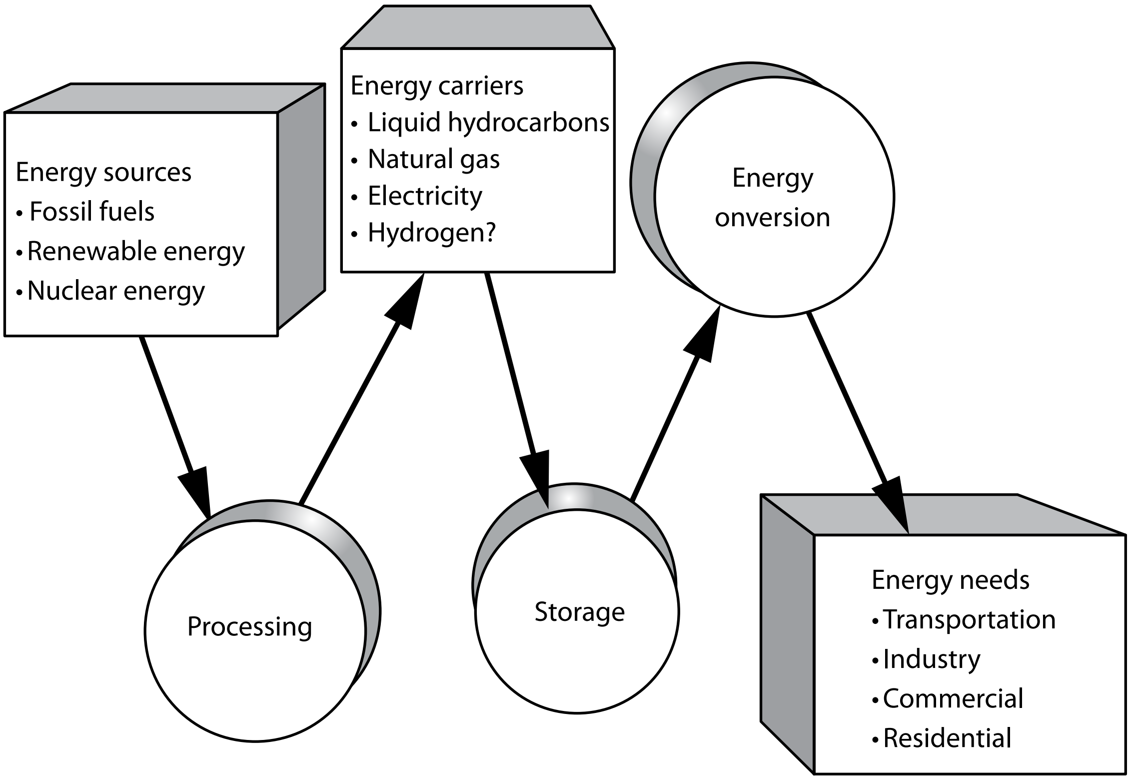
Figure 1 Energy consumption as a function of GDP



Source: World Bank, 165 countries, 2009 data

The 'energy conversion chain' is a convenient way to envisage energy use, and the impact of this use on primary resources and the environment (Evans 2007). A schematic of a generalised complete energy conversion chain is shown in Figure 2. The chain starts with just three 'primary' energy sources, and ends with the four end-use applications of these sources to provide heat, light and power for buildings, transportation, and industrial processes. In between the primary source and the ultimate end-use are a number of steps in which the primary source is converted into an energy 'carrier', or is stored for use at a later time. To take a familiar example, in order to drive our car, we use a fossil fuel, crude oil, as the primary energy source. The crude oil is first converted in a refinery into gasoline, the energy carrier for this case, and the gasoline is then stored in a fuel tank, ready for use by the engine in the final end-use conversion step. This is, of course, just one example, but any use of energy can always be tracked through the complete energy conversion chain in this way. One important lesson to be taken from Figure 2 is that there are only three primary sources of energy; fossil fuels, nuclear energy, and renewable energy,

Figure 2 Complete energy conversion chain



and only three energy carriers that are of significance today; refined petroleum products, natural gas, and electricity. Hydrogen, often billed erroneously in the popular press as an energy source of the future, is just a potential energy carrier, and must be "manufactured" using one of the three primary energy sources.

Electricity is one of three main energy carriers used to provide light, heat and mechanical power for our homes, factories and commercial buildings. The focus of this report is on electricity produced from low-carbon energy (LCE). According to the International Energy Agency (IEA) in 2006 fossil fuels accounted for some 67 per cent of the primary energy used to generate electricity. Following combustion, all of the carbon contained in these fossil fuels ends up as CO_2, the predominant greenhouse gas (GHG). Most of the remaining electricity is produced from LCE sources using either nuclear power or hydroelectric resources without any GHG emissions. With no international agreement to replace the failed Kyoto Accord on reduction of GHG emissions, electricity generation from fossil fuels is expected to expand in a 'business as usual' scenario in most developed economies. However, in the rapidly developing economies, particularly the largest ones such as China and India, the demand for electricity is expected to rise even faster than in the mature industrial economies.

Electricity is also expected to become a more dominant energy carrier in the future, as non-traditional uses, such as transportation become more important. The US Energy Information Agency has predicted that although overall demand for energy will double over the 45-year period from 1990 to 2035, the demand for electricity over this time will treble. This increase in demand for electricity will, in part, be due to the introduction of new electric vehicles. These will include small 'all-electric' vehicles with limited range, as well as 'plug-in hybrid' or 'extended range' electric vehicles which will likely be popular with consumers. Although the widespread adoption of this new technology should reduce the demand for petroleum fuels, and therefore GHG emissions from mobile sources, it will inevitably increase the need for electricity to be generated by low-carbon sources wherever possible. Since some 40 per cent of current electricity generation uses coal as the primary energy source, and 20 per cent uses natural gas, there will be an urgent need to expand the use of non-fossil fuels for electricity generation in the future.

Non-fossil fuels are now used for just over one-third of electricity generation, with hydroelectric power and nuclear power each accounting for about 15 per cent of total generation. Renewable energy sources other than hydroelectric power currently account for only about two per cent of electricity generation, mainly due to the high cost of generation and in some cases the need to restrict the amount of intermittent generation on the electricity grid. There are only three ways to generate electricity without producing GHG emissions – nuclear power, renewable energy, or fossil fuel generation together with full carbon capture and storage. The cost of new LCE generation is likely to be significantly higher than that associated with traditional fossil fuel generation which has been the main source of generation in most countries. In order to expand the development of LCE generation it may be necessary to introduce carbon pricing or regulation to make low-carbon technologies more attractive commercially. LCE technologies also have different time-scales for development and technological risks compared to traditional energy sources, which adds to the urgency to start planning now for a greener future. The challenges for expanding the use of LCE generation, both technically and financially, are huge, and this report starts to address these issues in some detail.

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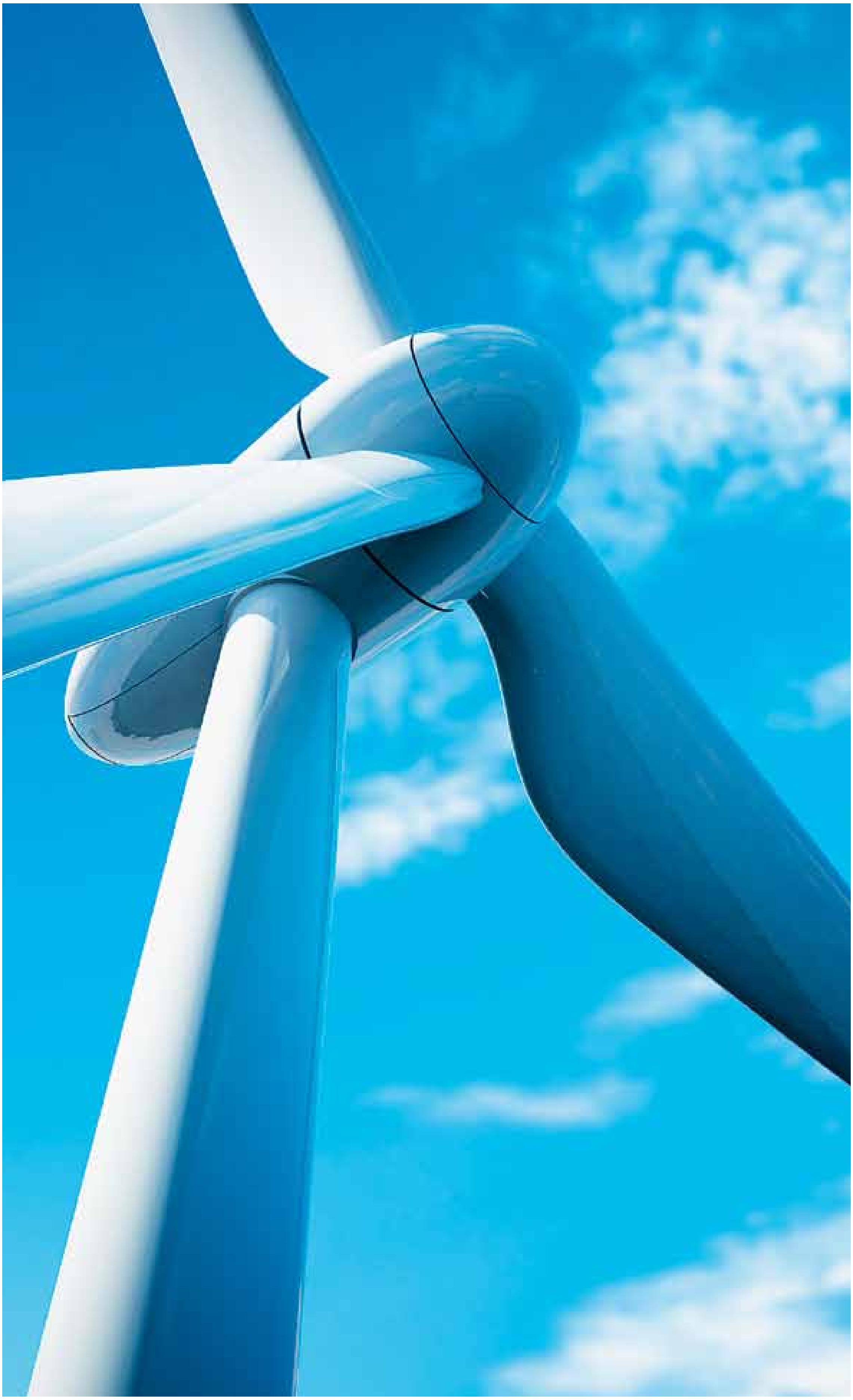


2 Technology Costs: Comparing Alternatives

As noted earlier, many LCE technologies for power generation have the potential to contribute significantly to reduction of carbon emissions world-wide between now and 2050. Further, it is generally accepted that a portfolio of LCE technologies will be deployed to meet future demand and greenhouse gas targets since no one technology can provide the overall solution. Some of these technologies may require government support, depending on the availability and cost of the technology or resource, to facilitate commercial deployment. The degree of support that will be necessary to accelerate the deployment of each of these technologies hinges primarily on the cost of that technology relative to traditional alternatives – the technology's cost competitiveness. In particular, there may be a variety of impediments to widespread deployment of emerging technologies, many of which are described later in this report, but a technology's potential reduction of carbon emissions will result from the scale of deployment which, in the absence of policy incentives, will in turn be determined as much by its cost competitiveness as by its emissions reduction potential per unit of electricity produced.

A variety of financial models can be used to assist in the assessment of financial viability of different technologies, including:

- levelised cost of electricity (LCOE); and
- net present option value (NPOV).

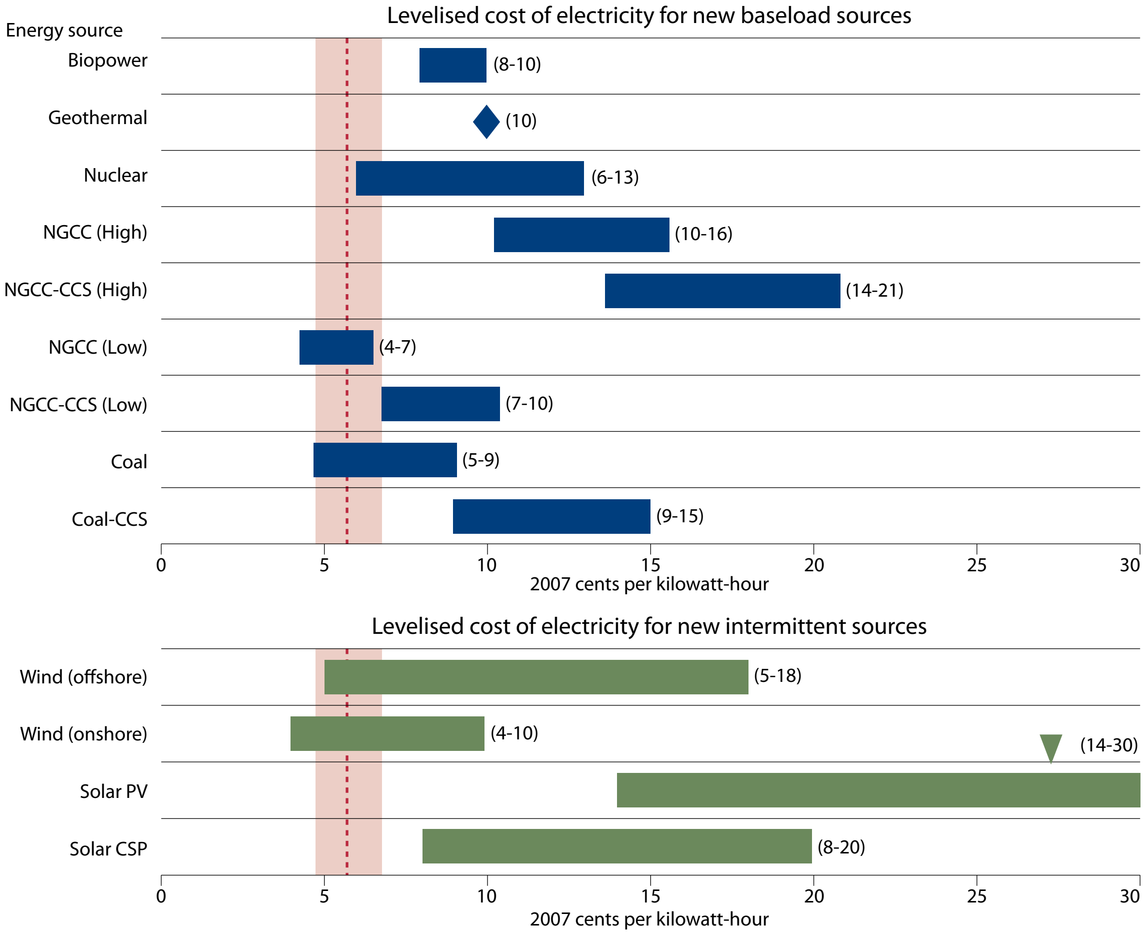
2.1 LEVELISED COST OF ELECTRICITY

A traditional way to compare different technologies is to calculate the so-called levelised cost of electricity generated by each technology. This is defined as the net cost to install and operate a power plant (computed as the discounted cost to some reference year of the full life-cycle costs of the generating facility) divided by its expected lifetime energy output, often expressed in cents per kilowatt-hour of electricity produced.

Figure 3 shows such a comparison from the 2009 US National Academies study which separates the comparisons into two groups of technologies – those designed to operate continuously (base-load generation sources) and those that operate intermittently depending upon resource availability (intermittent sources).

Some comments on Figure 3 are important for present purposes. The geothermal entry on this chart corresponds only to traditional hydrothermal technology, which is a mature and well-understood technology, as opposed to enhanced geothermal or technology for creating artificial aquifers in 'hot dry rocks', which involves emerging technologies with many sources of uncertainty in cost and performance. Hence, the figure shows a very low level of uncertainty in projected cost for geothermal. By contrast, the entry for nuclear power corresponds to so-called evolutionary nuclear plants which also utilise mature and well-understood technology, but projected costs fare highly uncertain because they are evolutionary. In the segment of the chart of intermittent technologies, note that onshore wind reflects costs competitive with conventional technologies in a number of regions in the US, and indeed in many parts of the world. However, because of the variability of wind resources, system integration costs become crucial to expanded use of wind technology and, as a result, much of that expansion world-wide

Figure 3 The potential range of costs for new sources of electricity



These estimated costs include plant construction, financing, operations, fuel and decommissioning, but not transmission or distribution. The dotted red line represents the average wholesale price for electricity in the US in 2007, which is not expected to change significantly through 2030. NGCC is natural gas combined cycle technology, CCS is carbon capture and storage, PV is photovoltaic and CSP is concentrating solar power. Those prices with (low) indicate potential prices with a low price for natural gas ($6/GJ) and those with (high) indicate potential prices with a high price for natural gas ($16/GJ).

Source: National Academies, 2009

has been policy driven by such mechanisms as financial incentives, renewable portfolio standards, or feed-in tariffs.

It is recognised that as a technology moves along the continuum of development from R&D through commercial installation, the type of risk tends to change. At the R&D level, technologies face a high degree of both technical and estimation uncertainty. Technology demonstration and commercialisation reduce technical and estimation uncertainties, but economic and other uncertainties always remain. The first-of-a-kind commercial plant will tend to have relatively high costs associated with it. As further commercial plants are installed, the level of learning results in increased understanding and improvements in the technology and the cost of delivery. This leads to a downward pressure on both the capital and operating costs.

The trend of reduced costs over time is demonstrated in an Electric Power Research Institute report (EPRI 2011). Estimated costs and the resultant LCOEs are presented for a number of technologies installed in both 2015 and 2025, with all dollars inflated to the year 2010. In both years the LCOE range for nuclear power are approximately the same. In 2015 the cost of coal and natural gas are lower than nuclear, whereas some biomass and onshore wind are competitive but offshore wind and solar are more expensive. For 2025, EPRI assumed that carbon capture and storage is available for coal and natural gas and this adds to their capital and the LCOE values. Further, the cost ranges for nuclear, biomass and wind reduce slightly whereas solar reduces to a greater extent and becomes potentially competitive.

The Australian Academy of Technological Sciences and Engineering (ATSE 2010) has conducted a study on the costs of low-carbon energy and found that for generating plant commissioned in 2020 there is a large range between the lowest and the highest LCOE values for 14 different technologies. However, in part as a result of technology learning and the resultant reductions in costs, the range for the LCOE values in 2040 for these same technologies is much reduced, to the point where many of the technologies are competitive. A similar trend is also observed in a recent study of 40 different electricity generating technologies conducted by the Australian Government's Bureau of Resource and Energy Economics (BREE 2012). In 2012 the lowest cost options are nuclear, combined cycle gas turbines and onshore wind. The study found that the differences in the cost of generating electricity, especially between fossil fuel and renewable electricity generation technologies, are expected to diminish over time and that by 2030 some renewable technologies, such as solar photovoltaic (non-tracking) and wind onshore, are expected to have the lowest LCOE of all of the evaluated technologies. Among the non-renewable technologies, combined cycle gas turbines (and in later years combined with carbon capture and storage) and nuclear power offers the lowest LCOE and are cost competitive with low-cost renewable technologies. Further, for some technologies, LCOE is projected to increase over time due to: projected weakening of the Australian-dollar exchange rate, rising carbon price and cost escalation factors.

2.2 NET PRESENT OPTION VALUE (NPOV)

Option values have historically been calculated in order to price options for share market investors. Option value is the value of a choice to make a future investment decision concerning an asset. It is particularly suited for evaluating an investment under conditions of uncertainty for costs and prices. The net present option value (NPOV) is a financial technique that was adopted in the ATSE model noted earlier to financially evaluate a range of low-carbon electricity generating technologies. The NPOV is characterised as the present value of a choice to make a future investment decision. The NPOV is the value created by financial uncertainty and volatility and the time into the future when a technology is commercially deployed, assuming that a rational investor will not invest then if the proposed investment earns less than the cost of capital. The NPOV complements LCOE calculations as it incorporates uncertainties and variations in future technology costs and electricity prices.

For NPOV purposes the capital cost of the investment, the operating costs and revenues (that is, the full life-cycle costs) are discounted at the cost of capital to calculate the probability distribution of the net present value (NPV) of a future capital investment. The NPOV is calculated from the NPV probability distribution; it is that part of the NPV distribution where NPV is greater than zero. It represents the value of a favourable financial outcome of a future investment and it is this that provides the current option value. It represents the maximum amount that could be expended now to have the future option for investment, given that a positive NPV can be achieved at the final investment. This preparatory expenditure could be allocated for a variety of purposes, including research, development and deployment (RD&D) for infrastructure development, with the aim of achieving a successful future commercial deployment of the technology. The NPOV is a function of the mean value and the variance of the NPV distribution. A decision-making space is constructed using NPV, variance and NPOV.

ATSE adopted the Monte Carlo model approach to calculate NPOV for the assessment of the value of various electricity generation options. Uncertainties considered in the ATSE model include:

- capital and operating costs, and the timing of these costs for the technologies under consideration and their probabilistic distributions;
- a variety of future scenarios for carbon and electricity pricing through emission trading or taxation schemes, and the associated uncertainties; and
- learning curves for the investment costs and operating efficiencies of each of the technologies, and their uncertainties.

ATSE has conducted an assessment of various technologies and has developed results for the NPOVs and LCOEs. The ATSE study (ATSE 2010) has shown that low LCOE and high NPOV are generally favoured by:

- low capital intensity ($ per amount of electricity produced for export);
- high operating efficiency and low auxiliary electricity load;
- low CO_2 mitigation costs; and
- high capacity utilisation of the generating plant.

The ATSE study used Australian Government estimates for a monotonic increase in the price of carbon over time. In the short to medium term, ATSE's work shows that, for Australia, efficient natural gas-powered combined cycle turbines, onshore wind and low capital-cost geothermal generation are the best financial options. The work also shows that longer-term investments (2040) – nuclear energy, low capital-cost efficient solar-thermal plant and gas CCGT firing with carbon capture and storage could all become financially viable options. Some coal-fired technologies with carbon capture and storage could also emerge as viable options, depending on favourable thermal efficiency and capital-cost learning curves and suitable low-cost CO_2 storage locations.

2.3 TRENDS IN COSTS AND OTHER FACTORS AFFECTING DEPLOYMENT

Emerging technology costs typically change much more rapidly than those of mature technologies as learning curves develop for newer technologies. For example, even among renewable power technologies, the costs of photovoltaic (PV) installed systems in the US fell by 22 per cent between 2007 and 2010 whereas the costs of other renewable options declined more gradually. IEA (Energy Technology Perspectives, 2012) projects that overnight investment costs of utility scale PV will fall by 74 per cent by 2050 but that the corresponding costs of onshore wind power – a much more mature technology – will fall by only 17 per cent, due at least in part to the assessment that the annual expected 'learning rate' for emerging PV technology is more than twice that of wind power technology as it is expected to develop by 2050. Trends in other factors affecting deployment are important as well, such as capacity factor, construction time, unit plant efficiencies, plant lifetime, availability of complementary technologies (e.g. storage), load following capability, regional variations in resource availability, and others. So, while metrics such as LCOE and NPOV are helpful for relative comparisons at a high level of abstraction, detailed assessments of the specific circumstances for possible deployment are essential for meaningful projections.

Co-authors

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3 Technology Assessments

3.1 HYDROELECTRIC POWER GENERATION

3.1.1 Current Status

Hydroelectric power generation is one of the oldest means of generating electricity, and is the predominant renewable electricity generation technology used today. Hydroelectric power generation represents by far the largest use of renewable energy to date, and the IPCC has estimated that just over 16 per cent of the world electricity supply was generated by hydroelectric plants in 2008 (IPCC 2010).

Hydropower plants can be divided into high, medium and low-head developments which rely on water falling from a significant height through turbines located downstream of a large storage reservoir. Hydro turbines consist of two major components: a fixed element and a rotating element. High head installations use one or more fixed 'nozzles' to direct water into a series of 'buckets' attached to the rotating element, or Pelton wheel, which in turn drives the generator. In the case of medium and low-head designs, a Francis turbine is used in which a series of fixed blades in the stator directs flow into the rotating element, or 'runner', containing another set of blading which turns the generator and directs the water into the outlet or draft tube.

Another category of hydropower generation is 'run-of-the-river' or 'water current' designs in which power is generated by the flow of very large volumes of water through turbines immersed in a river channel or ocean regions with strong currents. Low head hydro may be further divided into 'low head' developments in which the head is less than 15 metres, and 'very low head' with a head of less than 5m.

Hydropower plants, particularly the high and medium-head variety, can take up large areas of river valley land for the storage of water behind dams, and are often located in quite remote areas at some distance from major population centres. The development of such facilities is necessarily dependent on local geography, and most major hydroelectric facilities are located in countries with mountainous terrain, a large stock of lakes and rivers, and high precipitation.

China is relying on hydroelectric power to supply a significant portion of its rapidly increasing demand for electricity, and is now the largest producer of hydroelectric power in the world. The Three Gorges hydroelectric development on the Yangtze River, for example, has a peak capacity of some 18GWe and is the largest such plant in the world. Although the development of this massive project has not been without controversy, it is a major source of electricity supplying China's fast-growing economy without producing any greenhouse gas emissions. Canada, with a very large land area and relatively small population, is the world's second largest producer of hydroelectric power. Nearly two-thirds of the country's total electricity requirements come from hydropower installations (Evans 2007).

3.1.2 Initiatives

Since large-scale hydro power is well-established technology, with many installations worldwide, new initiatives are usually limited to the installation of newer and more efficient turbine 'runners'. Over the past two decades the use of computational fluid dynamics (CFD) software has been developed to the point where it can be used to make significant design improvements to turbine runners. Although the efficiency of most large 'legacy' turbines is already quite high, even a small improvement in efficiency can result in quite large increases in power output. For a typical medium-head Francis-type turbine runner, for example, a modern design using CFD techniques may result in an improvement in turbine efficiency from something like 88 per cent for a 'legacy' runner to nearly 93 per cent for a new machine (Cateni 2008). If the original runner had a capacity of 350MWe, this higher efficiency would then result in an increase of some 20MWe of generation capacity. Although the capital cost of replacing turbine runners can be high, it is a 'one-time' cost, and can often be a very cost-effective investment for utilities.

There are also many studies now underway to examine the potential for 'small-scale' hydropower generation, mainly using 'run-of-the-river' or 'water-current' type installations. These can be particularly attractive in rural or sparsely populated areas where there are largely untapped river systems. The size of these developments is usually less than 10MWe, while some individual or community based installations may be of the order of 100kWe or even less. Since there is usually no need to build large and expensive storage reservoir facilities, they can often be quite cost-effective. The limitation, of course, of this technology is that it is also very site-specific and each installation has to be essentially a 'one-off' design to suit the local environment. Nevertheless, there is quite a large potential for this type of small-scale hydropower, particularly in countries with large sparsely populated land areas.

3.1.3 Integration

An important feature of many large-scale hydroelectric plants is the potential to store electricity in the form of water held behind a dam. The ability to store energy in this form, and release it at very short notice to generate electrical power on demand, is equivalent to a 'battery'. The energy storage inherent in many hydroelectric plants can be used to address large daily and seasonal variations in demand for electricity which occur in most countries. This large-scale storage potential can also be used to buffer the intermittency inherent in many other renewable energy sources, such as wind or solar power. Since intermittent sources of electricity, like wind-power, often have a capacity factor of less than 30 per cent, their contribution to overall electricity production in a given utility system may be quite limited. With the storage capability provided by large hydro reservoirs, however, there may be a greater capacity for utilities to accept intermittent sources of electricity generation onto their systems. As such, the energy storage inherent in large hydroelectric reservoirs may be as important an asset to utilities as the actual generating capacity they provide.

In some cases, where there is little or no potential for conventional hydroelectric power generation it may be beneficial to build 'pumped-storage' units. In these systems water is pumped to an elevated storage reservoir using off-peak power and is then allowed to run back down through the reversible pump-turbine unit to generate power during peak demand periods. These units then operate like very large batteries, providing generation 'time-shifting' to accommodate high but relatively short-term peak electricity demands. As an example, a pumped storage scheme capable of generating 1.8GWe of peak power has been in place at Dinorwig in Wales since 1984. It takes approximately seven hours to 'charge' the reservoir to full capacity by pumping water into the reservoir. The turbines can then run for approximately five hours, providing some nine GWh of electrical energy, before the reservoir is emptied. In 2012 the world-wide total installed generating capacity of pumped storage units was just over 100 GWe (EIA 2012). Another advantage of these units is that like all hydroelectric plants, once synchronised, they can respond very quickly to accommodate rapid increases in power demand. This ability to provide fully 'dispatchable' power is an important asset that most hydroelectric plants are able to provide. Hydroelectric plants are also valued by utility operators because of their reliability, low maintenance costs and ease of operation with a limited requirement for operating personnel.

3.1.4 Risks

The potential for development of new hydroelectric plants near to large population centres, and therefore regions of high energy demand, is somewhat limited, and many of the most cost-effective sites have already been developed. Attention has been turning in recent years, therefore, to 'small-scale' hydroelectric installations, which are often community based in rural or fairly remote areas. These installations are typically less than 1 MWe in capacity, and do not usually involve construction of a dam, but rather rely on the flow of water in small rivers or streams. Such small-scale hydro installations can be very environmentally benign, since they have the same benefit of zero greenhouse gas production found in large-scale installations, but usually few of the environmental and social concerns associated with large-scale projects where there may be widespread flooding of river valleys and displacement of some of the local population. Just as in the case of large-scale hydropower, however, the opportunities for new small-scale hydroelectric power development are very site-specific. A further risk associated mainly with large-scale hydroelectric plants is related to dam safety, and the small, although finite, risk of dam failure with possible catastrophic consequences for downstream communities.

3.1.5 Investment Scale

Since each new hydroelectric power plant is built under unique local conditions, the cost of electricity from such plants can vary significantly. Recently the IPCC has estimated that the capital cost of a new hydroelectric plant would range from \$1000/kW to \$5500/kW for large hydro projects and from \$2500/kW to \$7000/kW for small projects (IPCC 2012). Although the capital costs of hydroelectric power plants are usually higher than those for thermal power stations, hydro plants normally have a much longer life expectancy, and with no fuel costs can provide a low-cost source of electricity. The IPCC report estimated the levelised cost of electricity from a large new-build hydroelectric plant, assuming a 40-year lifetime, a capital cost of \$3000/kW, a capacity factor of 45 per cent and a discount rate of 7 per cent, to be \$0.073/kWh. This makes it a very competitive form of renewable energy and major new hydroelectric plants can be expected in regions of the world with suitable topography and where widespread public acceptance can be obtained.

3.1.6 Timescale

The total global technical potential for hydroelectricity generation has been estimated by the World Energy Council to be greater than 16,000TWh per year, which is nearly five times the 3300TWh of electrical energy produced from hydropower plants in 2008 (WEC 2007). If fully developed, this amount of electrical energy would be close to the total global electricity production in 2008 of some 20,000TWh. Of course the time-scale for development of such a large increase in hydropower capacity will inevitably be very long, since the planning and construction of large-scale hydro developments can take on the order of a decade or more. The challenge for the future will be to take advantage of this enormous potential source of renewable electricity generation while at the same time minimising the impact on local populations and the environment.

Table 1 Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1	TRL 9	Now

See Attachment A for definitions of rankings

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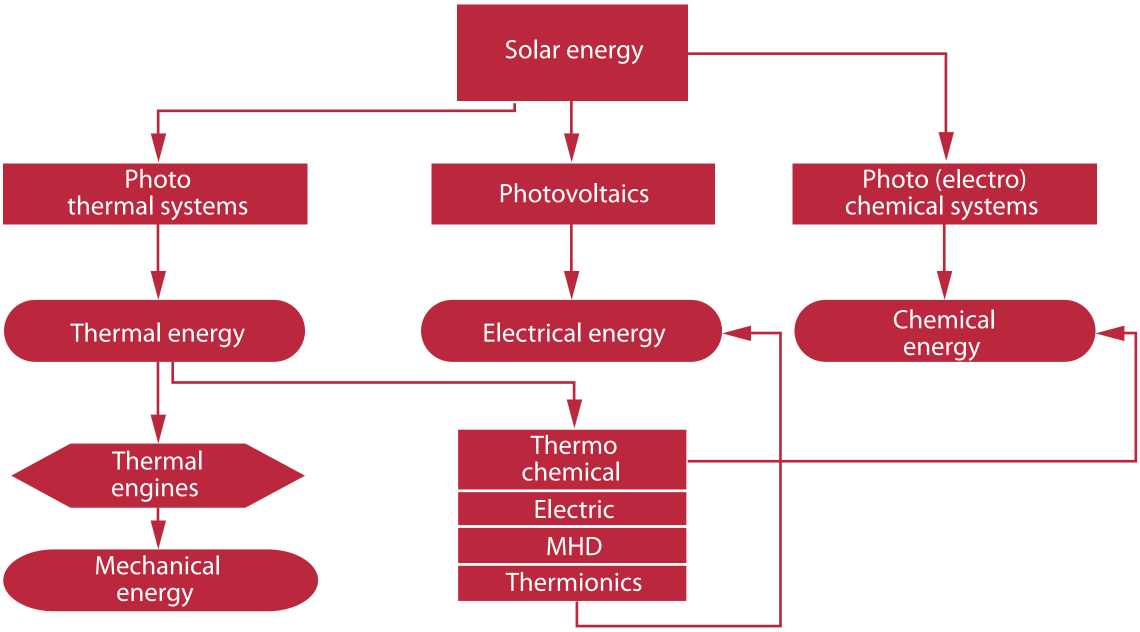
3.2 SOLAR ENERGY

3.2.1 Current Status

Figure 4 provides the spectrum of solar power technologies with low to high potential for commercial applications. They form the currently accepted basis for future energy technology portfolios broadly classified as thermal, photovoltaic and photochemical systems.

Figure 4 Current solar power technological options



Solar thermal systems convert solar energy directly into thermal energy often using concentrators. Electricity can be produced by using thermal engines or thermionic and allied devices. The most developed technologies for capture of solar radiation are parabolic dishes, troughs and power towers. The former are modular devices amenable to be grouped into dish farms to create medium-sized solar power plants. The parabolic troughs consist of long parallel rows of reflectors which are curved to form a trough to achieve energy concentration ratios between 10 to 100 and delivery temperatures up to 400°C. The power towers are low-cost installations and are equipped with efficient thermal storage systems which can offer dispatchable and high-capacity factor power plants in the future. They consist of a central tower surrounded by a large array of mirrors or heliostats to achieve energy concentration ratios as high as 800 and delivery temperatures up to 585°C. Delivery temperature is important as it affects the generation system type and efficiency. The approximate operating temperatures for photothermal power systems vary between 400 to 750°C. Their average energy conversion efficiency varies between seven and 20 per cent and are economically attractive at sites with an annual solar radiation exceeding 1300 kwh/m^2.

Photovoltaic systems (PV) convert photon energy into electricity by employing inorganic or organic semiconductor materials which can absorb photons with energy greater than their bandgap. They achieve light absorption, charge separation, transport and collection. Currently, the most commonly used material is crystalline silicon which is commercially available and has an efficiency approaching 20 per cent. However, other than in areas of high sunlight intensity, these PV systems are currently not normally economically competitive with conventional technology systems; nevertheless they have been widely deployed mostly with the aid of various forms of financial assistance. A number of possible new technology options are being researched. These include organic PVs, thin film PV materials, multi-junction cells, quantum dot sensitised systems and ultra-thin absorber devices with potential cost advantages. Recently, inorganic semiconductor nanocrystals have even been combined with organic materials to achieve more efficient energy collection. In both inorganic and organic PV technologies, several other options are being investigated globally for achieving better efficiency, sizeable cost reduction and making cells lighter and more flexible in use. They include dye-sensitised solar cells, multilayer organic planar devices, nanoscale blended donor and acceptor materials, artificial photosynthetic macromolecular structures and third-generation thin film PVs. All offer some potential but represent a specific tradeoff between efficiency, cost and ease of use. Further, it is currently not possible to identify the technically and commercially viable options amongst them.

Solar PVs are currently growing rapidly, albeit from a small base to reach 100GW capacity at the end of 2012 in more than 100 countries. These range in size from 1.5 to 10kW for single residential buildings, micro-power sources have capacities in the range of 10 to 100KW and small-scale solar power plants with capacities ranging from 10 to 60MW; roughly 90 per cent of them are grid connected. By 2015, nearly 200GW of PV systems may be installed around the world. The largest PV based power plant has a capacity of 97MW and is located in Canada. By 2030, PV systems could be generating approximately 1.8 TW of electricity around the world covering the electricity needs of nearly 14 per cent of the world population, provided further cost reductions and other improvements are realised to ensure the cost of electricity from PV systems are commensurate with other forms of commercially produced electricity.

Most photochemical systems focus on catalysed photolysis of water to produce hydrogen as an energy vector. Their current efficiency limit for splitting water is 41 per cent. The development of high-activity catalysts is crucial to the success of this technology. Other thermochemical options like carbothermic reduction of metal oxides using coke or natural gas and hydrogen production through direct water thermal dissociation (>2500 k) are at an early research stage.

3.2.2 Initiatives

Solar thermal systems are at the demonstration stage and some commercial scale installations are already operational. Their ability to overcome intermittency problems using hybridisation and/or thermal storage must be adequately demonstrated for large-scale electricity production. Trough technology is more advanced currently than its tower counterpart. Nearly 350 MW commercial solar thermal systems have been established in US. The tower technology has been successfully demonstrated on a pilot scale, but is yet to be commercially proven – although it is hoped to have lower energy cost deployed at scale.

The photovoltaic technologies have been experiencing intense research interest and at present the efficiency of crystal silicon solar cells has reached 25 per cent and that of thin film devices up to 19 per cent. The concept of concentrating PV is gaining importance since they magnify sunlight onto the solar cells that are anywhere from 250 to 500 times smaller than conventional PV solar panels. Recently nanotechnology facilitated deposition and growth techniques have opened new avenues for reaching still higher performance levels and there is little doubt their costs will continue to be reduced. However, all PV technologies have to overcome technological barriers associated with charge carrier generation, its separation and transport. Thermal and photochemical technologies must demonstrate higher performance and reliability prior to their commercial acceptance. More technological advances and breakthroughs are still necessary in this area.

3.2.3 Integration

As stated earlier, solar energy technologies face two near-term deployment hurdles when compared to their nonrenewable counterparts – namely high initial capital cost, low capacity factor and low despatchability on an overcast day. An integrated gas-solar combined cycle (IGSC) plant can provide additional power at peak demand with reduced natural gas consumption. This option was trialled in 2007 in Nevada, USA. Combining solar energy with conventional coal-fired plants is possible in regions with reasonably good solar conditions. The world's first hybrid coal-solar (thermal) power plant was established in Colorado, USA. These integrated systems are endowed with reduced greenhouse gas emissions, enhanced power-generating efficiency and output and electricity production at costs slightly great than coal fired power plants. Combining energy from waste and concentrated solar power was successfully experimented in Northern Europe in with approximately 33 per cent increase in electricity production.

The medium-term option is to hybridise multiple forms of renewable and non-renewable energy options with solar powered systems. A prefeasibility study was prepared recently for solar (PV)–wind–diesel hybrid systems suitable for power generation in small towns and villages. While the diesel engine component provides the good backup for reliability, the wind energy component provides uninterrupted power in winter and monsoon months. Another option is to integrate solar technologies into existing hydrothermal power systems. Such an attempt was made in the US in 2000. The long-term option may be to develop integrated solar power systems based on geothermal energy option. They will provide uninterrupted thermal conversion based on solar heat and low temperature geothermal energy which can be regulated according to the demand. The thermal water can also be used for irrigation purposes once it has cooled down. They could effectively combat desertification and create new opportunities in agriculture and food sectors as well.

3.2.4 Risks

The technology development and demonstration of solar energy systems prior to their commercialisation involves R&D, scale-up, technology demonstration and techno-economic feasibility analysis. The techno-economic risks associated with each of these stages are considerable. However, the development of a solar resource will have a positive impact on the local economy in terms of employment, personal income and industrial development. Table 1 broadly indicates the capital cost and projected electricity prices of solar power plants based on the current and future status of some of the potential technologies as identified by the Australian Academy of Technological Sciences and Engineering (ATSE) in 2010; the LCOE figures include a price on carbon. Enhancing the installed capacity of solar thermal power units to 4500+ MW at a single site has the potential to reduce the electricity costs to less than $0.06 /kWh. This needs an investment of some $1 billion per plant and is difficult to put into practice. In the case of PV-based solar power plants, a similar cost may be possible through the use of low cost wafer silicon or thin film amorphous silicon. Solar PV modules cost nearly 65 to 70 per cent of the total power plant cost and material cost reduction has a strong bearing on capital cost reduction.

Table 1 Levelised Cost of Electricity for Solar and other Sources

		Levelised Cost of Electricity, A$/kWh Investment Year:			Capital Cost*, A$/kW
		2020	2030	2040	
1	Solar Thermal - Parabolic - Central Receiver	 0.240 0.200	 0.200 0.170	 0.150 0.110	 3000-4000* 4000
2	Solar PV (Twin Tracking)	0.200	0.180	0.130	4000-8000
3	Geothermal	0.110	0.110	0.100	3400
4	Wind (onshore)	0.100	0.090	0.080	2000
5	Coal IGCC + CCS	0.170	0.130	0.120	6600

* For the period 2010–30. A$ = Australian Dollars

The levelised cost of electricity data presented here, while consistent with Figure 3, are different since they are applicable to a different country, with different cost structures and for different timescales for initial investment.

Source: Mora Associates, 2009, *CSP: Concentrated Solar Power, Research Report*, by P. Szczygielski and L. Wagner, March

3.2.5 Investment Scale

Globally it is accepted that current solar technologies have a long way to go to achieve grid parity (equal to today's conventional cost) electricity production and efficiencies approaching 70 to 75 per cent of theoretical limit. While a number of technological options in solar thermal power systems can reach grid parity levels before 2020, the solar PV and other systems may not reach the above milestones before 2025 due to technological complexities. Table 2 provides the current technology readiness levels of potential solar power systems for electricity generation and their perceived carbon footprint ranking systems. Advanced solar PV technologies require more applied research and larger scale technology demonstration to become more efficient, stable and reliable. Photo (electro) chemical systems require major technological breakthroughs to overcome low conversion efficiency and high cost.

Although the electricity generation from solar energy can be classified as low-carbon technology, it cannot be termed as carbon free since CO_2 emissions do arise in specific phases of its life cycle viz., energy capture, component manufacturing construction, maintenance and decommissioning. Through, lifecycle assessment (LCA), carbon footprints can be evaluated for various energy generation options. In order to achieve large-scale deployment, a cluster of pilot and demonstration projects have to be launched and tested at various parts of the world to showcase and validate various facets of promising technologies.

3.2.6 Other Risks

The major financial risk for solar power projects arises from the current lack of market competitiveness and short-lived government incentives. The latter may artificially make these plants competitive initially and later become unviable. There are other economic barriers that need to be overcome to secure public and private investments for solar energy projects in developing countries. The small and medium-sized enterprises still hesitate to undertake solar energy projects because finance is difficult to access, high initial investment costs and difficulties in meeting high collateral requirements of lenders for fixed assets.

Solar power systems are still confronted with technological risks that make them poorly competitive in an energy market dominated by fossil fuels. They are mainly due to modest conversion efficiency and intermittency. Technological risks associated with solar thermal energy systems are much less compared to photovoltaics since the latter is yet to resolve the mismatch between the solar photon spectrum and the semiconductor bandgap and optical losses due to reflection off the cell surface or shadowing by the conductor grid that collects the electric current.

Table 2 Technology Ranking Table

	Solar Power Option	Carbon Footprint Ranking	Technology Readiness Level (TRL)	Technology Status	Timescale for Wider Deployent, (years)
1	Solar Thermal	1-2	6-8	Demo under actual environment	10+
2	Advanced solar PV	2-3	3-4	Validation in lab environment	15+
3	Photo (electro) chemical	2-3	1-3	Basic to applied R&D	10-15

See Attachment A for definitions of rankings
Solar PV refers to advanced technology photovoltaic cells

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ATSE 2010, *Low-carbon Energy: Evaluation of new energy technology choices for electric power generation in Australia*, November 2010; seehttp://www.atse.org.au/resource-centre/func-startdown/286/

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3.3 GEOTHERMAL ENERGY

3.3.1 Background

Geothermal energy, in the broadest sense, is the natural heat of the Earth. Immense amounts of thermal energy are generated and stored in the Earth's core, mantle and crust. At the base of the continental crust, temperatures are believed to range from 200°C to 1000°C, and at the centre of the Earth the temperatures may be in the range of 3500 to 4500°C. The heat is transferred from the interior towards the surface mostly by conduction. This conductive heat flow means that temperatures rise with increasing depth in the crust by, on average, 25°C to 30°C per kilometre (World Energy Council (WEC) 2007). The total heat content of the Earth's crust is of the order of 5.4 x 1018 GJ, while the global electricity generation in 2008 was about 7 x 1010 GJ (or 19 x 106 GWh). The thermal energy of the Earth is therefore immense, but it is also very diffuse so only a fraction can be utilised. So far utilisation of this energy has been limited to areas in which geological conditions permit a carrier (water in the liquid or vapour phases) to 'transfer' the heat from deep hot zones to or near the surface, thus giving rise to practical geothermal resources.

Exploitable geothermal systems occur in a number of geological environments. They can be divided broadly into two groups, depending on whether they are related to young volcanoes and magmatic activity or not (see WEC 2007). High-temperature fields used for conventional power production (with temperatures above 150°C) are mostly confined to the former group. Low-temperature geothermal fields (normally unrelated to volcanoes) can be categorised as follows:

- resources related to deep circulation of water along faults and fractures;
- resources in high-porosity rocks at or above hydrostatic pressure; and
- resources in hot but dry (low-porosity) rock formations.

Geothermal fields with temperatures less than 90°C are more suited to direct use for space heating, rather than for electricity generation.

3.3.2 Current Status

Where an accessible high-temperature geothermal resource exists, electricity generation costs are competitive with other power generation alternatives and over 10GW of installed capacity has been developed. This represents about 0.4 per cent of current electricity generation and with technology improvements this could rise to 140GW installed capacity (Friedleifson 2008) (equivalent to about 1200TWhr per annum of electrical energy). This latter figure is consistent with estimates from the IEA that geothermal electricity generation per year will represent around 3.5 per cent of global electricity production in 2050 (IEA 2011). An upper bound for geothermal electricity capacity is expected to be about 1 to 2TW (IEA 2011).

Geothermal electric plants are normally built where high temperature geothermal resources are available near the Earth's surface. Electricity generation requires high temperature resources that can only come from deep underground. The heat is carried to the surface by fluid circulation. This circulation sometimes exists naturally: magma conduits bring heat close to the surface, and hot springs may then bring the heat right to the surface. If no hot spring is available, then a well must be drilled into a hot aquifer.

The heat produced from non-volcanic sources such as the breakdown of radiogenic elements in granites beneath the surface can be used to generate electricity. In these granite structures temperatures are estimated to reach some 200°C at depths of 5km beneath the Earth's surface. Access to these resources involves injecting a fluid, usually cold water, down one well, circulating it through hot fractured rock (either with natural permeability or from hydraulic stimulation), and drawing off the heated water from another well. This is known as 'hot rocks' or Enhanced Geothermal Systems (EGS). The EGS process has been successfully demonstrated in areas such as the west coast of the US, Germany's Rhine Valley region and Australia's Cooper Basin. Some sedimentary basins contain geothermal resources that are at medium temperatures

(120°C to 160°C) and have good flow rates for geothermal production. Geothermal energy reservoirs that exist in sedimentary basins are referred to as the Hot Sedimentary Aquifers (HSA). While opportunities exist to exploit non-volcanic sources of geothermal energy, this form of geothermal electricity generation has not reached its full potential. Accordingly, this section will focus on issues associated with EGS.

3.3.3 Initiatives

The following are some key initiatives that will accelerate investment in EGS & HSA:

- an increasing carbon price trajectory over a 10 to 20-year period within a stable policy framework; and
- the implementation of demonstration plants of significant size (> 50MW) to show that the technology is operable and to help to define the technological and commercial risks that must be addressed to achieve commercial-scale deployment.

3.3.4 Integration

Opportunities include the use of solar energy to boost water temperatures at the surface and thereby increase geothermal power generation efficiencies. As access to water may be limited in certain EGS developments, consideration is being given to the use of ground-loop cooling or novel air-cooled systems for heat removal.

Geothermal energy can be used in hybrid systems such as with fossil-fuel electricity generation to pre-heat the boiler feed water.

3.3.5 Risks

Much of the required technology can be transferred from the conventional geothermal and petroleum industries. Demonstration and early stage commercialisation projects have successfully shown that non-volcanic geothermal resources can be exploited to produce effectively emissions-free, base-load electricity. The technical challenges facing the industry are about improving project success rates and increasing commercial viability.

These challenges include the need to improve:

- publicly available geosciences data suitable for geothermal exploration companies;
- understanding of in-situ porosity and permeability measurements;
- seismic monitoring, including temporary deployment of detailed monitors during hydro-fracturing;
- slim-hole drilling techniques up to 4000m depth to demonstrate the geology, temperature and flow characteristics of the reservoir. This will enable the important characteristics of the reservoir to be assessed quickly and at lower cost compared to conventional drilling techniques;
- more efficacious hard-rock and high-temperature, high-pressure drilling technologies;
- understanding of fluid chemistry and rock mineralogy to predict the effects of scaling (mineral deposition that may inhibit fluid flow either in the rock fracture network or in the piping or power plant);
- drilling technologies to reduce the time taken to drill into harder rocks; and
- power conversion technologies to increase output from the resource.

3.3.6 Related Technological Issues

Geothermal energy has a distinct advantage over most other emissions-free renewable energy sources in that it is a continuous (base-load) power source. Often, however, geothermal resources are remote from the existing electricity grid and hence the economic viability of geothermal energy projects may be adversely affected.

3.3.7 Investment Scale

Most current geothermal plants around the world compete successfully in electricity markets with other generation technologies, including coal and hydro. The successful development of EGS and HSA projects (as for other renewable energy projects) will require successful management of the technological and commercial risks and effective and clear policy frameworks that provide incentives for investment. Policy frameworks for the future include market mechanisms that price carbon and those that assist clean technologies to enter national markets at commercial scale. Various projections suggest that geothermal energy will require an investment in the vicinity of $5000/kW when deployed at scale; for example, refer to data from the Energy Information Administration (EIA 2010).

3.3.8 Timescale

The timeframe for the commercial deployment of geothermal energy in electricity markets will be dependent on improvements in technology and its commercial viability compared to other competing technologies. While demonstration projects can be expected to occur in the shorter term, it is unlikely that projects of material size (> 50MW) will be developed before 2020 and it is expected that wide-scale commercial deployment will not occur for at least 15 years.

3.3.9 Other Risks

As with other emerging technologies, the geothermal energy industry needs to gain community acceptance for this new and basically unfamiliar technology. Geothermal projects will require access to water, and where water resources are scarce then access rights will require careful management and discussion by water planners and the geothermal industry. Risks associated with hydraulic stimulation/fracturing ('fracking') of geological formations to enhance the recovery of geothermal energy (such as the potential for induced seismicity, and the potential damage to aquifers and water supplies) will need careful evaluation and resolution given the issues associated with fracking used for the recovery of natural gas reserves. In addition, the geological uncertainty of the life and the productivity of the reservoir will need careful evaluation.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1	TRL 4 - 5	15+ years

See Attachment A for definitions of rankings

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3.4 MARINE AND TIDAL ENERGY

3.4.1 Current Status

Over the next decade, marine energy is expected to make only minor contributions to energy system change internationally. It is a resource unequally distributed between countries, so is more attractive in some areas than others; for example, the UK has especially good opportunities. The British Wind Energy Association has – rather ambitiously – suggested the UK could deploy 3GW of marine capacity by 2020. At the European level, the European Ocean Energy Association has suggested that marine energy could reach 3.6GW of installed capacity across the entire EU by 2020. However, over the longer term the Carbon Trust has estimated that around 15 to 20 per cent of UK electricity demand could potentially be met by marine energy.

It is still an emerging technology, and there is a need for substantial further research, development and demonstration before it can make major contributions to energy supply. For wave energy, a wide variety of device concepts including oscillating water columns, overtopping devices, point absorbers, terminators, attenuators as well as flexible structures are being developed and tested. Many are at unit sizes of around 25kW and are large, heavy systems, typically 1 to 10 tonnes per kW rating. Typical capture efficiencies are presently around 10 per cent, less than current solar PV levels. Power production is classified as intermittent as it depends primarily upon wind patterns, although in large oceans, waves can travel considerable distances and thus transmit energy from distant winds.

Tidal current energy exhibits less design variety, with most prototype designs based on horizontal axis turbines, but vertical-axis rotors, reciprocating hydrofoils and Venturi-effect devices are also being developed. Prototypes of 2MW unit size are undergoing in-water testing, generally successfully, although further refinements to designs will be needed. Amongst problems discovered are damaging dynamic loads arising from flow turbulence which have led to blade failures. Capture efficiencies are claimed to exceed 45 per cent, although this may not be maintained across the whole tidal velocity range. The technology can be regarded as near commercial but not service-proven. Deployment rates will also depend on the identification of economically attractive sites, often those where currents are locally enhanced by channel topography such as narrow deep estuaries or regions between islands which accelerate currents. The higher velocities increase output from a given turbine diameter and effectively reduce capital cost per unit maximum power. Tidal currents are predictable power sources, but not controllable.

The other form of tidal energy devices are based on barrages or tidal lagoons, which effectively capture the potential energy of water at high tide and then convert this usually through hydro turbines during the lower tidal periods. This is an established technology which can be exploited commercially today, but requires extensive civil engineering works at least comparable to those needed for river dams and thus of high but variable (depending upon the specific site) capital cost. Environmental impacts of large estuarine barrages can be high, potentially impacting tidal wetlands and thus the lifecycle of birds and a range of marine animals and plants. The advantages of barrages and lagoons are that the power conversion devices are commercially available, based upon river hydro technology and the power output is reasonably controllable since water can be released at any time other than high tide. However, capital costs and real or perceived environmental impacts mean that, historically, many proposed schemes have not been realised.

3.4.2 Initiatives

The wave energy concepts identified above are generally thought to hold the most promise, but none has yet shown any specific advantage over others. The oscillating, bottom-fixed wave device typified by the Oyster machine from Aquamarine Energy has so far proved functional and more reliable in operation than others. Although its application is limited to certain water depth ranges it is likely to achieve commercial exploitation: Ranking 2. Amongst the resonant energy devices the articulated, floating Pelamis machine has a prototype tested at a power rating of 750kW, although this has encountered mechanical problems and has not yet demonstrated greater potential reliability than other floating machines: Rating 4.

3.4.3 Integration

There is possibly some complementarity with energy storage technologies, and similar issues of connection experienced by offshore wind. Otherwise marine energy systems face unique challenges and it is presently not possible to identify associated developments that would speed deployment through integration or technology transfer.

3.4.4 Risks

The primary risks for wave energy systems are those derived from the hostile operating environment which creates challenges around durability, corrosion, erosion, and extreme events demanding expensive solutions to provide resilience. The inherently remote operation requirements mean that installation, monitoring, maintenance, control and integration, and grid connection require innovations beyond existing technological capabilities. The need to dramatically reduce costs through design improvements is also an imperative as learning curve reductions from the current base will not make systems economic. Finally there are likely to be significant legislative issues arising for deployment based on environmental impact and stewardship, plus an unknown effect of limitations on fishing regions plus public opinion on using 'unspoilt' areas.

Tidal current systems are sub-sea devices and thus avoid the specific problems of operating at the water-air interface, reducing corrosion issues and avoiding most of the extreme events risked by surface systems. Otherwise the technical challenges of remote operation, survival in the sea-water environment, and connection are similar.

Tidal barrage systems avoid almost all such challenges, but instead are inhibited by very high capital costs for the civil engineering and public resistance to their inevitable disturbance to the local environment, flora, and fauna.

3.4.5 Investment scale

The best projections suggest wave devices will require investment not less than $5000/kW when deployed at scale, and tidal current systems probably $2000/kW. Tidal barrage system investment costs are highly location dependent, but $10,000/kW is typical of schemes recently proposed.

3.4.6 Timescale

At present the general view beyond those who actively promote rapid adoption of marine technologies is that deployment of 5GW of systems world-wide is unlikely to occur before 2030 due to the development, engineering, and production cost improvements required to enable significant exploitation.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1	Wave energy TRL 4	Wave energy 15 years
	Tidal current TRL 5	Tidal current 15 years
	Tidal barrage TRL 9	Tidal barrage 5 years

See Attachment A for definitions of rankings

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3.5 WIND

3.5.1 Current status

Wind power technology is already deployed globally and deployment is continuously increasing and perhaps even somewhat accelerating. Wind power systems are either integrated into existing grids or run as stand-alone supply systems of electrical energy where – at in least some regions – previously no electricity was available. Significant questions remain with respect to the issues of intermittency of electricity generation from wind power and its limited capacity factors. Especially in industrialised countries quite often the best locations for wind power generation do not coincide with the industrial and metropolitan centres. This requires additional extensive efforts to upgrade or extend existing electrical grids.

The cumulated installed capacity worldwide in 2011 was 238GW (GWEC 2012). With respect to the installed capacity China has become the largest wind energy nation (with 62GW installed capacity) followed by the US (47GW), Germany (29GW), Spain (22GW) and India (16GW). During 2011 Asia (mostly China and India) was responsible for about half of the newly installed capacity with 41GW, trailed by the US with 17 per cent. The remaining third of the installations was in Europe (approximately 20 per cent) and the rest of the world (GWEC 2012). Different scenarios suggest this trend will be similar for the next decades. The most recent trend in Western Europe is to repower older units with lower capacity units to more efficiently use the increasingly rare places available for onshore wind production in densely populated regions.

In 2009 the global gross electricity production from wind was about 263TWh out of a total of 12,671TWh, or about 2 per cent of electricity generated worldwide in that year (EIA 2012).

The most cost intensive parts of the units are the rotor and tower which represent up to about half of the entire unit cost. Gearbox and generator follow as comparably cost intensive parts. The unit costs contribute to 70 to 80 per cent of overall upfront expenses. In addition, the costs for foundation and grid connection have to be considered (EWEA 2009). To consider an overall cost assessment, the additional expenses for necessary upgrades or extensions of the grid need to be considered. Storage systems of various sizes and types of technology for surplus electricity generated are unavoidable for both on- and off-grid wind-power systems. Especially for small-scale systems the combination of wind and biomass may provide simple but both technically and economically viable solutions. The flexibility of gas storage at biogas plants could be used to store biogas during periods of high wind power generation and to shift the power production from biogas to those periods when there is low wind power production or none all.

Wind power technology can be considered as a mature and competitive technology with regard to onshore power production. Offshore production technology is still marked by significant questions with respect to the cost-effectiveness and durability of wind power systems themselves as well as their connection to the onshore grids due to the aggressive nature of the operating environment. Nevertheless, increasing numbers of offshore wind parks contribute to technology development. Due to higher upfront and maintenance costs, offshore production cost are considerably higher compared to onshore production. Currently the financing of offshore installations is based on significant government subsidies due to their high-risk nature.

3.5.2 Initiatives

Feed-in tariffs (e.g. in Germany, Spain, China and Denmark) have contributed to the unusually fast development and deployment of wind turbines within the last decade. This energy-policy measure can be considered very successful with regard to increasing the share of renewable energies within an energy system in short time. A further beneficial measure is the setting of energy policy targets by governments for the share of renewable energies in the energy system or the development of a technology roadmap. A ranking of these and further initiatives can be found below*:

- feed-in tariffs (rank 1);
- energy-policy targets/roadmaps in combination with fixed commitments to technology deployments (rank 1);
- market penetration programs with low-interest loans or grants for investment costs (rank 2);
- removal of administrative hurdles for granting building permissions of wind

Initiatpower units quickly (rank 3);

- research and development budgets for universities and non-university research institutions (rank 4); and
- information campaigns for private and commercial consumers (rank 4).

There are several alternative tariff systems. The feed-in tariff has been very successfully applied in Germany and in some European countries, while it was not as effectively applied in South Korea. As an alternative a Renewable Portfolio Standard (RPS) system has been introduced in a number of countries including South Korea. A RPS ensures that the public benefits of renewable energy continue to be recognised as electricity markets become more competitive. It requires companies selling electricity to retail customers to support renewable energy generation. The RPS system is based on a tariff and it is regarded as viable in the case of South Korea. The tariff consists of both a system marginal price on electricity and a renewable energy certificate compensating for the carbon emission per energy unit. The system marginal price depends on the price of oil and natural gas worldwide which will vary but have a gradually up trend. The actual price of electricity per kWh can be about 50 per cent higher than those of feed-in tariff system.

3.5.3 Integration

The already significant deployment of wind energy generators causes increasing problems with respect to the integration of large amounts of electricity generated by them into existing grid regarding their topology and capacity. The intermittency of electricity generation and the significant spatial distance (in many cases) between location of generation and usage adds complexity. However, the integration and combination with the accurate forecast of weather on long-term and short-term basis, international grid connection with neighbouring countries as a back-up power supply source as well as the further development of a variety of storage systems (e.g. pumped hydropower, storage, hydrogen, methane, pressurised air storages, etc.) will help to accelerate investment and deployment of wind-power systems.

Another aspect of utilisation and integration of wind power exists in its off-grid application in hybrid mode together with other renewable sources in remote regions. This approach could be especially relevant for developing economies. Integration of a combination of source (e.g. wind, biogenic waste, PV and an appropriate storage technology) through a local micro-grid represents an attractive possibility with limited costs.

3.5.4 Risks

With regard to onshore wind energy production the technological risks can be considered as reasonable low, as large-scale deployment has been achieved worldwide already. A possible pitfall lies in the real-world operating life expectancies only estimated so far due to limited long-term experience in operating large wind turbines over the predicted life span of 20 to 25 years. Technology development is still ongoing especially in the field of gearboxes and increasing the capacity per unit.

With regard to offshore wind energy aspects like grid connection (distance to grid connection point), saltwater resistant concrete basements and the reliability of wind turbine/generator/gear unit components are of great interest and currently a source of persisting problems. The development of offshore technologies and the adaptation of onshore technology to offshore conditions are technically

* Initiatives will be ranked 1-5, where 1 is the most promising and 5 is perhaps promising

challenging. The long distances from mainland and the intensive material exposure due to maritime conditions result in relatively high maintenance costs and finally in higher production cost compared to onshore production.

The introduction of a significant amount of electricity from wind farms both onshore and offshore causes a major challenge to the equipment and management of both the transmission and distribution grid. The intermittency of wind requires the grid operators to heavily rely on wind forecasts for planning an appropriate mix with other types of power plants (fossil, nuclear, and other renewable) to fit the load curve at all times. The introduction of large amounts of electricity from wind farms into the lower-voltage part of the transmission grid or even the distribution grid will result in horizontal or even 'uphill' flows of electricity, i.e., from lower to higher voltage level grid elements – a situation the grid was not planned for. Here the future development of the grid at all voltage levels will have to focus on maintaining grid stability under this very challenging condition.

For both onshore and offshore systems the significant use of various metals as well as concrete results in a significant long-term binding of resources to be accounted for in the framework of life-cycle assessments. Especially for offshore systems this burden poses, at least currently, a significant challenge for this technology.

An aggressive R&D program is being carried out to reduce the cost of electricity in the case of offshore wind power by enlarging the wind farm itself, increasing the unit capacity of wind turbine generator up to 10MW, as well as cost reduction of foundations and improving the installation method. Grid parity for offshore wind farms is expected to be achieved within 10 years.

3.5.5 Investment scale

Capacities of wind power units range from about a few kW to up to about 7.5MW with specific investment costs currently ranging from $1300/kW (plants > 2.5MW) to $1800/kW (plants < 1MW). The Global Wind Energy Council (GWEC) estimates an increase of yearly global investments in wind power industry from about $68 billion in 2010 to $102 billion in 2015, to $137 billion in 2020 and $214 billion in 2030 (GWEC 2011). Up to 2030 the GWEC expects a decrease in specific investment cost from recently about $1700/kW to about $1400/kW (moderate scenario) (GWEC 2012)). A split of onshore and offshore is not made for these estimates but offshore systems tend to be more expensive for the reasons given above. Experimental systems currently tend to cost up to $3000/kW including the electrical connection to land.

3.5.6 Timescale

A significant increase in deployment of offshore wind parks within the next five years is most probable. The GWEC forecasts an average annual growth rate of wind energy production of about 10 per cent within the next five years and estimates that the cumulative capacity will increase from 197GW in 2010 to 460GW in 2015 (moderate scenario)(GWEC 2012). Since even larger wind power units can be deployed within months, technical improvements can be deployed very quickly. Current estimates are that large offshore wind parks can be built within two years' time even against the background of additional planning efforts, greater level of infrastructure, and more complicated grid connection in comparison to onshore wind parks. The experience from the first larger systems built so far is that the construction and operation is in an early phase of the learning curve resulting in delays for both the construction and the connection to the grid.

3.5.7 Other Risks

Especially in densely populated areas the need for acceptance of erecting of wind energy converters near houses has to be considered. Also characteristics of landscapes can be changed significantly by wind parks.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1	TRL 9	Onshore now Offshore 5-10 years

See Attachment A for definitions of rankings

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3.6 BIOMASS

3.6.1 Current status

The most important aspect of biomass use lies in the production of heat for both industrial and household purposes. This involves not only woody biomass but also various organic wastes in solid, liquid and gaseous form.

In the case of power production from various kinds of biomass (wood, straw, manure, bio-waste, energy crops, etc.), conversion technologies range from standard technologies (wood chip boilers in combination with steam turbine, biogas plants) to highly sophisticated ones (gasification plants combined with gas turbines or engines into combined heat and power (CHP) systems). Applied technologies range from technically mature to experimental ones. In 2008 about one per cent of power generation worldwide was based on biomass (IEA 2011b). Global gross electricity production from primary biomass totalled about 198 TWh in 2008 (IEA 2011a).

The third but smallest sector of biomass use is the production of biofuels for transportation purposes. Growing concern about petroleum supplies and environmental consequences of fossil fuels has driven interest in biofuels programmes all over the world. The EU aims at a 10 per cent share for biofuels in 2020. Other regions worldwide have similar plans. First-generation production pathways and fuels (biodiesel/FAME, ethanol from fermentation and biogas) represent the state of the art. Second-generation fuels (synthetic fuels from, e.g. Fischer-Tropsch synthesis, microbial pre-treatment of lignocellulose material, upgrading of plant oil with hydrogen) are in various stages of development but currently do not have a significant market share globally, although Fischer-Tropsch liquids provide about 40 per cent of the liquid fuel demand in the Republic of South Africa. A number of new developments are under way but still require significant R&D expenses. Lignocellulose biomass (LCB) is a possible feedstock for the production of second-generation bioethanol. LCB is less expensive than sugar or starch-based feedstocks, but its conversion to ethanol at present is more costly. The commercialisation of the LCB pathway requires various technological obstacles to be resolved. Microalgae are another potential way to harvest solar energy and turn CO_2 into biofuel. Although microalgae are not yet produced at large scale for bulk applications, recent advances – particularly in the methods of systems biology, genetic engineering, and biorefining – present opportunities to develop this process in a sustainable and economical way within the next 20 years.

The different technologies for heat and power generation as well as biofuel production can be classified with regard to the type of biomass used as fuel, the kind of conversion technology (combustion, gasification, fermentation) or possible interim products (gas, liquid). The low energy-density of biomass compared with fossil fuel require biofuels plants to be built in close proximity to the resources where biomass can be consumed or converted into a liquid fuel instead of transporting it to large centralised conversion plants. This contributes to the difficult economics of biomass-based transportation fuels.

3.6.2 Initiatives

In analogy to the observations for wind-powered systems, feed-in tariffs can be considered very successful with regard to introducing biomass-based electricity generation on a significant scale in a short timeframe. The ranking of measures deemed to be effective to accelerate deployment of biomass-based electricity generation is accordance to the one for wind usage*:

- feed-in tariffs (rank 1);
- energy-policy targets/roadmaps in combination with fixed commitments to technology deployments (rank 1);
- market penetration programs with low interest loans or grants for investment costs (rank 2);

* Initiatives will be ranked 1-5, where 1 is the most promising and 5 is perhaps promising

- research and development budgets for universities and non-university research institutions (rank 4); and
- information campaigns for private and commercial consumers (rank 4).

3.6.3 Integration

In the case of biogas, following gas cleaning including CO_2 separation and removal of contaminants like H_2S and NH_3, methane-rich biogas can be used in other places than the location of its production. By feeding into the existing natural-gas grid, biogas can be transported and used elsewhere for power and – alternatively – heat production or as transportation fuel. The blending of biogas with natural gas may also require, in addition the above-mentioned cleaning of the raw biomass, the adjustment of the heating value by adding other fuels, for example, LPG (propane/butane). The blending with natural gas could contribute to an acceleration of investment in and deployment of biogas production technology.

3.6.4 Risks

While quantitative substitution of fossil fuel by biofuel is not expected to be feasible, augmentation probably is a more feasible pathway. All countries in the world are looking for solutions for their growing energy needs using sustainable resources. The first-generation technologies for bioethanol production based on sugars and starches cannot provide long-term solution. They compete for land with food crops, resulting in misleading cost-benefit analysis. What is needed is an inexpensive, abundant and renewable raw material that does not interfere with food production.

In the case of biomass-based power production using well-established technologies (for example, combustion plants running on woody biomass or bio-waste, biogas plants) only economic risks have to be overcome. Nevertheless technical risks for example exist with respect to straw when used as fuel for combustion processes (there are associated corrosion problems). With respect to gasification plants the combination of technologies for gas production, gas conditioning and cleaning and gas conversion still needs significant improvement via R&D.

Since biomass is a fuel with a rather low specific energy content compared to coal or crude oil and biomass is widely distributed in forests and agricultural land, the transportation cost for sufficient biomass to feed a plant with a large capacity, e.g. > 100MW, is very high. Since transportation costs can influence the fuel costs significantly this may be an economic barrier for the deployment of biomass plants with capacities comparable to conventional power plants. This upper bound in terms of plant capacity leads to technological solutions for an enhanced utilisation of biomass in the energy system.

More decentralised solutions have to be implemented. Small-sized biomass units for an off-grid use have promise in rural areas of emerging economies. Deployable technologies are needed. Here a technology standardisation with viable unit sizes is desirable. The supply of applicable blueprints for building and installation not only by technically trained experts would clearly assist a fast spreading of this kind of equipment. Price stability of biomass resources is of concern, and that includes stability of transport costs.

3.6.5 Investment Scale

In Western Europe investment costs for biogas plants run on energy crops or manure range from \$3200/kWe up to \$5200/kWe depending on type of engine and capacity. Average biogas plant sizes are between 250 kWe and < 2MWe.

Investment cost for biomass power plants, e.g. wood combustion in combination with steam turbine, range between $3600/kWe up to $5200/kWe for CHP units and $2600/kWe up to $3900/kWe for condensation units. Average plant capacities for power production based on woody biomass lie between 500kWe and 50MWe. Investment costs for gasification plants in combination with gas engines are > $5200/kWe.

3.6.6 Timescale

The biomass potential worldwide is limited. The aspect of sustainability for biomass provision is a further limiting factor. In addition to the technical and ecological boundaries, the ethical aspects of competition to food and fodder production and the material use of wood for building purposes or paper production reduce the potential of biomass for a major role in global power production. Under these circumstances, power production from biomass will always be a local option not offering the possibility to meet a major component of power demand worldwide. It is most probably that the deployment of biomass technologies for power production will increase slightly during the next years. But compared to wind, water and solar power technologies, the deployment of biomass technologies will only achieve far lower growth rates.

3.6.7 Other Risks

Implementation of biomass heat and power plants in densely populated areas may lead to a decreasing public acceptance of this technology caused by an increase in traffic due to biomass transport with heavy vehicles and possible unpleasant odour from biological biomass degradation.

Currently, in many countries, the growth of biomass power is constrained by the lack of availability of biomass, as well as sharp increase in the cost of biomass once the commercial use of biomass (such as for biomass power generation) comes into existence. Consequently, issues that need examination include: land and water availability for biomass production; the combination of tree-species and soil types possible; and multi-type biomass fuel technologies.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1	TRL 9 First Generation	Now
	TRL 5 Second Generation	Five to eight years

See Attachment A for definitions of rankings

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3.7 GAS

NOTE: To achieve low carbon energy emissions status, gas combustion must be considered in conjunction with carbon sequestration; see Section 3.9.

3.7.1 Current Status

The use of natural gas (mostly methane) for power generation is a fully established technology. In 2011 it was responsible for 22 per cent of the total electricity generated worldwide. It is also a relatively 'clean' fuel. For the same energy output, it is emits about 40 per cent of the carbon released by burning coal, and about 76 per cent of the carbon from burning oil. This is partly because it has a higher calorific value (50MJ/kg LHV for methane) than coal (about 25MJ/kg) and oil (about 42MJ/kg); and partly because it has more hydrogen per unit of carbon (4:1 for methane, 0.8:1 for coal and about 2.2:1for oil). As part of the extraction, processing and use stages of natural gas there are releases of greenhouse gases (GHG). In some cases these releases can be considerable and when making comparisons with other fuels a full life-cycle analysis of GHG for each fuel source should be considered.

In addition, when used in a combined cycle, gas turbine technology provides some of the highest plant efficiencies currently attainable, approaching 60 per cent, and therefore some of the lowest emissions that are achievable while still using a fossil fuel.

The most common technology for generating energy from methane uses gas turbines. A gas turbine is similar to a jet engine. Air is compressed, the compressed air is mixed with methane and burned, and the hot gases expand through a turbine, doing work as they expand and cool. The expansion turbine drives both the air compressor and the electric generator.

The gas turbine may be run on its own, in which case it is referred to as open-cycle operation, or an OCGT. It is not very efficient, as the hot exhaust gas exits the turbine at temperatures between 540°C and 595°C. This represents a considerable loss of heat, which is why the efficiency can be as low as 35 per cent. However, the very simplicity of the gas turbine run open-cycle has some distinct advantages. It can be built in a very short time compared to most other sources of over 100MW. It can be brought up to power very rapidly, so that it can follow rapid changes in the demand such as occur in many power systems at peak periods. As such, it is almost the generator of choice for peak loads. It can also help balance supply where there are intermittent generators such as wind turbines or solar systems contributing to the supply. It can be fired with kerosene or even gas oil if there is any interruption in the supply of methane.

The exhaust heat can also be used to generate steam, and the steam used to drive a steam turbine to generate more electricity. In this case, it is referred to as combined-cycle operation, or a CCGT. Because the heat is recovered to do useful work, the efficiency rises close to 60 per cent. The exhaust gas is cooled to between 80°C and 135°C before passing to the stack. Depending on the selected gas turbine and the design of the generator, the high pressure steam conditions range anywhere between 4.3 and 17.2MPa (g) with temperatures of 482°C to 565°C. In larger plants, it is common to have two or three gas turbines providing steam for a single large steam turbine. Usually about two-thirds of the total power is produced from the gas turbines and one-third from the steam turbine. The steam from the steam turbine is condensed, and the condensate is returned by condensate pumps. State-of-the-art heavy-duty gas turbine designs have turbine inlet temperatures that reach 1315°C to 1370°C. With gas turbines running at high turbine inlet temperatures, the exhaust temperatures are high and it is possible to include a reheat stage in the steam turbine. A typical modern gas turbine is the GE 9FA. If two such turbines are combined with a single steam generator, the system efficiency is 57 per cent and the power at sea level is 787MW (EPRI 2010).

Methane can also be used to fuel reciprocating engines. Large machines derived from marine technology are available, giving electrical outputs as high as 18MW. They operate on a four-stroke Otto cycle, and can be designed to use either methane alone or methane and at least one other fuel, which has advantages when gas supply may be interrupted. The machines are massive, weighing over 300 tons, but a large installation may have as many as 24 units, giving a total of some 500MW. They are finding increasing use and have proved extremely reliable. They are relatively efficient, about 40 per cent at their rated power. The waste heat can be recovered in combined-cycle operation, taking the overall efficiency to about 50 per cent. A particular feature of their operation is the fact that they can reach full power in less than five minutes from a hot start, which makes them most suitable in load-following duties. Plant construction is also rapid, relative to the amount of power they can produce.

Methane can generate electricity directly in fuel cells. This promises to be highly efficient, because the losses are primarily those due to the internal electrical resistance of the cell. They are therefore leading contenders for minimising CO_2 emissions from fossil fuel use. However, this is still an evolving technology, with few installations >10MW in output. There is insufficient experience with large installations to determine the lifetime of fuel cells in bulk power generation. Many early designs relied on platinum internally, but more recent designs have found solutions that do not require large quantities of precious metals.

Methane is the main source of hydrogen and a source for other simple chemicals. Methanol is of particular interest.

3.7.2 Initiatives

The discovery of means of producing 'unconventional gas' from tight formations by hydraulic fracturing of horizontal wells has meant a huge expansion in natural gas resources in many parts of the world. Some five years ago the world had some 50 to 60 years of gas. Now shale and other unconventional and new conventional gas finds have increased that period to 200 years or more. If development obstacles can be overcome, more gas and lower prices are expected to lead to a rise of 50 per cent in global demand for gas between 2010 and 2035, according to the IEA. In the US, natural gas production has increased from 1.5Gm^3/day in 2007 to 1.8Gm^3/day in 2011 (BP 2012) and now shale gas contributes one-third of America's gas supplies. As a result, the price of gas in the US has fallen to less than half its price in 2007. The low cost of energy from this resource has meant a huge surge in facilities for generating power from natural gas.

Other sources of gas are also developing. For instance, the production of coal-bed methane is now a relatively mature technology, but there are deep coalfields which have still to be developed. Considerable reserves of natural gas as methane hydrate are known, but presently there is no experience in bringing this resource into production. The resource is estimated at between 1013 and 1015m^3. A further source of gaseous fuel is the underground gasification of coal. Deep coal seams are ignited while feeding oxygen or air into the seam, to generate a combustible mixture of carbon monoxide and hydrogen. This process has been developed in several parts of the world and is moving out of the demonstration phase in a number of projects.

As a result of the increasing supply of gaseous fuel, there is a surge of interest in extending power generation using combined-cycle gas turbines, as these have proved to have relatively low capital costs, rapid construction and to be flexible in operation, so that they can cope with quite rapid changes in demand. Moreover, the fact that they are more efficient than open-cycle plants and have lower carbon emissions for a given power output than other fossil-fuel power sources makes them attractive for the provision of base-load power. The use of pipelines for the transmission of gaseous fuels also means that power stations can be sited close to the ocean and use sea-water for cooling. Many existing power systems suffer from limitations on inland water supplies for cooling purposes, so the ability to site plant on the coast is a significant advantage.

Open-cycle gas turbines are widely employed for peak-load generation and for load following where grids incorporate intermittent sources such as wind and solar power. The widespread availability of cheap gas is likely to make this practice even more prevalent.

Research into higher temperature gas turbines would facilitate the combustion of gas with oxygen, and so improve oxyfuel combustion. This in turn would improve the economics of carbon capture for storage.

3.7.3 Integration

Some solar thermal systems incorporate thermal storage. There is a possibility for integration of open-cycle gas turbines with such solar systems, where the waste heat from the turbines is stored in the solar thermal store. In this way, the intermittency of the solar system can be much reduced and the disadvantage of the low efficiency of the open-cycle gas turbine can be overcome. The relatively low cost of the open-cycle gas turbine makes this quite an attractive integration. Reciprocating engines could potentially be used in the same way, but no such experience has been reported.

3.7.4 Risks

There are no critical technology risks in gas turbines or large reciprocating engines. The technologies are as fully established as could be expected. It may be desirable to have even larger turbines or engines, but the impetus for this development seems weak. Fuel cells remain an exciting but emerging technology. Their adoption for large-scale power generation presently seems remote. The technology for converting methane into hydrogen or methanol is proven at a large scale and could readily be implemented if the demand warranted it.

3.7.5 Related technological issues

Open-cycle gas turbines and reciprocating engine generation can be integrated smoothly into existing grids. Their relatively good dynamics allow a high degree of load following, so they are particularly suited to peaking duties. Combined-cycle gas turbines are less flexible, but there are developments which would improve their flexibility and make them suitable as mid-merit stations.

3.7.6 Investment Scale

A recent study has shown that CCGT is presently one of the lowest cost options for generation; the levelised cost of electricity from CCGT is some $0.065/kWh to $0.100/kWh (in 2010), for gas costing the equivalent of some $6/GJ. Capital costs are of the order of $550/kW to $700/kW installed for open cycle gas turbines and $800/kW to $1000/kW installed for combined cycle gas turbines. Production costs are of course vulnerable to gas price variations, but it seems likely, in view of the large gas discoveries in recent years, that prices will be stable in at least the medium term. OCGT and reciprocating engines are also highly favoured for peaking duties, and the reciprocating engines are very cost effective in mid-merit situations, particularly once account is taken of the relative speed of construction.

3.7.7 Timescale

It is estimated that a 790MW CCGT station could be constructed in 30 months. OCGT and reciprocating gas engines can be installed in even shorter times, always depending on the delivery times for the equipment. There have been occasions in recent years when the manufacturers have had full order books, and this has caused construction delays.

3.7.8 Other Risks

Provision of cooling water may be a limitation in some circumstances. Environmental permitting is always a risk, but gas turbine plants generally have been found acceptable even in urban environments. Few instances of installation of large reciprocating engines in cities have been identified, and it may be that concerns of vibration may mean that relatively remote locations are preferred.

3.7.9 Carbon Capture and Storage (CCS)

While gas-fired plants emit less than half of the greenhouse gases emitted by a typical pulverised-fuel boiler plant, they do not readily adapt to CCS except in the post-combustion mode. Precombustion or oxyfuel combustion requires replacement of the actual gas turbine in almost every instance. Achievement of reduced carbon emissions is therefore inherent, but achieving zero carbon emission is very costly.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
3	TRL 9	Immediate

See Attachment A for definitions of rankings

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3.8 COAL (INCLUDING IGCC & CARBON CAPTURE)

NOTE: To achieve low carbon energy emissions status, coal combustion must be considered in conjunction with carbon sequestration; see Section 3.9.

3.8.1 Current Status

Coal provides about 40 per cent of the world's electricity and this proportion is expected to increase due to the availability of coal in most regions of the world at a relatively low cost. An average coal power plant in the world has about 30 per cent efficiency and produces 1116g CO_2/kWh, which is about 2.2 times more than CO_2 form natural gas[1,2]. Coal also produces pollutants such as SOx, NOx, and particulates. For coal to be a competitive energy resource in a low-carbon society, the efficiency of coal-fired power plants must be improved, and the emission of CO_2 and pollutants must be reduced.

At present, coal power technologies include pulverised coal combustion (PCC), circulating fluidised bed combustion (CFBC), and the integrated gasification combined cycle (IGCC). PCC is the predominant technology, accounting for 98 per cent of world coal-fired capacity, CFBC accounts for the rest, and IGCC is not yet fully commercialised. Most IGCC plants operating or being constructed are at least partly government supported.

PCC will continue to be a predominant coal power technology, and it is crucial for PCC plants to be ready for higher efficiency and CO_2 capture. A high efficiency of 37 to about 42 per cent, which is comparable to IGCC, is obtained in supercritical pulverised coal combustion (SCPC)[3]. Even higher efficiency is expected in ultra-supercritical pulverised coal combustion (USCPC). Even though SCPC is a mature technology and is widely used, a large fraction of PCC is a conventional subcritical process, especially in developing countries. A mix of SCPC and USCPC is expected to grow in the next 10 years.

CO_2 capture in PCC is accomplished either by post-combustion capture or by pure oxygen combustion (oxy-fuel combustion). The post-combustion carbon capture removes CO_2 by scrubbing flue gas using a solvent such as amine. The post-capture process is in the deployment stage with several large scale pilot tests in progress. However, the process is challenged by problems such as corrosion, solvent degradation, and a high penalty on generation efficiency (since up to 30 per cent of the power generated is required to desorb CO_2 from the absorbent). Oxy-fuel combustion generates flue gas concentrated in CO_2, which makes the removal easier. The efficiency penalty is similar to post-chemical scrubbing, but it has better process economics and is expected to be a more viable technology in the future. A new oxygen production technology may further reduce the cost. Several pilot tests, some as large as a 30MWe scale, are in progress and oxy-fuel combustion is expected to be deployed in the next 10 years. Other CO_2 capture technologies for PCC that are in development are advanced reactive absorbents and other means of physical separations, such as membrane separation.

IGCC has a potential for greater use in the near future due to its high efficiency, easy adaptability for CO_2 capture, and a much lower level of pollutant emissions along with a lower water usage than conventional PCC. There are 17 IGCC plants operating at present and four plants, including one 630MW scale, are under construction worldwide; it is expected that there will be more than a 100 per cent increase in the number of plants by 2016[4]. IGCC technology has been dominated by three vendors: Shell, General Electric, and Phillips 66. They all use entrained flow gasifiers that operate at a high temperature and pressure, and sub-bituminous to bituminous ranks of coal are dominant fuel sources. Other minor vendors for IGCC include ThyssenKrupp Uhde (Prenflo process), Siemens, MHI, and the recently formed Uhde-KEPCO. They either have demonstration plants operating or projects being developed. China also has several on-going gasification projects and has developed their own IGCC processes. The largest Chinese IGCC plant of 250MWe is in the construction stage and uses a gasifier designed by the Thermal Power Research Institute in Xi'an. Apart from entrained bed gasifiers, fluidised bed gasifiers are also available worldwide at smaller scales for low rank coals (lignite in the US ASTM system and brown coal in the European system).

The carbon capture in IGCC using a physical/chemical solvent is a commercially proven technology, and takes much less penalty in efficiency compared to post-combustion carbon capture of PCC. Most commercially proven Acid Gas Removal (AGR) processes can be used for CO_2 removal. AGR processes frequently used in IGCC are Selexol, which is often used in GE processes, Sulfinol in the Shell process, amines (MDEA), and the Rectisol process. The most preferred process at present is a two-stage Selexol where H2S is removed in the first absorber and CO_2 is removed in the second stage. Even though the penalty on efficiency is lower than PCC, it is still at a 4 to 6 per cent level. This loss in efficiency in part can be made up by a hot or warm gas clean-up of H_2S and CO_2 using solid sorbents. A combined warm clean-up with an amine process can give a higher efficiency at lower capital cost and produce high purity CO_2 for sequestration. Other carbon capture technologies that are in development are advanced high temperature sorbents and membrane separation.

3.8.2 Initiatives

A number of technology developments are described in the previous section. In addition, the creation of a worldwide carbon market or a carbon constraint can make clean coal technology based on CCS economically more viable, and will help a faster deployment of carbon capture. Tightening regulations on CO_2 emissions and other pollutants will give IGCC more advantages as a clean coal technology than SCPC, and will help a faster deployment of IGCC.

3.8.3 Integration

SCPC with oxy-combustion requires an optimised integration with new oxygen generation. For IGCC, co-production of H_2 and chemicals along with power (poly-generation) may improve the viability of IGCC. IGFC (Integrated Gasification fuel Cell) is considered to be a future technology that can increase the efficiency significantly. Even though deployment plans for the near future are often shown in technology roadmaps of several countries, actual deployment timing is quite uncertain.

Improved efficiency can be obtained through combined heat and power (CHP) generation where demand for useful heat exists, as recognised in the CHP Directive by the European Union in 2004. High efficiency cogeneration plants can result in a major reduction in carbon emission.

For both SCPC and IGCC, a full integration of CO_2 capture, transport and injection needs to be demonstrated. Regulations and transportation guidelines need to be implemented to ensure safe transport, durability of the transport infrastructure and effective and efficient use of the transport capacity.

3.8.4 Risks

The two biggest risks are the high cost and operability of coal power combined with CCS. IGCC plants are not fully commercial due to high plant cost and low availability. The capital costs of an IGCC plant are about 30 per cent higher than subcritical PC without carbon capture, but are comparable to subcritical PC and SCPC plants with carbon capture. In order to be more cost competitive, the capital costs of IGCC need to be reduced. This can be achieved by several means, such as use of a CO_2-coal slurry instead of water-coal slurry, high temperature and high pressure sulphur/CO_2 recovery, advanced gas turbines, ion transfer membranes (ITM) for O_2 separation, etc. The availability of IGCC is expected to improve with an accumulation of operating experience with the planned increase in IGCC. Development of reference plants will significantly increase the reliability and availability of IGCC plants.

Commercial-scale USCPC power plants are being installed worldwide today with efficiencies as high as 44 per cent. Further improvements in efficiency require new materials for high temperatures and pressures in USCPC boilers and steam turbines. Development of new nickel-based alloys is in progress developed with the aim of 46 per cent efficiency.

Low rank coal makes up about 18 per cent of world recoverable coal reserve[5] and is one of the most under-utilised fossil fuel resources. Increased utilisation of low-rank coal in power generation requires major efficiency improvements and reduction in greenhouse gas emission, which demand a different set of technology developments. The efficiency improvement can be achieved in various ways, such as use of an advanced supercritical steam cycle and more efficient turbine, and pre-drying coal with waste heat, etc. IGCC using a fluidised bed or transport bed gasifier, combined with advanced drying technology, has potential for a greater application in the future. Use of low rank coal in IGCC using a high temperature entrained flow bed gasifier can also be explored by improving the feed system, such as using a liquid CO_2 slurry feeding or advanced dry feed system.

3.8.5 Investment

The addition of CO_2 capture capability in both IGCC and SCPC reduces efficiency and increases plant capital costs. With currently available technologies and bituminous coal as a fuel, SCPC and IGCC without carbon capture show similar efficiencies: SCPC at 39.9 per cent and IGCC at 39 to 42.1 per cent[6]. With carbon capture, SCPC has a much lower efficiency than IGCC, showing 26.2 per cent vs. 31 to 32.6 per cent for IGCC. The cost of electricity for IGCC without carbon capture ranges from $0.074/kWh to $0.0813/kWh (in 2007 $), which is higher than that of SCPC at $0.0589/kWh. The cost of electricity for the two technologies is more competitive than with carbon capture: SCPC shows $0.1066/kWh and IGCC ranges from $0.1056/kWh to $0.1194/kWh, depending on the vendor6. The capital costs for SCPC and IGCC are also comparable with carbon capture: for example, the total overnight cost (TOC) for IGCC without carbon capture ranges from $2300/kW to $2700/kW (in 2007 $), which is higher than that of SCPC at $2000/kW. The TOC with carbon capture for SCPC shows $4000/kW and IGCC ranges from $3800/kW to $4400/kW. (The TOC is equivalent to the present value cost that would have to be paid as a lump sum up front to completely pay for a construction project.)

3.8.6 Time Scale for Deployment

The individual technologies of CCS are making headway and it is important that each technology be demonstrated at full scale. It is also crucial to generate economic competitiveness by the design of an integrated CCS-optimised coal power plant through research and demonstration. Several demonstration projects of PCC and IGCC with CCS are planned under government sponsored programs, such as FutureGen (US), UltraGen (EPRI in US), ZeroGen (Australia), GreenGen (China), HypoGen (EU), etc., in the next several years[7-11]. The success of these projects will reduce uncertainties in cost estimates and feasibility of CCS and will make clean coal-power a strong competitor in LCE technologies.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1 or 2	TRL 7	10 years for IGCC 20 years for IGCC with carbon capture /USCPC with carbon capture

See Attachment A for definitions of rankings

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3.9 CARBON SEQUESTRATION

3.9.1 Current Status

For as long as people continue to use fossil fuels, a technology that is able to substantially decrease the CO_2 emittedfrom that use is carbon capture and geological storage (CCS). CCS involves the capture of CO_2 from major stationary sources (power stations, industrial plants etc.), compression and transport of the CO_2 (usually by pipeline) and injection into suitable geological formations such as deep saline aquifers and depleted oil or gas fields that will safely and securely store the CO_2 for thousands of years and longer.

All the individual components of the CCS chain are well known but there are few commercial-scale operations that demonstrate the integrated process. All of the operational large-scale projects at the present time are linked to petroleum projects in some way (Sleipner, In Salah, Weyburn, Snovit); the Gorgon Project, which is presently under construction and will be the world's largest storage project (more than three million tonnes CO_2 per annum under Barrow Island) is part of a major LNG project. A key technological challenge is to cost-effectively apply CCS to coal or gas fired power generation. The 2012 report on the global status of CCS by the Global CCS Institute (Global CCS 2012) indicates that there were75 existing or proposed large scale integrated CCS projects of which 4 are active, 4 under construction and the remainder at various stages of planning. G8 governments have made commitments to supporting 20 large-scale plants by 2020.

3.9.2 Initiatives

The following are some key initiatives that will accelerate investment in carbon sequestration:

- an increasing carbon price trajectory over a 10 to 20-year period that can be expected to realised with some certainty;
- demonstration plants that show the technology is operable and which can be used to help define the risks to deployment in other installations;
- regulations that can be used to manage identified risks associated with long-term storage of CO_2; and
- identification of safe and secure storage sites.

3.9.3 Integration

The energy used to drive post-combustion carbon capture and storage plants can consume up to 20 per cent of the total energy generated by a power plant, and this is a significant disincentive to implementation. With energy integration, i.e. making use of waste energy streams from power stations, this can be reduced to 10 to 15 per cent, but it is still significant. Although this is a large amount of energy, it is at a relatively low temperature, typically being in the range of 100°C to 120°C, which is used to run the boiler to release pure CO_2 from the loaded solvent. It is possible that at least part of this energy could economically be supplied by geothermal or solar. The integration of CO_2 compression and injection with wind power at offshore platform site may also be possible. Further, CO_2 storage in existing oil and gas resources can lead to enhanced gas and oil recovery given the correct geology and this is increasingly of interest in North America as a platform for CCS.

3.9.4 Risks

The high cost of CCS is a major risk, with capture likely to represent a major cost component of any CCS project. One option for bringing down capture costs is through gasification with pre-combustion capture, but this involves very high initial capital cost for integrated gasification and combined-cycle combustion (IGCC). Because of this, increasing attention is being given to post-combustion capture. The need to keep energy losses associated with solvent regeneration is a significant risk associated withpost combustion capture (PCC) but improved process integration can potentially address this issue in part. Hybrid technologies also offer potential advantages; these include for example gas-liquid membrane absorption, adsorption and hybrid organic-inorganic membranes.

Uncertainty about the deep geology is a technological risk in many areas of the world: Are suitable reservoir rocks present at the right depth? Is there a good impermeable seal? What is the likely porosity and permeability of the rocks? These types of questions can only be resolved through detailed geological surveys, including deep drilling and geophysics.

One of the advantages of CCS is that most of the existing electricity infrastructure can be retained. However there would be a need for a new pipeline infrastructure. It is important to minimise the possibility of stored CO_2 adversely impacting on other Earth resources notably groundwater and oil and gas deposits. Long-term monitoring of stored CO_2 will be necessary to give confidence in the technology to the community. Studies of sub-surface reactions of injected $CO_2$with minerals are important to understanding very long-term storage. The possibility also exists of surface mineral storage, using the reaction of CO_2 with aluminosilicates such as serpentinites to form carbonate minerals, but in general, costs of this option appear to be very high at present compared to sub-surface geological storage.

3.9.5 Investment

The existence of several petroleum-related CCS projects demonstrates that under some circumstances CCS in already viable. The challenge is to deploy CCS in the electricity generation sector in the absence of economic or policy drivers. At the present time CCS in a favourable location is likely to be significantly cheaper than some of the renewable options but the investment decision will be location and project specific. Like all clean energy technologies, CCS will require some form of government assistance to take it forward.

Projections suggest black coal, super critical with CCS, will require an investment some $4000/kW to $5500/kW when deployed at scale and this can be expected to drop to some $3000/kW after a further 10 years of deployment.

3.9.6 Timescale

CCS faces no insurmountable technological barriers and could be deployed now, as demonstrated by projects such as Weyburn. 'Economic' deployment will be totally dependent on what price is set for carbon, or what level of government financial assistance is available, or what society is prepared to pay for 'clean electricity'. The G8 support for 20 large-scale CCS projects by 2020 is the best indicator of time scale for deployment at the present time, but the large scale Gorgon storage project will be operational by 2015-16.

3.9.7 Other Risks

Not all countries have established a regulatory regime for CCS and this could inhibit its deployment if not addressed. However a key risk arises from community uncertainty regarding the safety of the technology. There are many technical reasons for regarding the CCS as safe but this has to be more effectively transmitted to the community. The CO2CRC Otway project in Australia has been outstandingly successful in securing community support for carbon sequestration on a modest scale.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1	TRL 6	10+ years

See Attachment A for definitions of rankings

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3.10 NUCLEAR ENERGY

3.10.1 Current Status

In 2011 the power production from fission reactors amounted to 2518TWh representing a share of 13.5 per cent of the total global power production (WNA 2013). The corresponding numbers for 2008 were 13.4 per cent (IEA 2011) and for 2010 2630TWh/12.9 per cent (WNA 2013b, IEA 2012). By 2011 the total number of commercially operated nuclear power plants was about 435 and the global installed capacity was about 375GWel (WNA 2011). Thus the average capacity is about 850 MWel per plant, and the overall load factor is about 77 per cent.

Thirty countries currently use nuclear technology for power production (WNA 2013). The countries with the largest power production were in 2011 the US (790TWh/2010: 807TWh), France (424TWh/2010: 410TWh), Japan (156TWh/2010: 280TWh), Russia (162TWh/2010: 159TWh), and South Korea (148TWh/2010: 142TWh) (WNA 2013a, WNA 2013b). An examination of the number of plants under construction shows clearly that China will soon be also one of the leading nuclear countries. In 2011, China had 29 plants under construction with 51 more planned, in Russia 10 (24 planned), in India seven (18 planned), in South Korea four (five planned), in Japan three (10 planned), in Pakistan two, in Slovakia two, and one each in Argentina, Brazil, Finland, France, the UAE and the US (WNA 2013a).

The existing reactor types can be classified by various criteria. These are the type of nuclear reaction (uranium or thorium nuclear fission), type of moderator (graphite, heavy or light water, light elements like beryllium or boron, organic material), type of coolant (water, molten metal like sodium, gas, or molten salt) and technology generation (I, II, and III, with generation IV technologies still under development).

The following are examples of the types of nuclear plants:

- in the category of Light Water Reactors (LWR), the Pressurised Water Reactor (PWR), the Boiling Water Reactor (BWR) and the European Pressurised Water Reactor (EPR), based on the PWR design with an evolutionary safety design. The standard modern LWR reactor types of Generation III are PWR and BWR;
- there are two types in the category of Heavy Water Reactors (HWR), namely the CANDU-Reactor (Canada Deuterium Uranium) and the Pressurised Heavy Water Reactor (PHWR); and
- under development are thermal reactors and fast reactors such as the Gas Cooled Reactors (GCR), the Advanced Gas Cooled Reactors (AGR) and the Liquid Metal Fast Breeder Reactor (LMFBR). These Generation IV designs represent alternative technological options with specific applications like the hydrogen production in the case of AGR.

Generation IV reactors may offer a chance for sustainable nuclear energy generation in the longer term. Breeder reactors are expected to achieve a significant reduction of toxicity of high-level waste, so reducing the storage time needed to a few centuries instead of millennia. These reactors are expected to be deployed commercially around 2030.

The LWR family of reactor designs has its roots in naval applications (surface ships as well as submarines) and was originally not designed to be optimal with respect to the efficient generation of heat and power. Their thermal efficiencies are less than 35 per cent due to lower steam parameters, mainly for safety reasons on ships in contrast to land-based power plants fired with fossil fuels.

Another handicap of current Generation II and III design lies in the low utilisation of the energy contained in the uranium fuel. In these reactors only about 0.5 per cent of the total energy available is actually used before the fuel rods need to be exchanged due to poisoning by fission products. This normally means reprocessing of these used fuel rods to remove the unwanted by-products. It is expected that Generation IV reactors consume a much higher degree of uranium fuel, for example, 90 per cent.

A principal remedy for the low fuel consumption of Generation II and III reactors is to reprocess the used fuel rods and to remove the unwanted by-products. On the downside, this processing of large amounts of radioactive material may contribute to the risk of proliferation. Plutonium generated in LWRs is not as effective as further processed weapon-grade material usable for standard nuclear weapons, but nevertheless it may be used in so-called 'dirty bombs' (DOE1994).

The nuclear fission technology has been used commercially since the 1950s and represents a mature technology within the constraints mentioned above. Due to the comparably high damage potential for human health and life as well as the environment in case of severe incidents, safety aspects are integral to the use of this technology.

Safety aspects are not just related to the operation of the nuclear power plants and the conversion technology but also to the treatment and storage of the continuously accumulating highly active nuclear waste. Worldwide the search for stable geological formations (granite, salt or clay) for the final nuclear waste disposal, especially for highly radioactive material, is still ongoing. Here, not only technological challenges need to be dealt with but at least equally important the public debate strongly influences this searching process. In Finland, this debate led to an almost unanimous parliamentary vote, accompanied by strong local support, for a deep geological repository. In Sweden, the process is at an earlier stage, but currently two potential sites for a deep geological repository are being investigated in detail. In the US, creation of the Yucca Mountain site for a deep geological repository is still, despite an earlier positive decision in Congress, heavily debated with an uncertain outcome. Even in France, with a significant public support for nuclear power, the search has not proceeded beyond developing an underground laboratory to assess potential sites for a deep geological repository (WNA 2013c). Consequently, the long-term deposition of high-level nuclear waste has to be viewed as an open challenge at least to the majority of most western democracies.

Alternative processing options like partitioning and transmutation (P&T), promising key technologies for reducing the radiotoxicity and volume of radioactive waste produced, are very sophisticated and energy consuming and are not yet ready to be commercially used.

Nuclear fusion has been a technologically promising goal for the past 50 years but must still be regarded as a technology quite distant from operational implementation. For the foreseeable future it will remain in a research and demonstration phase with possible commercial designs available around 2050+. Currently a focal point of activities with respect to nuclear fusion and its application can be found in Cadarache, France. The construction on this technology-demonstrator site began in 2010 with 34 nations collaborating. It is currently estimated that this project will cost $17 billion to complete. Operation is expected to start at the end of the year 2020 (Iter 2013). If a technically reliable solution can be found, huge further investments in development and implementation of this technology would be likely.

3.10.2 Initiatives

R&D for Generation IV nuclear power plants is still ongoing. Currently, huge investments in Generation III technology are being made, especially in China and Russia. Future Generation III+ and IV reactors may result in enhanced sustainability of nuclear energy. As mentioned above, higher thermal efficiency and significantly better use of the energy content of the uranium fuel combined with improvement of the overall system safety are the most important aspects of the introduction of Generation IV systems. These reactors are expected to increase the use of fast neutrons by a factor 60 compared with currently used reactor designs.

Another technological line of development is the small- to medium-sized Generation III reactors. Such smaller, modular reactors could provide scalable power at lower financial risk. They could also do this in remote off-grid areas (IEEE 2010). Two design examples investigated currently are NuScale and Hyperion.

NuScale represents a variant of a PWR. The basic design of a single module aims at a thermal power of 160MW. These independent modules can be combined into larger installations. The nuclear fuel assemblies sit inside a long core vessel, which in turn is housed in a secondary containment vessel immersed in water. Unlike conventional light-water reactors, which require large pumps to circulate water through the core, the NuScale reactor is based on convection. The certification process by the US Nuclear Regulatory Commission has been initiated, and the company expects to have first commercial installations in the early 2020s.

The Gen4 (formerly Hyperion) power module (HPM) is a fast, namely unmoderated, reactor with a thermal power of 70MW. This class of reactor uses a larger mass of fuel (uranium nitride), which releases many more neutrons. Also helping drive the process is the coolant, a lead-bismuth mixture. The reactor would be built underground. Instead of refuelling it onsite, the complete reactor would be replaced every 10 years. Currently no time for commercial deployment is given.

Additional design efforts are devoted to concepts aiming to integrate reactors with fuel-reprocessing facilities to reduce the risk of proliferation.

Thorium-based fuel reactor concepts may open another long-lasting pathway for the use of nuclear energy, although currently they are a long way from commercial deployment. An example for this reactor design is the liquid fluoride thorium reactor (LFTR) (Berk 2012). LFTRs employ a thorium fuel cycle where thorium-232 is used as fertile material and this is transmuted into fissile uranium-233. Natural thorium-232 has only trace amount of fissile material. The LFTR acts as a breeder reactor for uranium-233 through neutron capture. After neutron capture, the thorium-232 undergoes radioactive decay to produce uranium-233. Thorium is also much more abundant than uranium, and is in a single isotope, so it does not require isotope separation. Since a LFTR operates at a high temperature, its thermal efficiency of 45 per cent is higher than other power reactors.

In general, investment decisions in nuclear technology are influenced both by energy policy settings and by microeconomic aspects. While industry has taken advantage of the economy of scale to drive down power costs, the large upfront costs as well as long construction schedules make it difficult for utility companies to commit the large capital investments required to realise new nuclear reactors. For some utilities a single nuclear power plant can constitute the bulk of the utility's income base. Additionally, huge expenses for R&D are necessary for each new generation relying heavily on governmental spending.

Taking into account the challenges involved in increasing the number of installed nuclear power plants under the varying political, legal, and economic frameworks in different countries no single pathway or initiative can be identified resulting in a major growth of this field. A mixture of R&D, technology demonstrations, government subsidies, and consortia to reduce asset concentration risk under the different kinds of regulatory frameworks for safety regulation will be needed to maintain the current base of installed capacity and its possible long-term evolution. An international and wide-spread introduction of carbon prices and emission trading schemes may also contribute not only to an increased use of renewables but also to a wider use of nuclear energy technology.

3.10.3 Integration

Nuclear power generation is a stand-alone technology mainly for base-load electricity generation. The integration potential with other technologies is limited. The combination with fluctuating renewable sources like wind and PV leads (when preference is given to these as is presently the case in Germany) to the need for a very dynamic operational mode of nuclear reactors; this has been proven technically possible. An open question with respect to this dynamic operation is whether it will possibly have negative influence on the expected lifetime of the reactor components.

A possible exception is the use of process heat at about 950°C from pebble-bed reactors as part of an integrated coal gasification combined cycle process (IGCC) or similar chemical processes including generation of hydrogen. Currently there is no date for a market entry.

3.10.4 Risks

Clearly there are technological risks associated with nuclear power generation, as there are risks associated with the application of any technology. The level and nature of risk that is associated with events that are beyond the maximum credible accident are difficult to define and to quantify. The globally well-known accidents in Harrisburg, Chernobyl and Fukushima have shown that not all risks can be fully assessed in advance. It is possible to express risks for each technology in terms of number of deaths per TWh of electricity generated. This shows that fossil and renewable generation process chains are also associated with quantifiable risks (in some cases large, e.g. in mining of fossil fuels or construction of power plants). Nevertheless, a severe nuclear accident in a densely populated area of a highly industrialised nation may result in catastrophic consequences for that nation.

With respect to nuclear waste, there has been a significant progress in the development of matrices to hold high-level wastes and containers that have extended safety and life (NAP 2012). A possible pre-treatment before storing high-level nuclear waste can be the so-called transmutation and related separation technologies. These technologies, which are applicable for long-living and toxic radionuclides, are in advanced stages of research and development. They may represent a robust means of reducing the toxicity and storage life to less than 1000 to 3000 years for high level waste. These developments may result in reduced repository space, a reduction of the heat released to the immediate storage area, and the reduction of the overall radiotoxicity of the storage inventory (EPS 2004).

3.10.5 Investment Scale

Research and development activities for the further development of fission technology (Generation IV) and fusion technology will require huge investments. The major question of the final disposal of (highly) radioactive waste has to be solved, which will require further research and investigations into adequate geological sites and radiation protection.

A report by the Electric Power Research Institute (EPRI 2011) assumed that the technology of large reactors would be based on existing technology, so that the levelised cost of electricity would not change in the 2015 to 2025 time frame. The capital costs for a 1400MW PWR reactor with a load factor of 90 per cent are estimated to be $5100/kW to $5700/kW resulting in a levelised cost of electricity of $0.076/kWh to $0.087/kWh.

It is important to distinguish between the economics of nuclear plants already in operation and those at the planning stage. Existing plant operations and maintenance (O&M) and fuel costs (including used-fuel management) are, along with hydropower plants, at the low end of the spectrum. US figures for 2011 show costs of $0.0181/kWh to $0.0271/kWh (NEI 2011).

3.10.6 Timescale

The technology of Generation II and III reactor designs is mature and established worldwide. Despite this technology's maturity, construction lead times constitute a major impediment to deployment for nuclear power, particularly in times of uncertain load growth and competitive alternative technologies. To some extent this is the result of the large scale of units. A typical output is 900MWe. A thermal power station of this size takes almost as long to build, and faces the same uncertainties regarding load growth.

Generation IV reactors - especially breeder reactors - have been tested as prototypes and demonstration installations of various sizes in several countries (e.g. France, Japan, the US). Substantial operational problems have clearly showed the need for significant additional R&D activities. Creating extra fuel in nuclear reactors introduces new challenges; for example, plutonium produced can be removed and used in nuclear weapons. To extract the plutonium, the fuel must be reprocessed, creating radioactive waste and potentially high radiation exposures. For these reasons, US fuel reprocessing has been effectively stopped since the late 1970s, making the use of breeder reactors problematic.

3.10.7 Other Risks

A number of significant challenges stand in the way of a substantial increase in nuclear generation, part of them related to public concerns world-wide regarding nuclear waste (NAE 2012), proliferation of weapons-grade material, and safety, especially following the Fukushima accident. In highly industrialised countries, where public concerns are limiting the rate of nuclear power expansion, resolution of those concerns within the next decade is essential if nuclear power is to play an important role in expansion of LCE technologies by 2035.

The various kinds of societal reactions to the Fukushima accident given below represent by far not a complete list but highlight the breadth of country-specific political evaluations of respective local situations and responses.

A very specific response to the Fukushima Daiichi incident in July 2011 was the decision by the German government to phase out the nuclear power generation by 2022 and to switch over to a renewable based power production. In the year 2010 about 22 per cent of the German gross electricity production was generated in 17 nuclear power plants. This share will be reduced stepwise following a detailed plan for the remaining operation period of each plant. Currently, it is not yet clear how there will be compensation for the phase-out of the nuclear power generation. During a transitional phase, the continued use of old coal-fired power plants results will, at least in the near future, increase Germany's GHG emissions.

Japan's previous government, after an extended review of the events and consequences of the Fukushima Daiichi incident, announced in late summer 2012 its intention to shut down all nuclear power plants by 2030. This is being intensely debated in the country, with the newly (autumn of 2012) elected government intending to reverse this decision. Nevertheless, the government plans to introduce significant new regulations for the operation of existing nuclear power plants, making a restart of some of the existing plants questionable.

In other regions of the world the outcome of the Fukushima incident has been different. One example is Japan's near neighbour South Korea, which has also an active geology and 21 largely coast-based reactors producing 30 per cent of its electricity. Following careful review, that country has confirmed its plan to increase its nuclear network to 40 units by 2030 to produce nearly 60 per cent of its electricity demand. South Korean reactors are increasingly finding a world market for their designs.

Technology Ranking Table

Ability Lower Carbon Footprint	Technology Readiness Ranking	Timescale for Wide Deployment
1	TRL 9	Now (Generation II / III) 15-25 years (Generation IV) 35-50 years (fusion)

See Attachment A for definitions of rankings

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3.11 SUMMARY TABLE

Based on the information contained in each of the preceding technology assessments, the following summary table has been prepared. It should be noted that care should be taken in interpreting this table. Reference should be made to the relevant technology assessment to obtain appropriate detail and some of the information is subjective and the assessments will vary from country to country.

See table over page ▶

Comparative Assessment of Various LCE Technology Options

	HYDRO	SOLAR	GEOTHERMAL (Hot dry rocks)	NATURAL GAS	MARINE/ TIDAL	WIND	BIOMASS	COAL Plus Carbon Capture	NUCLEAR (GW Scale)
Technology readiness level (TRL) (see Attachment A)	9	6 -8 (TH) 3 - 4 (PV)	4 - 5	9	4 (Wave) 5 (Tidal) 9 Tidal barrage	9	9 (1st Gen) 5 (2nd Gen)	7	9
Timescale for wide deployment (years)	Now	10+ (TH) 15+ (PV)	15	Now	15+ Wave & Tidal 5 Tidal barrage	Now (onshore) 5-10 (offshore)	Now (1stGen) 8 (2nd Gen)	10 IGCC 20 IGCC + CC	Now Gen II/ III 15-25 Gen IV 35-50 Fusion
Ability to lower carbon footprint (see Attachment A)	1	1 – 2 (TH) 2 – 3 (PV)	1	3	1	1	1	1 - 2	1
Most promising initiative for accelerating deployment	Design standardisation	TH: efficient thermal energy storage	Hot dry rock demonstration plants of > 50MW	NG from unconventional geological formations Fuel cells	High efficiency devices	Feed-in tariffs and commitments to technology deployment	Feed-in tariffs and commitments to technology deployment	Carbon market and carbon emission constraints	Higher efficiency and improved safety Reduced capital cost
Integration and combination of technologies – possibilities	Pumped storage system	PV backed by pumped storage; solar-coal & solar-gas hybrids	Use solar for additional water heating & geothermal for heating water in fossil fuel generation	Use hybrid solar & OCGT, also use waste heat with solar thermal storage. Use with CCS	NA	Combined with PV &/ or pumped storage	Biomass to biogas & supply to natural gas grid	IGCC & SCPC need integration with CCS	Stand alone technology Process heat from pebble bed reactors as part of IGCC
Risks for deployment: Engineering Environmental Social Economic (See Note #2)	 Low High Moderate Low	PV: High Moderate Low High	 High Moderate Moderate High	 Low Moderate Low Low	 High Moderate Moderate High	Onshore: Low Low Moderate Moderate	 Moderate Low High High	 Moderate Low Moderate High	 Moderate Moderate High High
Engineering challenges for deployment at scale	New site selection	New site selection	System integration and grid connection	Deep drilling & extraction from unconventional wells Combine with CCS	Onshore-offshore electrical networking; device lifetime and costs	Offshore wind energy installations	Costs of transporting fuel to plants Develop small-size plants for off-grid	High cost and operability of coal power with CCS	Reducing the capital cost

1 TH = solar thermal power systems. PV = advanced technology photovoltaic cells; these include organic PVs, thin film PV materials, multi-junction cells, quantum dot sensitised systems and ultra-thin absorber devices.

2 The listed Risks for Deployment are highly subjective and will certainly vary from country to country.

3 Nomenclature

CCS	Carbon capture and storage	GW	giga watt	IGCC	Integrated gasification combined cycle	NG	Natural gas
OCGT	Open cycle gas turbine	PV	Photovoltaic – advanced technology	SCPC	Supercritical pulverised coal	TH	Solar thermal power systems

4 Technology Overview – Broad Findings

4.1 PROMISING INITIATIVES TO ACCELERATE INVESTMENT AND DEPLOYMENT

A wide range of LCE technologies for power generation has the potential to contribute significantly to reduction of carbon emissions world-wide between now and 2050, but virtually all of them will require some kind of substantial initiative – fundamental innovation, technology development, demonstration at market scale, market incentive, or other action – to change the deployment course these technologies are already on throughout much of the world. That is, a substantially increased role for LCE technologies will likely require substantial initiatives, especially over the next two decades if they are to make a significant difference in reduction of emissions by 2050.

A number of the most promising possible initiatives that could have a profound influence on development and rate of adoption of LCE technologies are common to all such technologies, such as various mechanisms that place an actual or de facto price on carbon; expansion, improved control and efficiency of electric power transmission and distribution; and development and deployment of electricity storage or other mechanisms for dealing with generation variability common to many of the relevant emerging technologies.

Among the most important factors affecting the need for LCE technologies is the rate of increase in energy demand. The most recent International Energy Agency (IEA) World Energy Outlook (2011) projects that, at expected rates of growth in worldwide energy use, in order to limit average global temperature rise to no more than a 2°C, 80 per cent of the total energy-related CO_2 emissions permissible in 2035 are already locked in with existing capital stock (power plants, factories, buildings, etc.). Moreover, if significant progress in reduction of global carbon emissions is not achieved by 2017 then emissions from existing facilities leaves no room at all for additional infrastructure, unless expansion involves zero net increase in carbon emissions.

The rate of increase in energy demand also influences the scale and unit size of power generation technologies most suitably deployed to meet that demand. Large-scale, large-unit-size power plants with long construction lead times are typically only practical at high rates of demand growth with relative certainty that such demand will materialise. Smaller scale, more modular power plants with shorter lead times are generally better matched to meeting uncertain and lower rates of demand growth. Of course, with a large population of smaller scale modular power plants, instead of larger central scale plants, the transmission and distribution system would need to be configured and controlled quite differently, especially if system involves coordination of intermittent generation, such as solar or wind, and associated storage and/ or generators with load following capabilities.

In addition to promising initiatives that apply to essentially all LCE technologies, each technology has its own features limiting the rate of commercial deployment. Some technologies require substantial continued development or fundamental innovation, despite being on a fast development track already, to reduce cost or mitigate performance risks and compete with traditional options. Many have geographic constraints that limit their potential in many parts of the world. Tragic or costly experiences with some quite mature technologies have led to deployments at much lower rates than expected.

The following summarises many of the most promising initiatives that could lead to accelerated development and deployment of each LCE technology and country considered in this report. An assessment of the most promising initiatives to accelerate investment and deployment of the individual technologies is given below.

4.1.1 Hydroelectric Power

Hydroelectric power generation is for the most part a mature, well-developed and widely deployed technology. This is especially true for large-scale hydropower, although modest increases in turbine efficiency can still yield significant increases in capacity at existing and some new facilities. An engineering initiative to examine potential for capacity expansion might be the most important prospect for increasing capacity from existing large-scale facilities, since the prospect for major expansion of new large-scale hydro world-wide is modest and geographically concentrated. Even a small improvement in efficiency of an existing facility can result in substantial increases in generation output. Small-scale hydropower has much more potential for substantially increased deployment, but the obstacles are much more site-specific. It is possible that more standardised designs could help facilitate more rapid deployment, especially in countries with large sparsely populated land areas. Perhaps the most attractive new potential for hydropower might be much more widespread deployment of pumped-storage capabilities, which can complement intermittent renewable power technologies, such as solar and wind, since the combined capacity factor of solar/wind coupled with pumped storage would make the combination much more cost competitive than either technology alone.

4.1.2 Solar Electric Power

The likely most promising initiatives for accelerating the deployment of solar technologies vary considerably by technology, especially for photovoltaics (PV) versus solar thermal or concentrating solar power (CSP), although there are some initiatives that could dramatically affect the prospects of all solar technologies.

Despite dramatic reductions in cost in recent years, the future prospects of PV hinge largely on future cost reductions in both raw materials and in fabrication of PV cells and modules, such as manufacturing economies realised with automation in large capacity plants for silicon based PVs, utilisation of lower-cost materials (commodity elements such as copper, zinc, and tin) or continued development of silicon-based technologies, multi-junction PVs and/ or solar cells with absorber layers that rely on quantum physics (e.g. organic-based hybrid PV cells). The most promising initiatives that address both these cost dimensions are accelerated R&D and building platforms for large-scale deployment. Additional factors affecting cost vary by location such as cost of land, options of orientation (e.g. rooftops), level of solar insolation, and perhaps especially availability of power network interconnection and regulatory policies affecting that interconnection.

Cost is the major factor limiting the rate of deployment of CSP technologies as well. In many respects CSP technologies are relatively mature in terms of basic technology design and configuration. Nonetheless, additional R&D will continue to bring costs down but increased economies of scale in manufacturing and installation are essential for CSP to become widely competitive, i.e. beyond the most attractive solar resource locations across the globe where they are often cost competitive already. An R&D focus on more efficient power cycles (Brayton, organic Rankine, or super critical CO_2) could improve CSP's prospects as well, and continued development of low cost reflectors and receivers may show promise. Among the most important needed developments is a highly efficient mechanism for thermal energy storage which may in at least some situations be a more effective means of addressing the variability of solar power than electricity storage technologies.

4.1.3 Geothermal Power

Geothermal power generation technologies from conventional vapour and liquid dominated geothermal resources are relatively mature. Continued technology improvements are possible, such as with binary power cycles and improved corrosion control, but increased deployment is limited primarily by resource location and access to the power grid. The implementation of sizeable demonstration plants (>50MW) will help define the technological and commercial risks that must be addressed to achieve expanded deployment.

Enhanced geothermal technology or power generation from 'hot dry rocks' is a much a less mature technology but perhaps with much more widespread resource potential world-wide. Enhanced geothermal technology development and experience with deployment are essential to demonstrate the technology and reduce uncertainty for application to widely different geological circumstances. Necessary R&D includes development of reliable analytical models for predicting how fractures develop and for estimating the capacity of the resulting reservoir as well as development of techniques for deep-hole high temperature and pressure drilling up to depths of 4000 metres to demonstrate the geology, temperature and flow characteristics of the enhanced geothermal reservoirs. Some recent enhanced geothermal system demonstrations have also experienced unexpected induced seismicity, which may ultimately play a limiting role in siting enhanced systems.

4.1.4 Natural Gas

Technologies for producing 'unconventional gas' from tight geologic formations by hydraulic fracturing of horizontal wells has led to a huge expected expansion in natural gas resources in many parts of the world, if these resources can be produced at the scale current estimates suggest. This means that power generation using combined-cycle gas turbines could show great promise for reduction of expected carbon emissions, at least relative to single-cycle gas plants and coal fired generation. They have relatively low capital costs, can be rapidly constructed, and in operation can cope relatively easily with rapid changes in demand making them very attractive options of power systems in both base load and cycling applications. With extension of pipelines for the transmission of natural gas power plants could be sited much more flexibly than other options as well, for example, closer to sources of cooling water. Natural gas turbines can also be used for peak load generation and for load following where grids incorporate variable sources such as wind and solar power. The greatest challenges to rapid expansion of unconventional gas resources are ensuring prudent and environmentally responsible development as well as development of scalable infrastructure for both production and delivery.

4.1.5 Marine and Tidal Energy

Many R&D challenges remain to transform marine and tidal energy technologies into commercially viable options. For wave energy, for example, a wide variety of device concepts including oscillating water columns, overtopping devices, point absorbers, terminators, attenuators as well as flexible structures must continue to be developed and tested. Equipment durability, energy capture efficiencies, and assessing resource potential for candidate sites will all also be important determinants of the ultimate deployment potential by 2050. Finally, for tidal energy, the environmental impacts of facilities in sensitive estuarine areas and tidal wetlands can be substantial and uncertain requiring careful analysis.

4.1.6 Wind and Biomass

Power generation from wind continues to be the fastest growing renewable electric power technology world-wide. In China alone wind generation of electricity expanded from 2 TWhin 2005 to 27 TWh in 2009 and IEA projects wind generation in China will grow to 590 TWh by 2035. Growth in wind generation in Europe has been policy-driven, perhaps most significantly by feed-in tariffs in Germany, Spain, China and Denmark that provide guaranteed grid access, long-term contracts for the electricity produced, purchase prices that are based on the cost of generation. In the US, wind capacity expansion has also been policy-driven by federal and individual state tax credits and renewable portfolio standards in many states. These policies have led to explosive expansion of wind power capacity world-wide and significant improvements in technology cost and performance. As the penetration of wind generating capacity expands in a power system control region, integration of wind turbines into the power system requires special attention to cope with the operating characteristics of a low capacity factor relative to alternatives and resource intermittency. New capabilities that make it easier to integrate the wind power plants into the power system and to increase their typically low capacity factors are essential to expanded utilisation of wind power. Especially important is development and deployment of controls that enable modern turbines to remain connected to the power grid during voltage disturbances and reduce the draw on the grid's reactive power resources.

Generation of electricity from biomass feedstocks (biopower) typically falls into three categories of biomass: wood/plant waste; municipal solid waste/landfill gas; and 'other' biomass, including agricultural byproducts, biofuels and selected waste products. Each type of biopower technology faces its own technical challenges for substantial increases in deployment, but one challenge common to all categories is the competition between using biomass to generate electricity or to produce liquid transportation fuels. In particular, conversion from raw biomass into syngas or other fuels might render biomass more attractive for transportation applications. For example, the US Department of Energy (DOE) essentially terminated its biopower programs in favour of biofuels for transportation following legislative requirements to greatly expand the use of biofuels in transportation. In addition, currently the long-term potential of biomass is limited by the low conversion efficiency of the photosynthesis process. As a result, biopower faces two classes of challenges: (1) technical challenges, which can likely be addressed by aggressive research, development, and demonstration, and (2) policy/economic challenges that could be addressed by incentives, regulation, or reducing the incentives for pushing the use of biomass in transportation.

4.1.7 Coal (including IGCC & Carbon capture)

Coal dominated the incremental growth in world primary energy demand and accounted for 40 per cent of total world-wide electricity generation in 2010 and over half of electricity generation in non-OECD countries. The future of coal world-wide will likely be principally policy-driven. With weak controls on carbon emissions, coal remains the dominant fuel. With some mechanism for controlling carbon emissions, the continuing expansion of coal use will hinge on the degree of government intervention, although the IEA projects that even with substantial controls in non-OECE Asia, especially China and India, coal will be the dominant fuel in any event. Under such circumstances the stakes are very high to reducing the emissions of coal fired electricity generation via emerging technologies, such as Integrated Coal Gasification and Combined Cycle (IGCC) technology, carbon capture and sequestration (discussed in the next section), and policy instruments that place an actual or de facto price on carbon.

4.1.8 Carbon Sequestration

Carbon sequestration is largely an unproven technology, at least at the scales necessary to make a sufficient difference in carbon emissions reduction by 2050, although it is proven and commonly applied in many oil and gas fields. It is essential that carbon capture and sequestration be demonstrated at large scale in power generation applications and in a wide variety of geologic circumstances within the next decade for it to be counted upon as a significant contributor to reduction of carbon emissions. Even if the technology is proven at scale, some certainty on a carbon price trajectory over the next 10 to 20 years will be essential as well to make the technology cost effective compared to alternatives. Finally, development and promulgation of regulations that manage identified risks associated with long-term storage of CO_2 will be just as important.

4.1.9 Nuclear

Following the March 2011 accident at the Fukushima Daiichi power plant in Japan, a number of governments are revisiting plans for nuclear power expansion, such as early retirement of nuclear plants in Germany; cancelling of plant life extension projects in Switzerland; decommissioning of plants in Japan; and delays of projected massive expansion of nuclear capacity in China. Nonetheless, nuclear power is a mature and widely deployed technology comprised a significant fraction of power generation in many nations, and a large fraction of current carbon-free power generation around the world. Many developing nations have expressed interest in nuclear power.

A number of significant challenges stand in the way of substantial increases in nuclear generation, including high cost and large capital investment requirements relative to other options as well as public concerns world-wide regarding nuclear waste, proliferation of weapons grade material, and safety, especially following the Fukushima accident. In highly industrialised countries where public concerns are limiting the rate of nuclear power expansion, resolution of those concerns within the next decade is essential if nuclear is to play an important role in expansion of the use LCE technologies by 2035. For example, the US National Academies 2009 study noted earlier concluded that sufficient reduction in cost and demonstration that evolutionary nuclear plants are commercially viable can be achieved by construction of a suite of about five plants over the next decade. The report also concluded that failure to demonstrate the viability of nuclear power during the next decade in the US would greatly restrict options to reduce the US electricity sector's CO_2 emissions over succeeding decades through 2020. Another possible important possibility is demonstration of small scale modular nuclear reactors, which responds to arguably the most problematic features of traditional nuclear facilities, i.e. very large capital requirements that pose an asset concentration risk to many utility systems. That is, potential failure of a single large plant creates a substantial financial and operations risk.

4.1.10 Replacement or Plant Betterment of Existing Fossil-Fired Generation

Even as IGCC and CCS technologies mature, substantial improvements in the existing inventory of fossil-fuelled power plants are possible and could represent substantial reductions in carbon emissions. For example, most US coal-fired power plants in service today were built before 1984. Today, in many situations, the benefits of new technology may be outweighed by the benefits of extending the useful lives of existing generating facilities, rehabilitating such facilities to improve performance or upgrading capacity, for example, with modern supercritical boilers, or repowering such plants with alternative fuels, such as natural gas with combined cycle gas turbines. All of these plant betterment options may be very promising opportunities since in many situations rehabilitating and extending the lives of such units may be achievable at lower anticipated total capital costs than that of new capacity. Prospects may be especially promising if units are located at sites close to load centres. In many instances, plant betterment can also improve generation efficiency considerably and/or upgrade capacity. Additional benefits from such projects include possible improvements in fuel flexibility or substantially reduced pollution emissions of existing generating units at less cost relative to that of new capacity.

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4.2 INTEGRATION AND COMBINATIONS OF TECHNOLOGIES TO ACCELERATE INVESTMENT AND DEPLOYMENT

There are many possible combinations of technologies, but not all of them achieve the purpose of reducing emissions for a given quantity of energy produced. In what follows those combinations in which there is no clear synergy are not considered. Accordingly, consideration is given below to those combinations where the power is greater than the output of the individual technologies; for example, where one technology may reduce a constraint on the deployment of the other, or alternatively, where there is an overall reduction in the carbon emissions by the utilisation of the combination.

4.2.1 Hydro

Many large-scale hydroelectric plants have the potential to store electricity in the form of water held behind a dam. The ability to store energy in this form, and release it at very short notice to generate electrical power on demand, is equivalent to a 'battery'. The energy storage inherent in many hydroelectric plants can be used to address large variations in demand for electricity which occur in most countries. As the hydroelectricity is carbon-free, and the variations in demand would otherwise cause variations in carbon emissions, then the availability of this carbon-free 'battery' can reduce the overall emissions from the generation system.

A variant of this is the pumped storage system, in which water is pumped into a reservoir at times of low electrical demand, and released from the reservoir to generate electricity at times of high demand. Although the overall efficiency of the pumped storage is high, it is nevertheless the source of some additional carbon emissions during the storage phase. However, this problem is becoming less with improvements in combined pump and turbine design. Pumped storage efficiencies of over 80 per cent will probably be achievable in the near future, as pump and turbine designs are improved by the use of computational fluid dynamics. The use of pumped storage in a grid to even out the load profile can introduce efficiencies in the total generation and transmission system sufficient to result in an overall drop in emissions.

In many areas, wind or solar energy supplies and user demands can be seriously out of phase. While the renewable energy sources may have capacity factors as high as 30 per cent, the out-of-phase problem may require renewable power to be cut at times of high generation and low demand, so reducing the delivered capacity to well below 30 per cent. The provision of some form of hydro storage allows the intermittent source to balance its production and so achieve a delivered capacity closer to its generated capacity. The problem of intermittency is aggravated when conventional generation is used in the combined heat and power mode. Under these conditions, the turndown available in the conventional generation plant is restricted by the need to continue to produce heat, so the capacity of the system to accept power from intermittent sources is reduced.

Hydropower or pumped storage also assists with the balancing of system loads to meet changing demands. Large conventional stations providing base load have relatively slow dynamics. The dynamics of hydropower facilitate load following. The losses in a hydropower system can have less impact on overall system efficiency than the drop in efficiency caused by reducing the load on a large thermal power station. Most systems have peak loads that at times exceed the capacity of, and are of such short duration, that relatively inefficient gas turbines operated in open cycle are employed to meet the load. Open-cycle gas turbines have a relatively large carbon footprint. The availability of hydropower or pumped storage capacity in the system can reduce if not completely obviate the need to employ gas turbine peaking power and thus lead to lower carbon emissions.

Pumped storage is also possible using air as the medium instead of water. This requires large underground structures that can contain the air under significant pressures, and such structures are relatively rare, so this possibility is limited to a few areas where there is a favourable geology. Moreover, the cycle efficiency using a gas rather than a liquid is significantly lower. Thus this alternative does not have quite as much economic synergy as pumped storage with water.

4.2.2 Solar

Solar thermal systems are often provided with storage of thermal fluid to enable them to continue to generate power for several hours when there is low or no solar input. They therefore have less intermittency than most other renewable sources of energy, and can more readily be incorporated in existing grids. However, the fact that they have a primary thermal output enables them to be integrated into fossil-fuelled generation facilities. For instance, the solar heat may be employed to preheat boiler feed water and thus either reduce the fuel load or increase the electrical output of the system. This option has been quite extensively explored, particularly for retrofits to existing fossil-fuelled facilities as a means of saving fuel costs. It appears very promising economically. Solar thermal power has also been married to open-cycle gas turbine installations used for peaking power, and by reducing the load on the gas turbine system, has reduced the carbon emissions significantly. Solar thermal power can also be integrated into geothermal stations to either increase the output or reduce the geothermal load.

A further option for solar thermal is to use it as a source for process heat. Again, there have been a number of promising studies of this possibility. Some of the most interesting of these applications have been in combined heat- and power-systems, with power generation during the day and some of the stored heat being distributed for space heating by night. Again, if such systems are integrated into a fossil-fuelled facility, then the fossil fuel can provide backup for the solar system in the event of low insolation.

Solar PV offers some opportunities for integration that would enhance its deployment. Under some circumstances solar PV can produce more power than the system demands require. In this case the output of other generators can be reduced with a consequent reduction in emissions. A combination of solar PV and a reasonably flexible fossil-fuelled station such as a closed-cycle gas turbine thus offers some possibilities for reducing the carbon load and taking full advantage of the output of the PV system.

Solar PV backed by pumped storage has been discussed in the previous section. The advantage derives from the pumped storage rather than from the PV system. Off-grid solar also requires storage, which is usually provided via batteries. Lead-acid batteries, even with daily cycling, are only about 50 per cent efficient. However, there are new battery systems under development that may radically change this picture. Lithium-iron phosphate batteries have the promise of increasing the efficiency of storage to over 80 per cent; allow deep and rapid discharge; and may have a life of as long as 25 years in this duty. If this is so, then PV could become competitive with grid power generation.

4.2.3 Geothermal

Opportunities for geothermal energy include the use of solar energy to boost water temperatures at the surface and thereby increase geothermal power generation efficiencies. Alternatively, geothermal energy can be used in hybrid systems such as with fossil-fuel electricity generation to pre-heat the boiler feed water.

4.2.4 Marine and tidal

No synergistic possibilities other than those associated with storage have been identified.

4.2.5 Wind

There are no obvious synergistic possibilities other than storage that would facilitate the wider deployment of wind.

4.2.6 Biomass

Biomass contributes towards a lower carbon energy system because it is carbon-neutral. Its integration into any system therefore reduces the level of emissions from that system. Biogas can usually be brought up to pipeline specifications for natural gas systems without undue costs, in which case it can then be fed directly into the pipeline system. Alternatively burners can be adapted to a lower specification feed and the gas used directly, thus saving the emissions associated with the natural gas that has been displaced.

Solid biofuels can be employed directly as a source of process or space heating, or can be incorporated into gasification systems either wholly or as a partial substitute for fossil fuels. Liquid biofuels are already making a contribution, and there are no particular identifiable developments that would facilitate their wider uptake.

4.2.7 Gas

Because natural gas has a 4:1 ratio of hydrogen to carbon, it is theoretically possible to convert natural gas into liquid fuels by incorporating carbon dioxide in the feed. At present the best of the gas-to-liquid processes is essentially carbon-neutral, with some of the carbon dioxide generated in one part of the process being consumed in another. Advances in heat integration as well as carbon utilisation are improving the prospects for this process to become a carbon sink.

Some solar thermal systems incorporate thermal storage. There is a possibility for integration of open-cycle gas turbines with such solar systems, where the waste heat from the turbines is stored in the solar thermal store. The intermittency of the solar system can be much reduced and the disadvantage of the low efficiency of the open-cycle gas turbine can be overcome. The relatively low cost of the open-cycle gas turbine makes this quite an attractive integration.

4.2.8 Coal

Many of the opportunities for coal arise from carbon capture which has been discussed in an earlier section. One of the possibilities is for conversion of existing pulverised fuel facilities to operate at higher temperatures and pressures, so increasing their efficiency and reducing the emissions per unit of energy. A facilitating technology for oxyfuel combustion would be improved oxygen separation, and there are a number of directions in which developments are taking place.

The production of liquid fuels via Fischer-Tropsch synthesis is not carbon efficient, but it does generate essentially pure carbon dioxide so that capture costs would be very low. The alternative direct liquefaction via the Bergius process produces liquid fuels very efficiently, but requires large quantities of hydrogen. Thus an enabling technology might be the production of hydrogen by the use of process heat from nuclear reactors. Integrated gasification combined cycle (IGCC) could permit co-production of H_2 and chemicals along with power (poly-generation), which seems likely to improve the viability of IGCC.

The thermal efficiency of all power stations can be improved – and the carbon dioxide emissions thereby reduced – if low grade heat can be put to use. This is the case in combined heat and power (CHP) systems, in which heat is distributed either as low-grade steam or hot water. CHP can raise the thermal efficiency of a coal-fired power station to as much as 85 per cent. Widespread adoption of CHP could have a significant effect on global emissions.

4.2.9 Carbon capture and storage

Carbon capture and storage is one of the technologies that is designed to be integrated into power generation systems to reduce carbon dioxide emissions. Nearly all projections of means for reducing emissions globally include a measure of carbon capture and storage. There are three variations on the theme, namely pre-combustion capture, post-combustion capture and oxyfuel combustion.

Pre-combustion capture is best illustrated by the integration of gasification of the fuel and combined-cycle combustion of the gasification products, which are primarily carbon monoxide and hydrogen. The technology can be applied to coal and other fossil sources and biomass. The greatest technical advances seem to lie in the development of improved gas turbines adapted to a gas composition different from that of conventionally-fired turbines, and operating at higher temperatures. The US Department of Energy has an extensive study in progress, aimed at reducing the capital cost of plant to <$1600/kW capacity and, by 2015, achieving close to zero carbon emissions at a cost <10 per cent above the cost of conventional plant. Overall, plant efficiencies of the order of 45 per cent appear achievable. Several demonstration plants are in operation in the US, Europe and Japan.

Post-combustion capture involves the absorption of carbon dioxide from the flue gases, usually in a liquid. Regeneration of the liquid and release of the absorbed carbon dioxide requires significant energy, which can be as much as 20 per cent of the output of the station. Work is in progress to try to reduce this, but the potential for saving energy is limited. It is possible that at least part of this energy could economically be supplied by geothermal or solar. There are numerous demonstrations taking place, because this process can readily be integrated into existing facilities (provided there is sufficient space).

Oxyfuel combustion involves separating the oxygen from air, and using the separated oxygen to combust the fuel. The major energy demand is in air separation, and there is extensive work in progress in this area. A 30MW pilot plant has operated in Germany since 2008 and a number of >100MW demonstration plants are planned. Some of these include circulating fluidised beds and can use both fossil and biofuels. There have been several studies of the possibility of retrofitting conventional pulverised fuel boilers, with promising economics relative to post-combustion capture.

All carbon capture projects have an additional energy penalty in the compression of the recovered carbon dioxide prior to storage. The pressure must be above about 7.4MPa (73 atm) for the gas to be in the supercritical state necessary for efficient pipeline transport and storage. CO_2 storage in existing oil and gas resources can lead to enhanced gas and oil recovery given the correct geology.

4.2.10 Nuclear

Nuclear power generation is a stand-alone technology. The integration potential with other generating technologies has to be considered very low. One exception is the use of heat at about 900°C from pebble bed-reactors as part of an integrated coal gasification combined cycle process (IGCC). Russia has several cogeneration nuclear plants which together provided 11.4 PJ of district heat in 2005. Russian nuclear district heating is planned to nearly triple within a decade as new plants are built.

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4.3 RISKS TO DEPLOY LCE TECHNOLOGIES AT SCALE

The risks and barriers associated with the commercial deployment of low-carbon energy (LCE) technologies are many and varied in nature. They have to be overcome if the global target of cutting carbon emissions significantly is to be met. The deployment of LCE technologies on a very large scale encounters a variety of risks depending upon the maturity levels of the various technologies. They include:

- engineering / technology;
- environmental;
- social;
- safety;
- financial; and
- legal risks.

4.3.1 Engineering / technology

As LCE technologies move progressively along the RD&D continuum, for example from bench to pilot and then to semi-commercial level of operations, they will have lower engineering / technology risks. The technological risks of early stage LCE options arise from the difficulties in demonstrating that they are cost-effective. Engineering risks include developing high-throughput manufacturing systems, in proving the reliability and maintainability of ever-larger-scale implementations, and/or providing robust process control or automation options. Engineering risks may also arise from integration with grid based electrical systems.

4.3.2 Environmental

Environmental risks of LCE technologies can arise during energy generation as well as utilisation phases. Sometimes, they can be resource or location specific. For example, large land requirements in the case of solar thermal power systems may have negative impact on native vegetation, wildlife habitat loss and water drainage problems in heavy rainfall areas. Similarly, high temperatures associated with concentrating solar thermal systems can pose risks to the avian population in the vicinity. Components of LCE systems containing environmentally hazardous materials can create undesirable waste situations if they are not properly handled. Environmental risks in such systems need to be mitigated; for example, they can make it necessary to evolve purchase schemes for new LCE systems with provision for take-back options. Another serious environmental risk may arise in CO_2 sequestration programmes leading to leakage of CO_2 to the atmosphere after geological storage which may have undetected geological flaws. Also, the construction of large-scale CO_2 transportation pipelines may disrupt natural habitat and animal migration patterns. There is need to standardise environmental due diligence arrangements for LCE systems like solar, wind, hydroelectric and others as is done for conventional power generation systems.

4.3.3 Social

LCE systems can give rise to social risks. For instance, they can interfere with the existing land use patterns, soil compaction, water access, drainage channel alterations and increased runoff / soil erosion in special designated areas. During the construction and operation phases of major LCE projects, disruption of public services, high influx of working personnel and equipment from other areas and social justice related issues in case of those sections of the population that receive little or no benefits from the LCE developments can pose high social risks. For example, wind energy farms have created social risks due to their encroachment into farm lands and perceived health risks to nearby residents. Hydroelectric projects, of even medium capacity, have created problems associated with human displacement and land acquisition let alone the environmental issues associated with dams.

4.3.4 Safety

Safety related risks can occur when unsafe situations develop during start up, normal operation and shutdown phases of LCE systems. For example, there is a risk that solar PV systems that are integrated into the grid will continue to supply energy even when the rest of the grid is shut down.

4.3.5 Financial

Major financial risks can occur in LCE plants due to their initial lack of market competitiveness without government subsidies. There may be other economic barriers that need to be overcome to attract private sector investments on a larger scale, such as achieving an adequate rate of return on investment. Several LCE projects suffer from high financial risks since bank finances are difficult to access, initial investment is high enough for small and medium-scale entrepreneurs to hesitate before venturing into this area, and to cause difficulties in meeting high collateral requirements of lenders for capital assets. It must be added that LCE technologies are yet to demonstrate routinely sound business models with minimum financial risks.

4.3.6 Legal

Some of the LCE technologies can also present legal risks which act as barriers for their commercial deployment. A typical example is CO_2 transportation and storage after its capture from thermal power plants. In the event of significant leakage of CO_2 into the atmosphere, long-term liability issues may arise. Government regulations need to address such issues with adequate institutional framework for their monitoring and reporting and the need to consider appropriate mitigation strategies. Storage facilities, both underground and under ocean may cross national borders with legal risks to be addressed at international level. Legal issues may also arise during the integration of technology with the emission trading schemes.

The existence of the risks highlighted above implies that private sector is likely to under-invest in the initial phases of LCE technology deployment without government intervention and/or support. To help resolve this impasse, governments need to judiciously employ a set of policy instruments to encourage the adoption of LCE technologies despite the perceived risks. The financial risks associated with investments in LCE technologies will certainly emerge as the central problem in many projects in both developed and developing countries. It would be appropriate to appraise stakeholders to the risks associated with the world's climate from the carbon intensive technologies currently being practiced and to compare and contrast those risks with the risks identified above in relation to low-carbon technologies. Clearly, innovative mechanisms are needed to remove or ameliorate the barriers posed by the various risks associated with LCE technologies as highlighted above.

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4.4 ENGINEERING CHALLENGES TO DEPLOY LCE TECHNOLOGIES AT SCALE

Many of the LCE technologies proposed for future use have been demonstrated in functioning test facilities, whether in laboratories or pilot plants. However, the transition from those early demonstrations to equipment at production scale, whether in terms of plant size or in large numbers of devices operating at smaller unit scale, can pose engineering or economic barriers as challenging as the development of the basic technology. The range of risks was discussed in the previous chapter and here the specific engineering challenges are addressed.

4.4.1 Hydroelectric Power

The deployment of hydroelectric power at large scale is an established and incumbent technology. Challenges in further deployment are primarily encountered in the identification of suitable sites, notably where dams are required to be created which displace agriculture or habitations, and in the associated civil construction. Sites not involving dams are usually both much smaller in scale and likely to be envisaged for local consumption of the electricity generated or connection to a local existing transmission network in more densely populated and developed countries.

Hydrogenerators are available through an international supply chain which may be regarded as capable of delivering machines using current technology to a wide range of specifications and scales likely to meet the vast majority of needs.

4.4.2 Solar Energy

Conventional solar PV is now an established technology, and although there are numerous technical developments envisaged, as discussed earlier, the primary challenges for large scale deployment are found in the integration of very large numbers of modest scale systems with existing and future electricity networks. Most of these are likely to be connected at the distribution network level, whose current design means that the export of surplus power to adjacent distribution systems or to the transmission network poses a number of operational problems if all the power harvested is to be usefully delivered to meet demand at national level. A new generation of distribution systems, often called smart grids, is postulated as a solution to the problem, but in addition to substantial development requirements this will require large investment for infrastructure replacement in developed countries. The intermittent (diurnal) profile of power production also requires the provision of either large-scale storage systems or the maintenance of equivalent power levels of back-up generation operated on a daily cycle. This is likely to be differently located to the highly distributed PV systems and will require further network capacity to connect it.

Concentrated solar power systems are likely to be constructed at large unit sizes, typically hundreds of megawatts, and so probably connected to the network in a similar manner to conventional power stations. However, their physical size and need for reliable solar insolation means they may be remote from cities and other demand centres and so need long transmission lines, possibly using new forms of high-voltage direct current transmission.

4.4.3 Geothermal energy

Other than the technical issues discussed earlier in the review of geothermal technology status, there are few specific issues in deployment at large scale. Geothermal power plants using new directional drilling techniques can tap energy from a wide area so there is reasonable flexibility in their location within the resource area. Since they can generate continuously there are no significant integration issues for connection to existing networks.

4.4.4 Marine and Tidal energy

These technologies face probably the greatest engineering challenges for deployment at scale. Apart from the technical and development barriers still to be overcome, the reliable installation, connection to the network, operation and maintenance will require a large engineering effort and an associated infrastructure including both ships and ports. Manufacture and delivery in volume of what are likely to be large heavy devices, up to 10 tonnes per kilowatt as previously noted, implies a substantial and sophisticated industry with heavy delivery capabilities.

Wave energy is a relatively diffuse resource so power must be collected from multiple devices over a large area, typically several square kilometres. For large systems, normally sufficiently remote from the shore to preclude unit connection, a subsea electrical network will be required for local power management and subsequent transmission to shore. As the power delivered will be intermittent the associated demands for the onshore electrical network could be considerable. However, as the power levels practically realisable from wave energy for any one country will probably be less than that from wind measures taken to manage the latter may handle wave energy effects anyway.

Tidal power may be generated from tidal turbines positioned remote from shores, or from estuarine systems which usually have some structural connection to land. The former will need systems similar to those for wave energy to effect a connection, while the latter can be handled by conventional connection arrangements.

4.4.5 Wind

There is already considerable experience in the deployment of onshore wind, so the engineering challenges are well known and means have been developed to handle them to date. Further levels of deployment will increase primarily issues around power management on the electrical network rather than the installation of the turbines themselves. As the amount of wind power delivered to the network increases as a percentage of the total so the management of its intermittent nature will become more demanding. As previously discussed various means to do this are known: increased interconnection of national systems to attenuate the geographical variations in wind power production at any time, storage systems (albeit expensive), and improved forecasting of weather. The most proven approach is to provide back-up power plant, usually gas, coal, or oil, which has financial implications since the back-up plant has a low load factor and ensuring its availability, especially in open power markets, requires some careful preparation. It also increases the need for network capacity since the back-up plant is typically located remote from the wind turbines.

Offshore wind remains a technology in development, although increasingly deployed internationally. A major issue in further substantial deployment, in addition to the intermittency effects, will be the monitoring, operation, and maintenance of increasingly remote wind farms. In addition to the necessary skilled workforce, the infrastructure requirements will be large, with specialist vessels for installation/ disassembly at sea, and onshore maintenance and storage capabilities for the probably large components, notably blades.

4.4.6 Biomass

Increased use of woody biomass is not expected to present any insurmountable engineering problems. Although it would require additional local processing plants, handling systems, storage, and conversion devices, these are all presently available and scalable. The major issues are likely to be assessment of environmental impacts and costs.

4.4.7 Gas

There are no new major issues identified for increasing use of natural gas. Should shale gas be increasingly exploited then its production may require new techniques for well drilling if these are in currently populated areas so as to minimise disruption to residents. There will also be a need for enhanced underground monitoring given the possibility of geological disturbance. However, these are not seen as providing engineering obstacles.

4.4.8 Coal, specifically CCS

As discussed in the previous sections, the main issues with CCS are the capital and operating costs of the plants. There is no real engineering concern over the viability of the technology, and the primary barrier today remains financial. There is no economic model for power production that justifies the cost and risk of constructing a full-scale plant. Should these be overcome then few engineering challenges beyond efficiency improvements and the increased burn of fuel, perhaps 20 per cent more for a given power output, can be foreseen. There is speaking broadly no other difference from constructing a conventional plant.

4.4.9 Carbon Sequestration

The identification of secure storage locations, and the construction of CO_2 pipelines are the two issues for sequestration. Although these remain to be resolved in most areas of the world, there is little doubt pipelines can be constructed and the gas injected once the decisions to proceed have been taken. The risks and barriers are seen as social, political and economic rather than engineering.

4.4.10 Nuclear Energy

Other than the well-known financial costs, and political and public opinion issues, the main barrier to substantially increased deployment of current fission reactors is probably production capacity for the key major components, such as the forged pressure vessel for PWRs. Given investment and commitment there is no reason to believe this cannot be overcome. Questions remain about the availability of uranium for fuel, and although it is alleged that present identified reserves may be derived more from today's market than physical resource, this needs to be confirmed.

At the present state of development, it is not possible to foresee engineering issues that may arise from a future deployment of Generation IV systems.

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4.5 CHALLENGES FACING INDUSTRY AND GOVERNMENTS

The electric power industry in many parts of the world faces growing electricity demands coupled with pressure to meet national greenhouse gas mitigation targets. The reduction of CO_2 emissions from the electric power industry will be crucial in achieving total emission targets, which require CO_2 emissions to peak at 32.6 Gt no later than 2017. The challenges for dealing with growing electricity demands and reducing greenhouse gas emissions require a viable portfolio of low-carbon emission (LCE) technologies, while overcoming the obstacles present in development and deployment of each technology.

As reviewed in the first report by the CAETS Working Group, deployment of LCE technologies requires a large-scale investment in serious research and development efforts, large-scale demonstrations and market developments. Investment often entails high risk and large uncertainties, presenting enormous challenges to both government and industry (CAETS 2010). In addition, each country has a different set of complex energy problems, and the deployment of LCE technologies in different countries will require unique implementation strategies to ensure viability.

4.5.1 Challenges for government

The deployment of LCE technologies can result in more efficient use of energy and emission reduction, and also benefit the national economy through green growth (NZ 2012). In the process, government needs to play a crucial role in development and deployment of LCE technologies. The main role of government is to set policies and provide incentives to stimulate market activities. The incentives can be given in terms of manipulation of taxes and other statutory hurdles and, in certain cases, they can be direct financial investments.

A recent OECD report showed that there exists a close link between key policies and the generation and diffusion of LCE technologies (Hascic 2010). The report noted that the rate of innovation has accelerated in many LCE (they used the term "climate change mitigation technologies", CCMTs) technologies, coinciding approximately with the passage of the Kyoto Protocol. This has occurred in technologies such as wind power, some solar, biofuels, geothermal and hydro. The report noted that even though the most important determinant of innovation is general innovative capacity, public policy makes a difference in inducing innovation and the international diffusion of technology.

For LCE technologies that require long-term development and large scale investment, governments must provide leadership in basic research and development efforts as well as demonstration and deployment of the technologies. Government, collaborating with industry, needs to set a direction for research and development. That direction should include challenging and yet attainable goals for LCE technology development and market transformation. Government also needs to provide supporting initiatives, policies and direct financial incentives and investments, and to ensure that the implementation plans gain societal acceptance.

In the power sector, one of the crucial policy issues is how to manage the electricity supply mix and demand. On the supply side, the most critical factor that determines which LCE technology will be concentrated on and developed to commercial scale is how best to proportion the supply among fossil fuels, nuclear and renewable energies. The decision can vary depending on each country's energy resources and the status of innovative capacity. No matter what the situation, governments should make the improvement of energy efficiency, expansion of renewable energies, and greenhouse gas reduction from fossil fuels top priorities if they are to demonstrate that they support a carbon emission target.

Deployment of a new LCE technology requires government to raise public awareness, to provide education and training, and to prepare and provide necessary regulatory requirements and implementation guidance. For example, deployment of carbon capture and storage will require safety regulations for the transport and storage of carbon dioxide, which should include equipment certification, construction and design guidelines, licences and long-term monitoring for possible long-term environmental effects.

For nuclear power generation, which is considered to be a LCE technology in a broad sense, government must re-examine security and safety. The Fukushima disaster in 2011 revealed that there remained some failure modes that could be induced by beyond-design events. Some countries are moving toward phasing out existing nuclear reactors or reducing nuclear dependency for their power supply. However, in some developing countries, the expansion of nuclear power is essential for growing electricity demands and emission reduction targets and for the country's energy security. For nuclear power to remain as a major viable option in the LCE technology portfolio, governments must make strengthening security and safety regulations and developing corresponding technologies a priority.

Commercialisation of LCE technologies and the achievement of grid parity may not happen just through market mechanisms but may require government intervention to create a market. In commercialisation, it is important to involve the private sector either through partnership development with the government or through creating environments for the private sector to invest. Public financing will be a necessity, and government funds can be used to leverage private funds. The tactics to stimulate the deployment and commercialisation of LCE technologies include establishing financing options with mechanisms for long-term investments, risk-sharing arrangements and market incentives, as well as supporting policies such as a carbon tax, emission trading, renewable energy standards, Renewable Portfolio Standard, feed-in-tariffs, green public procurement and eco-labelling. Grid modernisation, including smart grid, energy efficiency enhancement and development of low-carbon infrastructure can also enhance the economic benefits of LCE technologies.

4.5.2 Challenges Facing Industry

In many countries, even though government plays a leading role in the deployment of LCE technologies through policies and financial support, industry is still challenged by market uncertainties, rapidly changing technologies, investment risk and regulatory and rule change risk. Industry needs to proceed cautiously when developing its own investment strategies, including investment timing, financing options, technology selection, and market penetration. Industry also needs greater insight and readiness for future government policy changes, technology innovation and new market opportunities so that it can have optimised, flexible investment strategies that can produce profits even in a policy-dependent market. For example, front-runners of the photovoltaic industry benefited from the world market supported by government policies and experienced a remarkable growth. However, the financial crisis in Europe since 2011 depressed the PV market resulting in oversupply and price reduction, causing a deficit for most companies.

Technology selection for investment is also crucial. For a system that requires large investment once a technology is selected, it may not be possible to introduce change for a couple of decades. For emerging technologies where the technology is rapidly changing and can be replaced by a more efficient and cost-effective technology, limited market participation may be necessary. Market participation will provide the chance to build up the brand while continuously developing new technologies to maintain a leading edge in the industry.

For technology developers to compete in the market, it is necessary to build credibility in the industry through long-term demonstrations and installations. For a competitive technology, a company needs to find an emerging market for demonstration and installing credits. A technology that requires a large-scale demonstration can be implemented through international cooperation.

For a successful deployment of LCE technologies, a well-structured partnership between industry and government is crucial. In the future, the willingness to invest by industry, rather than government-led efforts, will be important and will bring greater realistic economic benefits. In addition, deployment of LCE technologies that requires a long-term investment, large corporate, rather than government, must take a key leadership role with the government left to provide supporting policies and eliminate statutory hurdles.

4.5.3 Public Acceptance

Another important aspect that government and industry must develop for successful implementation of LCE technologies to establish 'social acceptance' or 'public acceptance'. For instance, with the 2011 Fukushima incident, public acceptance of the nuclear industry dropped significantly. Rebuilding public acceptance will require open communication on technological issues, as well as long-term environmental and local health issues. Sufficient and appropriate information must be provided to avoid misunderstandings. It is also necessary to provide continuous environmental monitoring, education and training, and public participation in decision-making processes. It may also be necessary to better understand the dynamics of public views through rigorous social research to look into factors that combine to shape public acceptance.

For the renewable energy industry, while the consumer, in general, has developed a positive consensus of the need for renewable energies, the community acceptance has varied from not-in-my-backyard (NIMBY) to please-in-my-backyard (PIMBY). There are many cases of wind energy installation that showed that early community involvement is crucial for community acceptance. The lack of community acceptance is more likely to cause costly delays, creating many problems for developers.

Involving the public and stakeholders at the earliest stages of the planning process is a crucial factor. Mason et al. (Mason 2010) describe an acceptable development as one where potential positive impacts can trade-off negative impacts, and that has sufficient trust building. Often the cause for opposition is a lack of information and transparency. It is important for industry and local government to provide appropriate, easy to understand technical information. The costs and benefits to the community need to be made clear and the public input must be reviewed critically and incorporated if appropriate.

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Authors

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5. Conclusions and Recommendations

CONCLUSIONS

Achieving a transition to a lower-carbon electricity generating system is technically feasible provided significant investments are made to scale-up the development and deployment of LCE technologies (including carbon capture and storage) for electric power generation over the next decades, that timely, consistent and significant government policy action is taken.

The following conclusions are relevant:

- There is no single preferred LCE technology. Rather, the costs of different LCE technologies are expected to broadly converge over time. Hence a portfolio of technologies can be expected to be deployed.
- Promising initiatives in prospect for each LCE technology are identified, but significant technical and financial risks must be overcome for their widespread commercial deployment.
- Opportunities are identified where a number of LCE technologies may be integrated with either other LCE technologies or with fossil-fuel technologies to expedite their possible commercial deployment including the lowering of greenhouse gas emissions of those fossil fuel technologies and deliver increased generating efficiency.
- Currently, most emerging LCE technologies do not have intrinsic commercial advantage over those technologies used today, so they will need sustained government support for research, development and deployment (RD&D).
- First-of-a-kind (FOAK) technologies have high risk and financial support is not readily available to support commercial deployment. There are opportunities for government support and this may include some form of subsidy (for example, cash or tax benefit).
- Even with support, major engineering challenges must be overcome to achieve a low-carbon electricity generating system.
- Substantial investments are required in new electricity generating plant. For example, it is estimated that $6.4 trillion, is required to be invested over a 10-year period for electric power generation technologies.
- Successful deployment of LCE technologies normally requires partnerships between industry and government and that appropriate public policy settings can make a clear difference in inducing innovation and in the international diffusion of LCE technologies.

RECOMMENDATIONS

It is not within the scope of this report to recommend either particular technology development strategies or electricity generation technology mixes; these subjects are clearly the province of individual nations.
Recommendations for possible consideration include:

- GHG reduction is a global issue – hence international RD&D collaboration should be supported with adequate resources, including for large –scale demonstration projects and particularly in critical areas such as carbon capture and storage.
- Governments and industry should work closely to ensure the strategic development and the acquisition of skills and resources for research, development, manufacture, deployment and possible international diffusion of LCE technologies.

This report has been prepared as a resource for use by:

- Those CAETS academies that may wish to engage with key stakeholders (including governments) in their respective countries about strategies that might be adopted to deploy LCE technologies for electric power generation as a means to achieve progress towards a low-carbon environment.
- CAETS when it wishes to engage with relevant International organisations and inform them on: the technical and financial feasibility of particular LCE technologies; what are the promising initiatives that could be undertaken to accelerate their deployment; and what are the risks to be addressed.

Attachment A: Rankings for Technology Assessments

1. ABILITY TO LOWER THE CARBON FOOTPRINT

Ranking	Life cycle reduction of CO_2 generation compared to standard coal-based generation
1	80–100%
2	60–79%
3	40–59%
4	20–39 %
5	0–19%

2. DEFINITION OF TECHNOLOGY READINESS LEVELS

TRL 1 Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviours of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept: Proof of concept validation. Active research and development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8 Actual system completed and 'mission qualified' through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. verification and validation (V&V) completed.

TRL 9 Actual system 'mission proven' through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

Author Biographies

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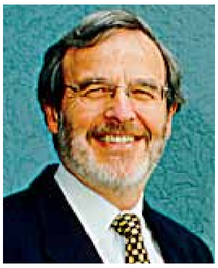

Dr Vaughan Beck is the Senior Technical Adviser to the Australian Academy of Technological Sciences and Engineering (ATSE). He was until recently the Executive Director – Technical (ATSE), responsible for the Academy's research projects and the development of policy advice to government in areas such as climate change, energy, water, built environment, innovation, technology and education. Dr Beck has led the development of significant research reports for ATSE on a wide range of technical policy issues, often leading multidisciplinary teams and involving industry, academia, research and government stakeholders.

Dr Beck is currently the Chair of the CAETS Working Group on Low Carbon Energy and he is also Deputy Chair of the Expert Working Group, Australian Council of Learned Academies project on Engineering Energy: Unconventional Gas Production – Shale Gas.

Dr Beck has qualifications in mechanical engineering, structural engineering and a PhD in fire safety engineering. His research relates to risk engineering and the built environment and includes building performance under cyclonic conditions and fire safety and protection.

Dr Beck was appointed as a Visiting Professorial Fellow at the Warren Centre of Advanced Engineering at the University of Sydney in fire safety systems. Dr Beck's research into building fire safety systems, and the program of reform that he led in Australia, was adopted in Australia and subsequently in a number of overseas countries. Following this, Dr Beck was appointed as Professor and foundation Director of the Centre for Environmental Safety and Risk Engineering at Victoria University, and subsequently as Pro Vice Chancellor (Research) at Victoria University.

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Professor Peter Cook is one of Australia's foremost scientists and technology leaders in the areas of energy, greenhouse technology and sustainability. He is a Professorial Fellow at the University of Melbourne, a company Director, consultant, senior adviser and author.

Professor Cook has been a consultant and adviser on resource and energy issues in Australia, Finland, Greece, Germany, Japan, Netherlands and Portugal. He has been a consultant to NASA, various national governments, and a range of companies, and has served on Boards and Advisory Boards in Australia, the UK and for international bodies.

Until 2011, Professor Cook was the foundation Chief Executive of the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC): previously he was Director of the British Geological Survey (1990–98) and Division Chief/Associate Director of the Bureau of Mineral Resources (1982–90). Professor Cook has held academic positions in the UK, Australia, France and the US, and has received many awards and honours for his work. He is the author or co-author of more than 160 reports and publications. He was a Coordinating Lead Author for the IPCC Special Volume on CO_2 Capture and Storage; his book *Clean Energy Climate and Carbon* was published March, 2012.

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Professor Geoff Stevens is a Professor of Chemical Engineering in the Department of Chemical and Biomolecular Engineering at the University of Melbourne. He completed a PhD at the University of Melbourne on hydrodynamics of two-phase flow and after working in industry for a period returned to the university. His current research focuses on CO_2 separation, solvent extraction and ion exchange, and soft tissue engineering and biocompatible materials.

Geoff leads an internationally recognised separations group in the Department, is the Director of the Particulate Fluids Processing Special Research Centre, a Project Leader in the CRC for greenhouse gas remediation (CO2CRC) and Director of the Peter Cook Centre for Carbon Capture and Storage. He is Secretary General of the International Solvent Extraction Committee and is on the editorial boards of various publications including *Solvent Extraction and Ion Exchange* and the *ChemEng Journal*.

Geoff Stevens was President of the Academic Board and Pro Vice-Chancellor at the University of Melbourne, has served as a Member of the International Advisory Board of the *Chinese Journal of Chemical Engineering*, is a Fellow of ATSE, Fellow of IChemE, Fellow of the Australian Institute of Mining and Metallurgy and was elected Secretary General of the International Committee for Solvent Extraction. He has held academic positions in China and Japan.

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Professor Robert Evans is Professor of Mechanical Engineering at The University of British Columbia (UBC). He obtained a BASc degree in mechanical engineering from UBC, an MASc from the University of Toronto and his PhD from Cambridge University. Dr Evans previously served as Head of the Department of Mechanical Engineering, as Associate Dean of Applied Science, and as founding Director of the Clean Energy Research Centre at UBC. He is a Fellow of the Canadian Academy of Engineering, the Institution of Mechanical Engineers, and the Society of Automotive Engineers. Dr Evans is the author of *Fueling Our Future: an Introduction to Sustainable Energy*, published by Cambridge University Press, which was short-listed for the 2007 Donner Prize for the best book on public policy published by a Canadian author. The book is also available in Chinese and is now being translated into Turkish and Arabic.

GERMANY

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Professor Frank Behrendt, born in 1959, studied chemistry at RWTH Aachen and Heidelberg University. He received his PhD in 1989 from Heidelberg University for his work on modelling of diffusion flames including detailed chemical reaction mechanism. Additional research on catalytic ignition and combustion led to his employment at Stuttgart University in 1999.

Since 2001 he has been a Full Professor and Head of Chair for Energy Process Engineering and Conversion Technologies for Renewable Energies at the Berlin Institute of Technology (TU Berlin). His scientific work focuses on the experimental investigation of two-phase flows exemplified by the gasification of biomass in various types of reactors. These experiments are complemented by modelling and simulation efforts as well as their economic and ecological evaluation.

In 2007 he became Speaker of the Innovation Centre Energy and responsible for the coordination of all energy-related research at Berlin Institute of Technology (TU Berlin).

In the same year Behrendt was elected as member of the National Academy of Science and Engineering (acatech), where he is the International Representative for the topics Energy and Resources. In 2013 he was elected into the Board of the Council of Engineering Academies Technological Sciences and Engineering (CAETS) and is a member of the CAETS Standing Committee on Energy.

Professor Behrendt serves as adviser on the boards of numerous foundations, centres, councils and agencies.

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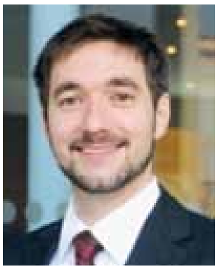

Dr Andreas König graduated in 2003 in forest science at the Technical University Munich. From 2004–10 he worked as project manager and head of the bioenergy research group at the Institute of Energy Economics and Rational Use of Energy (IER) at the University of Stuttgart. His fields of work during that time were: production and provision of solid, liquid and gaseous biomass; generation of heat, electricity and biofuels; geothermal and solar thermal heat and power generation; energy system modelling; life cycle assessment; and potential analysis. In 2009 he received a doctoral degree in energy economics and energy engineering from the University of Stuttgart; the title of his dissertational thesis was 'Comprehensive analysis and assessment of competing energetic utilisation pathways for biomass in the energy system of Germany till 2030'.

Since 2010 he has been working as project coordinator at the National Academy of Science and Engineering (acatech).

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Dr Baldev Raj has served in the Department of Atomic Energy, Government of India, over a forty-two-year period until 2011. As Distinguished Scientist and former Director, Indira Gandhi Centre of Atomic Research, Kalpakkam, he galvanised the community of scientists and engineers for advancing challenging technologies related to fast breeder test reactor and prototype fast breeder reactor. He has cultivated excellent schools in nuclear materials and mechanics, non-destructive evaluation, nanoscience and technology, corrosion, welding, separation sciences and technology, robotics and automation, and energy systems and strategies. He is a key driver of a unique high technology Prototype Fast Breeder Reactor of 500MW(e) and Closed Fuel Cycle Technology to realise energy security and sustainability in the 21st century and beyond, and an acclaimed specialist in materials for energy systems, medical technologies and archaeometallurgy.

Dr Raj is currently President, International Institute of Welding and President, Indian National Academy of Engineering. He is Fellow of the Indian National Science Academy; Indian Academy of Sciences; National Academy of Sciences, India; The Third World Academy of Sciences; German Academy of Sciences; International Nuclear Energy Academy; and Academia NDT, International.

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Chemical process development and design, reaction engineering, modelling and hazard analysis are his specialisations. His research group is currently working in process intensification for green reactions, CO_2 capture and decomposition, and ionic-liquid-mediated reactions. He has published more than 120 research papers, filed 45 patents, edited three books and received nine national awards.

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Professor Myongsook Oh is a Professor of Chemical Engineering in Hongik University in Seoul. She obtained her BS degree in chemical engineering from the University of California at Berkeley, and her ScD from the Massachusetts Institute of Technology. Before joining Hongik University, Dr Oh was associated with Lawrence Livermore National Laboratory and Texaco, Inc. in the US. Beginning with her ScD thesis on softening coal pyrolysis, she has worked on the conversion of fossil fuels for more than 30 years, including oil shale retorting, coal pyrolysis, gasification of various feed stocks and the vitrification of nuclear waste. She has continued working on coal gasification in Korea, providing leadership in gasification slag rheology and refractory corrosion.

The other areas where Dr Oh devotes her efforts are engineering education and women in engineering program. She now serves as Director of Seoul Regional Center to support women in the STEM area, is a Vice President (VP) of the Korean Society for Engineering Education, and a VP of the International Federation of Engineering Education Societies. She has also served on several government committees. She is an active member of ACS, KIChE, KSIEC, ASEE and KSEE. She is a member of the National Academy of Engineering of Korea.

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He joined KERI in 1985 and has served as the president of KERI for six years. He has also served as the Director of Center of Power-IT National Program of Korea during 2005–09.

In those capacities, he has involved many energy policy issues, including restructuring of electricity market, electricity demand and supply planning, and long-term R&D planning of energy technology.

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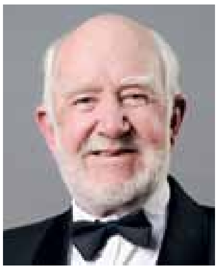

Professor Philip Lloyd was educated in chemical engineering at the University of Cape Town and nuclear physics at MIT. After a brief spell with the South African Atomic Energy Board he joined the mining industry and spent 15 years in industry-related R&D. He then became part of the international construction industry, and oversaw a number of major projects around the world. When that came to an end, he embarked on a third career: part-time consultant and part-time professor. His consulting has covered a wide range, from troubleshooting problems with major processing works to acting as an expert witness before the International Court of Arbitration. His academic work has concentrated on energy and the environment, and he was nominated as part of the IPCC team that shared the Peace Prize in 2007. His interests range from finding better ways for poor people to cook, to understanding and quantifying climate change. He is presently a Research Professor at the Cape Peninsula University of Technology in Cape Town.

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He has been active in energy systems research for over 30 years, developing new generation, conversion and system technologies, and has extensive interactions with UK and international government bodies on energy policy development and new technology deployment. He has recently been appointed the UK–China Science Focal Point for Energy and Renewables.

John is a graduate in Mechanical Engineering from Imperial College, London, where he also spent five years in computational fluid dynamics research. He is Past-President of the UK's Institution of Engineering and Technology, Fellow of the UK and Australian national Academies of Engineering, Professor of Engineering Cardiff University and Fellow of Queen Mary University of London.

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Dr Peter D. Blair is executive director of the Division on Engineering and Physical Sciences of the National Research Council (NRC) in Washington, DC. The NRC manages program activities for the National Academy of Sciences (NAS), National Academy of Engineering (NAE) and Institute of Medicine. Dr Blair also served as director of the Academies' series of studies, *America's Energy Future: Technology and Transformation*, initiated by the NAS and NAE at the request of Congress to inform the national debate about the role of science and technology in shaping the nation's energy future. From 1996 to 2001, he was executive director of Sigma Xi, The Scientific Research Society, and publisher of *American Scientist*. From 1983 to 1996 he was assistant director of the Congressional Office of Technology Assessment and director of OTA's division on industry, commerce, and international security and energy research program manager. Earlier Dr Blair was cofounder (in 1978) and principal of Technecon Analytic Research, Inc.; from 1976–96 he served on the faculty of the University of Pennsylvania. He holds a BS in engineering from Swarthmore College (1973) and, from the University of Pennsylvania, an MSE in systems engineering (1974) and an MS (1975) and PhD (1976) in energy management and policy.

NOTES

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4 Provide an international forum for discussion and communication of engineering and technological issues of common concern;
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OPPORTUNITIES FOR LOW-CARBON ENERGY TECHNOLOGIES
FOR ELECTRICITY GENERATION TO 2050 – Working Group Report

International Council of Academies of Engineering and Technological Sciences (CAETS)