Renewable and Nuclear Electricity:
Opportunities, Challenges and Policy Recommendations

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1. Introduction

Economic growth and electricity supplies are strongly linked when economies are developing. While the developed world may be able to meet rising electricity service demand with improved end-use efficiency, worldwide power demand is, nonetheless, expected to significantly increase due to economic growth outside the OECD. A failure to satisfy power demand in the developing world would not only constrain economic growth, but would also sustain “energy poverty” experienced today by 1.4 billion people with no access to electricity. The UN Millennium Development Goals, adopted in 2000, placed a high priority on eradicating energy poverty.

Also, in order to achieve the greenhouse gas emission goals endorsed at the 2009 G8 Summit, the electric power sector must produce substantially less greenhouse gas emissions per kWh. Since nuclear and renewable power plants produce essentially no greenhouse gas emissions, the future world-wide fleet of power plants must include a substantial share of renewable and nuclear plants or other zero-emission technologies.

The power sector investments needed to support both economic growth and emission reduction are formidable. The IEA estimates that $17 trillion must be spent for new power plant and transmission infrastructure between 2013 and 2035. While it is evident that zero-emission power plants must constitute a major part of this investment — $6.2 trillion for renewable power plants (IEA, 2013b) — there is a significant controversy whether it is practical for renewable energy to expand sufficiently to meet this need, or whether governments should give nuclear power support comparable to that provided to renewable energy to allow for more electricity and less greenhouse gas emissions. This paper is intended to inform this debate by examining the technical and economic challenges faced by nuclear

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1 The IEA estimates that electricity demand will increase by 2.3%/year through 2035 driven by demand growth of 3.3%/year outside of the OECD (IEA, 2013a).

2 At the 2009 G8 Summit in L’Aquila, Italy, a goal to reduce world-wide greenhouse gas emissions in 2050, relative to 2005 emissions was endorsed by the G8 members. In addition, governments of the countries that constitute 80% of total GHG emissions have agreed to take measures to significantly cut GHG emissions. This is the best reason to explain why this paper does not address coal with CCS.

3 Multiple studies by the IEA, IIASA and others conclude that 1) very significant cuts are necessary in the power sector to achieve deep greenhouse gas emission cuts, 2) the emission reductions in the power sector can be achieved at relatively low costs compared to other sectors, and 3) while there is some room for “transitional” low GHG technologies such as natural gas or coal with carbon capture and storage, it will be necessary to have a large share of renewable and nuclear power to reduce world-wide greenhouse gas emissions by 50% by 2050. Consequently, natural gas plants with waste heat recovery, coal plants with CO$_2$ capture and storage, or natural gas plants with CO$_2$ capture and storage can all contribute to significant power-sector emission reductions in many countries: the ultimate goal must be a high percentage of zero-emission renewable and nuclear plants.
and renewable power: cost, safety, environmental impacts, public acceptance and integration into the electrical grid.

2. Key Messages and Policy Recommendations

- World-wide economic growth will require continued power sector investments to meet growing electricity demand. While electricity demand growth in the OECD will be relatively modest, most serious studies, including the International Energy Agency’s World Energy Outlook 2013, project that the developing economies will increase electricity demand by over 3 percent per year over the next several decades (IEA, 2013a).

- What should be pursued along with the above is the eradication of energy poverty, particularly that of electricity, which has a critical importance for human dignity and capacity building. As increased global electricity production does not necessarily resolve this problem, special efforts should be made for the redistribution of electricity in impoverished or detached areas in an environmentally compatible manner as much as possible. Recent advances in PV technology can greatly assist in this regard.

- Governments of the largest world economies are committed to substantial reductions of greenhouse gas emissions. For example, on September 6, 2012, nations of the world’s leading economies ranked climate change, along with growth, jobs, investment and trade, as a key issue of the future; one that will extract ever higher costs if “we delay additional actions,” (G20, 2013).

- Multiple studies have shown, world-wide, that the power-sector would have to achieve deep cuts in greenhouse gas emissions in order to make significant cuts in overall emissions. The studies show that a large share of energy-sector emissions come from the power sector. The studies’ cost analyses also show that reducing greenhouse gas emissions in the power sector is relatively cost effective compared to reducing emissions in other sectors, especially the transportation sector.

- While replacement of coal-fired plants with natural gas or fossil-fuel plants with carbon capture and storage can facilitate progress in cutting power sector emissions, the share of carbon-free power sources, such as renewable energy and nuclear power, must constitute a much larger share of power sector generation if overall emission goals are to be achieved.

- New renewables (e.g. wind, solar, modern biomass and biofuels, tidal, wave and ocean energy) are widely regarded as clean, indigenous and sustainable sources of energy. Therefore, they are favoured by many governments and the public as a whole. However, their present contribution to global energy consumption is still limited (about 3% in 2013 and only about 10% even for heating) since their economics are often not yet favourable, especially at the margin. In most instances, they need to be supported by state subsidies and regulations. They suffer from high investment costs
and, as a result of the intermittent and diffused nature of wind, solar, and tidal, relatively low utilisation factors.

- The costs of renewable technologies have come down as a result of research, development and demonstration and technology learning that is gained with commercial experience. Cost breakthroughs in several renewable technologies can be expected especially given the considerable investments government and industry are making to achieve lower costs.

- Government policies to promote the growth of renewable energy or nuclear power that result in high electricity costs are not sustainable as high electricity costs and limited electricity supplies are harmful to economic growth.

- If renewable energy programmes or initiatives for new nuclear power are based on overly optimistic technical assessments, costs are likely to exceed sustainable levels. The strongest proponents of both nuclear power and renewables tend to have an overly optimistic view of the contribution their favoured technology is likely to make to future energy demand. Nuclear growth is limited primarily by the long lead time and the public opposition to new nuclear plants. New renewables are limited primarily by the inherently lower energy densities and by the massive demands their large scale deployment puts on other parts of the electricity supply system.

- Policies should ensure the uptake of the most cost-effective technologies. Policies should not prematurely force the uptake of technologies that require technological advances or technologies that cannot be expected to experience significant cost reductions when applied on a commercial scale.4

- Policies should consider the full costs and benefits of power sector technologies. Important benefits may include the elimination of pollutants such as toxic particulates, sulphur, mercury, volatile organic compounds and nitrogen oxides from fossil-fuel power plants. Cost may include pollution, resources required to construct renewable or nuclear power plants and their necessary transmission grids, adverse impacts on wildlife or property values and, for nuclear plants, the possible release of radiation during plant operation or the disposition of spent reactor fuel.

- Cost-effective electricity storage would significantly improve renewable and nuclear power economics, reducing the costs for meeting peak power demands and reducing the need to dispatch power at low prices when supply outstrips demand. Storage benefits intermittent renewable technologies such as wind and solar plants. Storage

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4 Wind energy is an example of an initially costly technology that achieved large cost reductions as a result of commercialization. Cost reductions from commercialization are often referred to as “technology learning.” It can be used to justify subsidies to technologies that are not currently competitive if it is expected that, with expanding commercial production, costs will come down. A “learning ratio” is often used to measure the cost reduction achieved by a doubling of commercial capacity.
also benefits base load power plants like nuclear which cannot be easily cycled to follow load.

- Research, development and demonstration to develop cost-effective storage should be a priority of governments.

- Likewise, research, development and demonstration to reduce the cost or address shortcomings of renewable and nuclear technologies should also be a governmental priority.

- Significant reductions in power sector greenhouse gas emissions will require reductions in renewable and nuclear power costs. Cost reductions can be achieved through commercial application but also require research, development and demonstration.

- Nuclear power plants are currently not likely to be built in most OECD economies without government backing as the financial risks to utilities, other energy companies and banks are too large. Building nuclear power plants in the United States is particularly challenging as long as low U.S. natural gas prices persist ($4.70 per million Btu as of 19 June, 2014).

- The prospects for nuclear power are much better outside the OECD in more centrally planned economies. The prevalence of state-owned power companies, generally lower construction costs, and the prevailing regulatory environments help explain why the bulk of planned nuclear power plants are in Russia, Asia and the Middle East.

- Modular nuclear power reactors may offer significantly lower costs, better scalability, improved safety and reduced economic risk, and their development should be a governmental priority.

- Left to the private market, nuclear power investments are unlikely in the OECD. OECD governments should explicitly consider how and if they want nuclear power to help reduce national carbon emissions. The alternatives include:
  
  - Currently forgo significant reliance on light-water reactors as a means to achieve GHG goals and wait to see whether commercially available modular nuclear reactors would be competitive;\(^5\) perhaps by waiting to see whether nuclear reactor projects outside the OECD (and those few within the OECD) achieve the necessary cost reductions that might make nuclear reactors more attractive to investors in competitive power markets;

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\(^5\) Assuming that there would be an overall scheme such as cap-and-trade or GHG taxes to financially reward technologies that produce lower GHG emissions.
Develop modular reactor designs that could greatly reduce on-site costs, provide a manufactured product with a predictable customer cost and improve the economic competitiveness of nuclear power;

Provide financial backing to enable the construction of light-water reactors, perhaps with the expectation that successful experience with the technology may eventually lead to commercial acceptance of the technology in competitive power markets;

Assume that development of nuclear power is not likely to be a means to achieve deep cuts in GHG emissions.

- If OECD governments choose to forgo support for nuclear power by either not assuming part of the financial risk involved in building current-technology reactors or by not participating in developing modular reactors for widespread deployment, then there is less likelihood that deep cuts in power sector carbon emissions will be achieved. If governments hope to achieve the desired increased electricity production and CO₂ reductions primarily by the (subsidised) expansion of renewable power, then there is a likelihood that this will not succeed and that increased use of fossil fuels and/or failure to meet the goals will result.

- If nuclear power is to be deployed successfully in countries without a current commercial nuclear program, several cultural attributes must be present. A political culture that can make a long-term commitment, provide for an independent regulatory agency with both authority and resources, and assure independence of courts to enforce contracts is crucial. Equally crucial are a set of social-culture issues including freedom from corruption, holding safety as paramount, a commitment to transparency in management practices and communication, and a strong continuity of institutions. Without these, a nuclear-power program is less likely to achieve an adequate safety record.

- Nuclear power has always been linked to concerns with proliferation of nuclear weapons, specifically the potential misuse of nuclear power reactor or fuel-cycle technology to make weapon-usable material directly, or to extract it from a power-reactor or a fuel cycle facility by either a government or a non-governmental group for malevolent purposes. If these concerns are to be managed in the future, it is necessary that the international protocols based on the Non-Proliferation Treaty be maintained and expanded. This includes mandatory agreement to the NPT’s Additional Protocol, along with a world-wide commitment to ostracize states that openly flaunt the NPT.

- The development of fusion energy could offer future supplies of energy on a scale orders of magnitude larger than current known energy resources. Considerable scientific and engineering progress has been made to develop fusion energy. While we are at least a few decades away from the first commercial scale fusion power plant, it is recommended that governments continue to provide the necessary research funds to advance fusion power.
The support for fusion energy research, recommended above, should be part of a much larger R&D agenda to enable commercially significant supplies of GHG-free electricity, including advanced renewable power technologies, new energy storage technologies and modular nuclear reactors. While not discussed in this paper, research and development of carbon capture and storage technologies may also lead to significantly reduced power sector emissions while still utilizing the large world-wide reserves of coal and natural gas.

3. Key Challenges to Expanding Renewable Energy

The purpose of this section is to outline and evaluate the challenges presented by increasing penetrations of renewable electricity generation. These generation sources primarily include solar and wind, which are growing rapidly and are new enough to the grid that the impact of high penetrations is not fully understood. The challenges associated with solar and wind will be examined qualitatively, and to the extent possible, in terms of the costs they might imply to the system over and above the costs associated with deploying and operating the electrical generation equipment. Hydropower is generally well integrated into existing operations, but has much less potential for growth. Tidal, wave, run-of-river hydro and geothermal sources are currently much more limited both in quantity and growth. Energy efficiency is sometimes considered an energy “source,” but is not usually combined with renewables; nonetheless, it is discussed below because the potential for more efficiency would obviate the need for renewables (or for more nuclear) to some extent. Special challenges posed in developing countries are presented as well.

The intrinsic nature of solar and wind power is very likely to present greater system challenges than “conventional” sources. Within limits, those challenges can be overcome, but at a cost. Later sections of the paper will draw on a variety of sources to identify a range of such costs, at least as they are foreseen by researchers helping prepare ambitious plans for grids to obtain high shares (30-50%) of their megawatt hours from primarily solar and wind generation.

Since a primary policy rationale to including renewables is reduction of carbon emissions, prospects for high (30-50%) penetrations of renewable power will be a key focus, even though they may require significant technology improvements. These issues also raise the question of what role is appropriate for nuclear power (a non CO2 power source whose capacity can be expanded) in helping integrate renewables into grid operation.

3.1 Some Power System Fundamentals

Modern electric power grids are really a technological marvel, even if routine. Electric power, delivered as needed on demand, is a very valuable resource for industry, commerce and everyday household life. In addition to the simple availability of easy-to-use energy, the value is much increased by virtue of the reliability and the “quality” of the supply. Power must be
supplied to user within voltage tolerance limits, and rigidly maintained frequency (60Hz in the US).

Power systems are typically very large networks drawing on many generating sources of power and dispatching that power to many loads. This involves large scale “transmission” of power to nodes and “distribution” of power to users who range from very large industrial complexes to ordinary homeowners and everyone in-between. These systems are extensively thought out and planned.

The degree of difficulty for maintaining such a system is substantially exacerbated by the fact that power flows are virtually instantaneous and that power storage opportunities are very limited. Thus, any upsets in the system (large power plants or industrial users tripping offline, transmission line breakdowns, etc.) must be offset on the order of seconds. Further, like any mechanical equipment, power plants must be periodically shut down for planned maintenance. Additional reserve power must be available to supply power during these periods.

The two most basic measures of electricity are megawatts (MW) which connotes the flow rate of power or capacity of generation, and megawatt hours (MWh) which indicates energy usage.

Costs associated with power sources occur at three levels. First there are the costs associated with the generation facility itself. These are capital costs for land, equipment and construction, and ongoing operating and maintenance costs. The given facilities must be connected to the grid, and the grid must be capable of carrying sufficient power to desired nodes which gives rise to additional costs — both capital and operating. Finally, all power systems have substantial infrastructure whose primary purpose is to maintain grid stability and reliability. This need is acute because, at least for now, the possibility of storing electricity is very limited and ranges from very expensive to impossible.

Solar and wind power are fundamentally different in character from traditional fossil fuel sources (or nuclear and hydro.) Such “conventional” facilities are normally described by their capacity for power production in terms of MW. That capacity is generally available on a dispatchable basis for the system operator. Fuel (coal, oil, reservoir water, uranium) is stored on site or piped in (natural gas). While breakdowns do occur, they are rare.

Solar and wind are also rated according to capacity. However, these ratings are based on specified conditions: 1 KW/square meter insolation and 12 m/s wind, for example. But these conditions are not achieved at the discretion of the operator, but rather are subject to nature.

Consequently, both solar and wind energy present intermittency issues to system operators. These are time of day, seasonal and even idiosyncratic. Solar and wind produce energy according to sunshine and wind available. Either of those can change very suddenly. But power demand doesn’t fall, so the shortage situation must be dealt with. Wind availability may be ill timed according to time of day or seasonal power needs. In addition, both solar and wind at utility scale require substantial expanses of land for deployment and good insolation or wind availability. Thus, these sources may require substantial transport of power from
locations not convenient to the grid. Conventional sources have similar problems, but face fewer location constraints since their fuel is more transportable or ubiquitously available.

Up to a certain level of penetration of intermittent renewables, these issues don’t present unique challenges for grid operators. While rare, breakdowns from conventional power generation equipment certainly occur and variations in load occur frequently. Operators have developed a number of tactics for dealing with these. Spinning reserves, for example, can be brought online very quickly to offset power sags or meet load coming onto the system. Power is already transported long distances in particular circumstances.

However, these features come at a cost. Currently such costs are often subsumed into aggregate system operation costs. Since renewable sources tend to draw more heavily on these resources, they are in effect being subsidized by grid operation. (They can be charged directly for such services, but currently, given their small portion of total supply, this is not often done.) This implicit subsidy is in addition to direct subsidies that renewables are often currently provided.

As the proportion of solar and wind power to conventional power grows, the operational realities of these issues come to light. To the extent possible, some exemplary costs imposed by renewables will be evaluated. A number of European nations are planning for substantial increases in solar and/or wind shares for their power sources. The California grid currently provides excellent examples which will be explored. Further, as current energy policy, particularly in California, dictates unprecedented shares of renewable power for future years within utility planning horizons, ultimate limitations of such power are being investigated and will be examined here.

### 3.2 System Costs versus Facility Costs

All large power plants require substantial capital investment for site locations, structures and equipment. In the case of “conventional” power plants (coal, oil, natural gas, hydro and nuclear), these are all directed toward turning some sort of turbine which is attached to generation machinery. These capital investments are usually expressed in terms of dollars per MW. These generators produce alternating current power. That power must be conditioned and transferred to the grid. Critically, all of these spinning generators must be synchronized, i.e. spin at the same speed.

Except for hydro, these conventional plants have fuel costs. All have operating costs similar to what would occur in any factory and require significant periodic maintenance.

### 3.2.1 Connection

Solar and wind power installations require high capital expenditure per MW of rated power (which does not have the same connotation as conventional plants). Solar PV power needs specific equipment to “condition” produced power to convert direct current to AC, increase voltage and maintain grid synchronization. Additional steps must be taken to ensure that solar
PV installations meet grid requirements for upset conditions. Grid operators prefer that wind farms install additional equipment to support grid interaction, providing, for example, the ability to curtail wind output.

### 3.2.2 Transmission

Large scale power facilities generally need their produced power transmitted to the grid for ultimate delivery to system nodes and then distribution among users. Such transmission costs tend to be higher for solar and wind relative to their rated capacity because of the location limitations cited above, and because, relative to their rated power, they have relatively low load factors. Transmission is generally sized to accept the highest output likely from such facilities. This is especially true when plans for renewable energy set ambitious goals for production. Higher per MW costs spread over relatively fewer MWh means higher cost.

Nuclear facilities also often bear relatively high transmission costs. For safety considerations, they have a redundancy in connection to provide greater assurance for cooling water pumps. This is in addition to onsite backup diesel or other power.

### 3.2.3 Balancing and Adequacy of Supply

Over and above these facilities costs, power grids require system infrastructure to maintain the continued operation and stability of the grid. While solar and wind inherently place disproportionate demands on this infrastructure, these are not different in kind from conventional sources.

Solar and wind power availability may tend to vary on a predictable daily and/or seasonal cycle. Solar especially can be expected to have a daily cycle. During any off cycle, if power demand doesn’t fall in concert (the solar cycle tends to almost coincide with peak daily power demand), standby power must be available (at least according to most current standard practice). This same requirement applies to conventional power which needs backup power (i.e. “reserve”) for maintenance cycles. Conventional sources must be ramped down as solar and wind are ramped up to keep the system in balance. Some baseload facilities, coal and nuclear primarily, have historically run more or less continuously at full power in most systems. System goals set for renewable power generation (i.e. California’s 33% of electricity retail sales from renewables by 2020, but to a greater extent 50% in the future which is under consideration) require displacing power from these facilities.

Further, solar and wind have inherently more volatile output than conventional sources whose variability is tied basically to relatively rare breakdowns. For solar and wind respectively, sunlight may be obstructed, and wind may stop blowing. These events are likely to have some warning, but they are akin to breakdowns in mechanical equipment. The problem is exacerbated in that these effects may be correlated among a range of solar installations or wind farms.
The principal means of providing these needs is first spinning reserve, usually a coal or oil plant, gas turbine, or hydro, intentionally running at less than full capacity. So situated, these may be ramped up (or down) very quickly to respond to very short term situations.

With greater warning, provided by weather forecasts in the case of renewables, and maintenance planning as well as equipment monitoring, reserve facilities can be fired up and brought online to fill in gaps in demand. Again, these are typically gas-fired fossil fuel plants or hydro. Such units typically provide needed power at lower incremental cost through greater efficiency. Simple cycle gas turbines are used for spinning reserve because they have lower capital costs than most other capacity options.

### 3.3 Flexibility

The flexibility of the contribution of new renewables to the electricity supply varies. Although hydroelectricity is generally reliable and provides flexible supply (except in periods of prolonged drought), it can also store huge amounts of water/power to be used when necessary. This advantage is also assisted by pumped hydro storage, which involves pumping water uphill into the reservoir at off-peak and then releasing it when needed. Biomass (subject to land and water availability, and food requirements) and geothermal can provide reliable renewable sources. However, other new renewables (particularly solar and wind) present formidable challenges to the transmission supply operators due to their intermittency, unpredictability, and changing meteorological conditions. This intermittency is delaying or preventing electricity markets from accommodating and meeting the ambitious renewable goals set by energy planners in some countries.

The flexibility of national electricity grids to accommodate variable power sources is enhanced by: achieving geographic and technological diversification of variable energy sources, improving local energy management and increasing prospects of energy-storage schemes, and also by trading with other electricity grids.

Nuclear plants pose other types of system challenges in that they most often dispatch power below cost when power demand is low. They need some time to ramp up and down their load and follow system. Some existing LWR-type plants have limited ability to significantly vary their output to match changing demand. PWRs, as well as CANDU and BWR, have load-following capability, which will allow them to fill more than baseline generation needs. Some newer reactors also offer some form of enhanced load-following capability. For example, the Areva EPR can slow its electrical output power between 990 and 1,650 MW at 82.5 MW per minute.

In the generation dispatching schedule, renewables production is “free,” and it is a “must dispatch” source of generation. This is followed by nuclear. Correspondingly, if the system has minimum load, such as at weekends, and a surge of wind occurs, renewables and nuclear output may exceed demand. It is not easy to ramp down load on nuclear quickly or shut down other dispatchable facilities in the generating system. These events lead generation to significantly exceed load. If there are enough regional interconnections, neighbouring systems
can accommodate some of this excess generation (as regularly happens with Denmark’s wind energy generation); but what happens if those systems have the same problem? For example, it has been found that offshore North-West Europe periods of calm quite regularly coincide across a wide area of ocean. The least-cost solution is to offer incentives to consumers to take more load by various means including negative pricing. This means that nuclear output is not only offered free, but consumers are actually paid incentives to take it. We are not talking here of a hypothetical case, but actual incidents experienced by the European system in recent years. In other cases, the power output of these plants is simply curtailed. If new renewables, particularly the wind component, is increased, then this dispatching problem is going to become more acute. Whether this will lead to an increase in the disadvantages and costs of nuclear generation, or to the fuller exposure of the frailties of new renewables to the advantage of nuclear remains to be seen.

3.4 System Cost and Renewable Share

A number of countries and states in the US have put forward very ambitious goals for the share of power provided by renewable sources. California calls for 33% electricity retail sales from renewables by 2020 (originally 20% by 2017), not including hydro. Finland, France, Germany, Republic of Korea, and the UK have ambitious goals as well. Denmark is already deriving 30% of its power production from wind, but exports power to nearby countries in times of surplus. Maine, Massachusetts, New Hampshire, New York and Maryland have already cut their power sector emissions by 40% with renewables and gas. Consequently, much study and planning has been undertaken to understand the consequences of these goals. These are potentially two fold. First total cost of power per MWh increases (on a fully allocated cost basis which includes the cost of capital) because renewable generation is at least now relatively expensive, and because system costs per MWh increase as the share of renewables increases.

System costs increase because proportionately more balancing and back-up resources are required to compensate for the intermittency of those increased renewables.

The second concern is the extent to which there is a limit to the share of renewable power, at least as provided by wind and solar that can’t be dealt with without some dispatchable fossil fuel power in the system.

A recent study illustrates these factors specifically with respect to Germany and presents data across nations. This is summarized in Figure 3.1:
As can be seen, there appears to be a strong positive correlation between consumer power costs and the percentage of solar and wind penetration. A more subtle insight is that the cost impact from penetration will vary by system.

Specifically in Germany this situation has also reduced revenues for “traditional” fossil fuel operators. On a real time basis, grid power is priced on the basis of what is in effect an essentially continuous auction based upon marginal generation costs. Solar and wind have zero marginal cost or are designated as “must run” facilities (perhaps for this reason). The availability of substantial “free” resources lowers prices overall. And in the case of solar, these reduced prices often coincide with peak power demand.

Given the nature of the auction, conventional suppliers bid their short run costs and don’t generate unless these are covered and they are dispatched. However, they typically depend on “high” peak prices to make significant margins above cost in order to cover capital costs. These peak prices have been substantially reduced (Figure 3.2).
Poser et al. note that:

“This situation is making cost recovery even more difficult. This means that the owners of the plants have to write-off the money they originally invested. …RWE [a major German electric utility] recently announced a write down of €4.8 billion on assets, mainly power stations, and a net loss of €2.76 billion ($3.8 billion) on total sales of €54.1 billion, its first full-year loss since 1949. 59.” This situation is not unique to Germany. One of Australia’s largest electric utilities, Energy Australia, also announced a significant write down due, in part, to gas-fired generators becoming uneconomic because of the rapid growth of solar power and the rapid increase of electricity prices for customers.

Generators’ financial difficulties have already translated into lower stock prices and credit ratings. In terms of the magnitude of share price reductions, power utilities have fared badly. According to the MSCI (Morgan Stanley) European utilities share price index, the top 20 energy utilities have lost more than half a trillion dollars since their peak in September 2008.” Adding significant amounts of renewable power on grid have reduced wholesale power prices overall, and harmed the financial viability of utilities serving the grid.

3.5 Energy Efficiency

Multiple studies show that energy efficiency could be the most important method to reduce greenhouse gas emissions while maintaining energy service consumption. Under the IEA New Policies Scenario, total energy demand increases by one-third from 2013 to 2035, rather than 45% under current policies (see Figure 3.3). Efficiency, especially in end-use sectors, accounts for three-quarters of that reduction. The IEA “Efficient World” scenario is even
more aggressive, reducing global primary energy demand by 50% compared to the “new policies” case (IEA, 2013a).

Both the IEA and IIASA emphasize the importance of energy efficiency to reduce the required demand for new power generation. In IEA’s “new policies” scenario an additional $3.4 trillion of cumulative investment through 2035 will be made in energy efficiency compared to their “current policies” scenario (IEA, 2013a). IIASA estimates that $15 trillion will be needed through 2050 (Johansson, Patwardhan, Nakicenovic, Gomez-Echeverri, eds. and et al., 2012). These investments produce an impressive payoff with IEA estimating $6.1 trillion in energy savings, and IIASA estimating $57 trillion in avoided heating and cooling costs alone. Nonetheless, as shown in Figure 3.1, while energy efficiency investment significantly reduces the global growth in primary energy demand, significant global growth remains. The estimates of electric power demand growth cited above, account for investments in energy efficiency required by new energy policies.

**Figure 3.3 Comparison of energy demand in IEA New Policies Scenario vs. Current Policies Scenario**

Realizing this efficiency potential will require strong, sustained policies. The IIASA Global Energy Assessment suggests governments need to address split incentives, such as when energy users and building owners have different time horizons for recouping investments, and recommends strong building and appliance standards coupled with information and awareness programs. Policies like these would help nations reduce future energy demand, with benefits including reductions in GHG emissions and other pollutants and significant job creation.

### 3.6 Challenges Outside of the OECD

Outside the OECD, electrification started rather late, but is gaining momentum. The share of electricity in the Total Final Energy Consumption is 16% in 2011, which is expected to grow
to 22% in 2035 according to the IEA New Policies Scenario. The annual growth rate of electricity demand between 2011 and 2035 is estimated at 3.3%, which is much higher than the growth rate of non-OECD Total Final Energy Consumption (2.0%).

Although energy consumption needs to grow at rates high enough to support economic development, rapid expansion of fossil fuel use will have deleterious effects on the environment. Therefore, in emerging countries, a major energy policy objective should be the “decoupling” of economic growth from energy consumption growth. Along with efforts to promote energy conservation and efficiency, clean energy supplies such as nuclear and renewables will be needed; gas is a cleaner-burning fossil fuel than coal, and will help reach GHG targets, but is not sufficient to decarbonize the electricity sector. However, there is uncertainty whether the electricity sector will attract enough investment to meet growing demand, especially in unstable countries. Business models as well as regulatory regimes tested and practiced in OECD countries will not necessarily be applicable to emerging economies due to the difference in not only developmental stage but also social, political and cultural background. Energy subsidies present a particular problem, as growing demand places burdens on national budgets and discourages energy efficiency. As several OECD energy companies have discovered, money will have to be found to fund new plants, and non-OECD countries in particular will be hard-pressed. Theft of power, corruption and other problems has caused several foreign power investments by independent power companies to fail.

### 3.7 Energy Poverty

However, the largest challenge, which may even dwarf the challenges discussed above, will be the “eradication of energy poverty,” especially electricity poverty, in the least developed countries and regions. This is an indispensable part of the efforts under the first goal (“Eradicate extreme poverty and hunger”) of the UN Millennium Development Goals adopted in 2000.

There are several causes of energy poverty, the most obvious of which is living in a community that has no, or very limited, access to electricity. Energy poverty can also exist in geographical regions that have adequate electricity supplies, especially urban areas in less-developed countries. In these circumstances, the inability to afford electricity and associated end-use equipment are among the many consequences of poverty that cause suffering to hundreds of millions of people including malnutrition and preventable disease. These are problems that have existed throughout human history but are incongruous with the opportunities provided by today’s technologically advanced economies. As Pope Francis said recently in Rio de Janeiro, "No amount of peace-building will be able to last, nor will harmony and happiness be attained in a society that ignores, pushes to the margins or excludes a part of itself."

There are 1.4 billion people around the world that lack access to electricity, some 85% of them in rural areas (Figure 3.4). In some countries, this problem is widespread. For example, 74% of the population in Myanmar lack access to electricity (OECD NEA, 2012). Because it is critical to the quality of human life, access to electricity should be facilitated above all else.
Without electricity, the opportunity for education of younger generations will be reduced severely, with serious negative implications on human capacity-building.

**Figure 3.4 Number of People without Access to Electricity in Rural and Urban Areas in the IEA New Policies Scenario (unit: millions of people)**

In this regard, a leapfrogging as seen in telecommunication (bursting into mobile phone bypassing the stage of landline phone) should be widely materialized by making the best use of renewables. Micro-grids using locally available energy sources, such as solar and wind power, will be an important option rather than waiting for the investment in large-scale generation and centralized transmission systems. Low-cost, off-grid solar power, as seen in remote villages in India, is a good start. In a nutshell, every effort should be mobilized to overcome such chronic energy poverty as soon as possible, though the particular combination of solutions relevant to each country will vary.

While renewable energy technologies, micro-grids and interconnections to national power systems are able to provide electrical services to many communities that now do not have them, energy poverty will not be eliminated without outside intervention. Many governments are unable to finance these initiatives without outside aid. In addition, outside aid cannot solve problems in countries with corrupt governments or countries torn with ethnic or sectarian warfare, a condition too often present in communities that do not have access to electricity services.

It is beyond the scope of this paper to discuss the existing sources of funding for energy poverty projects, such as the World Bank, its Global Environmental Facility and other
institutions except to note that much work needs to be done to finance energy poverty projects. We only note that renewable energy technologies have features that make them especially valuable for application in remote communities and to power micro-grids.


The scope of this section includes the current status and future prospects of commercial nuclear electric power, with emphasis on issues of safety, physical security, proliferation, and economics. (Issues related to radioactive waste are discussed elsewhere in this paper.)

Discussions of these issues are presented separately for the current fleet, for new reactor designs similar in size to the current fleet and for prospective new reactors of substantially smaller size. Also, this section discusses the issue of expansion of commercial nuclear power into new countries.

4.1 Reactor Safety

The fundamental issue that makes nuclear power reactor installations different from other industrial undertakings is, of course, the possibility that a major accident could release large amounts of radioactivity into the environment, endangering offsite populations and contaminating offsite land and property, possibly for a long time. As the world saw with the accident at Fukushima in Japan in 2011, this is a real possibility, even in the most advanced countries, and not merely a threat confined to countries with lesser technological prowess.

What do we know now about the likelihood of such accidents? The answer is that we know considerably more than was known two or three decades ago. We understand the origins of these accidents, we understand the variety of ways in which they might progress, and we can estimate the likelihood and the consequences of the many different accident scenarios. The advances in our analysis methods, and in the collection and use of the operating data needed to support them, have been remarkable world-wide in recent years.

We analyse “safety” by working out, in as realistic a way as we can, the likelihood per year that a large accident might occur. We now have methods that enable us to perform such an analysis, which is intrinsically probabilistic in character, and these analyses are now done routinely around the world. The community has settled on two different figures-of-merit, one being the annual frequency that a reactor will suffer a core-damage accident, and the other the annual frequency of a so-called “large” release of radioactivity, defined as sufficient to cause prompt radiation-induced fatalities offsite.

Based on what we know today, the annual frequency of core damage of one of the reactors in the worldwide operating fleet is estimated to be, on average, in the range of around a few times $10^{-5}$ per year. This is a typical value. It varies considerably from one to the next individual reactor even in the same country or even operated by the same company, and it is known only within a factor of three or so, or even less well, depending on the analyst and the design. However, based on what we know, the worldwide average is believed to be in the
range just cited. The likelihood that any such accident will progress to a large release is small, perhaps in the range of a few percent to ten percent. This means that the frequency of a large release is likely in the range at or above $10^{-6}$ per year or so, as a worldwide average.

There is ample evidence, based on objective assessments of many different indicators that the general safety performance of today’s operating fleet has substantially improved over the last 15-20 years. This is a worldwide trend. The indicators include rates of initiating events that might cause an accident if not mitigated, failure rates of vital safety equipment, rates and severity of operator and maintenance errors, major improvements in fire protection and changes in the designs to provide better safety system backup and reliability. Another significant improvement has been the worldwide sharing of operating experience and a diligent effort worldwide to learn from this experience. Although the improvements vary from plant to plant, they have occurred worldwide.

Whether today’s performance is adequately safe will not be addressed here. This is both an individual judgment that people make differently and a societal judgment made differently by different countries. Thorough risk-based assessments, including assessing risks associated with alternative sources of energy, are to be encouraged.

There is a vital caveat that must be discussed, of course. Like any technology, nuclear-power technology can be mismanaged, and a major accident could occur at any time. (As an example, consider the fact that for a passenger flying in a commercial aircraft, the safety performance is 30 to 100 times better on average than it was 40 years ago, and incontrovertibly so. But a plane crash could occur on any day. Yet if it did, even though it would a tragedy, it would not contravene the strong evidence that commercial flight is indeed much safer on average than it was decades ago.)

So too with nuclear power reactors. If the worldwide performance is in the range of a few times $10^{-5}$ per year, and if there are close to 500 reactors today, one such core-damaging event might occur on average every several decades. Yet one could occur tomorrow. Crucially, what worries the reactor safety community is that if a major error of some kind were made, as happened in Japan with the decision to place the Fukushima reactors at a tsunami-vulnerable site without adequate protection, the likelihood of an accident would be higher. What to do?

It is important to note that we do know how to achieve a safety level like the above. A few vital attributes of the enterprise must all be present: (a) We must incorporate the appropriate safety features in all existing reactors, including improvements in equipment reliability and in the training of operators; (b) we must apply all lessons learned from operating experience worldwide; (c) we must emphasize safety culture everywhere; (d) we must remain attentive to aging issues, including equipment aging, staff aging, and institutional fossilization; (e) we must maintain the morale of staff, taking care to infuse the enterprise with a generational “mix” that includes both experience and youth; and (f) crucially, we must maintain and reinforce a vigorous and independent regulatory agency in every country, enhanced to the maximum extent possible by a strong international framework for establishing high safety
standards, provision for technical assistance and peer reviews of design and operational safety and sharing and disseminating lessons learned and best practices experience.

If the above attributes are all present and attention is paid to maintaining each of them, the existing worldwide operating reactor fleet can continue to achieve the safety performance noted above. This is true not only for the light-water power reactors (LWRs) that comprise the bulk of today’s operating fleet, but also for the others operating today: the heavy-water reactors, the gas reactors, and the Russian RBMK water-graphite reactors – but only if “operated well.”

Why can’t we do better with the existing large LWR reactors? Based on our understanding of the design of the existing LWR reactors and of how they are operated, certain limitations seem to make it difficult to achieve, say, an order of magnitude better fleet average than the above. These limitations involve the way the designs call on safety equipment when in trouble, the reliability of the equipment, the way operators are relied on, and the interplay among these factors.

However, for new LWR designs, especially those with more passive safety features and those whose design has taken maintenance and reliability into account from the start, the community of reactor safety experts has reason to believe that much better safety performance will ensue — perhaps an order of magnitude better. A few reactors with these advanced designs are now under construction around the world.

Why are these advanced LWRs better? There are many reasons besides the two crucial ones mentioned above (passive features, and design for reliability and maintenance). The new designs have greater embedded “engineering margin” in many different places; they have fewer and better components whose failure matters; they are easier to operate and more tolerant of operator error; and they are simpler to understand, and hence to analyse if an off-normal event were to occur. Crucially, they have included a number of advanced technologies that simply did not exist when the earlier nuclear plants were designed, such as advanced computer-based information systems, digital instrumentation and control systems, advanced operator-training simulators, and advanced materials in many different aspects of the design.

What about the safety of other advanced designs? There are two quite different types: (a) First are the proposed new smaller LWRs, the so-called “small modular” LWRs. There is reason to believe that their safety performance should be every bit as good as that of the new large LWRs, and in some ways perhaps better, because they have fewer components and simpler operations in many areas. Because most of the technologies used in these smaller LWRs are very similar to those in today’s large LWRs, these smaller LWRs probably have a “head start” in reaching commercial viability, compared to other advanced reactor designs. (b) Second are various advanced reactors other than the smaller LWRs. Some are large and some are small. They include advanced gas reactors, homogeneous reactors, liquid-metal reactors, and a few others. Among these are a few advanced designs using fast-neutron cores; these offer the capability to use the energy in the fertile heavy metal in the fuel as well as the fissile content, along with the capability to destroy the actinides to reduce the residual high-level waste
burden substantially. Effectively, such reactors would use a greater percentage of the original energy contained in the fuel, and would alleviate some of the longest-lived contributors to the nuclear waste burden.

All of the smaller new design concepts, whether they are thermal reactors or fast reactors, possess a set of safety-improvement features that are intrinsic to their smaller size. Specifically, the smaller size makes thermal transients and many other upset conditions easier to design against and also to control if an upset condition were to occur. Some smaller designs also require less standby safety equipment, which is an advantage for simplicity, for lower capital cost, and for easier and thus less costly maintenance. But even the largest of these advanced designs has several very attractive safety features, often involving passive safety design concepts and easier operation. The issue, of course, is that until any of these is actually designed in full and then built and operated, we cannot really know. (Admiral Hyman Rickover famously once remarked along the lines that a “paper reactor” is always safer and less expensive than a real one.)

What about the safety of power reactors potentially to be deployed in “newcomer” countries, meaning countries without a current commercial reactor program? The key issue is likely one of culture. First is the political culture, which involves a long-term national commitment and public acceptance if the launching of a nuclear–power program is to be successful. And crucially, a country needs a culture in which an independent regulatory agency with authority and independence from politics can operate appropriately. Second is the social culture. While many of these “newcomer” countries have strong social cultures, some do not. A culture of corruption, or a culture that does not hold safety as paramount, or a culture without commitment to transparency in management practices and communication, a strong continuity of institutions and a tradition of follow-through, is less likely to foster the environment needed to achieve an adequate safety record. Finally, in any “newcomer” country, there is the need for technical and financial infrastructure. This is true across the board, including routine technical infrastructure such as maintenance and electronics-instrumentation-electricity-grid support, the availability of competent craft labour, and spare-parts availability. A country also needs a financial infrastructure to support a large industrial installation like a nuclear power plant, including an insurance infrastructure and a trustworthy court system to enforce contracts. Without all of these various “cultural” attributes, power reactors in a “newcomer” country are unlikely to achieve an adequate safety record.

Thorium-fuelled reactors: All of today’s operating reactors, and almost all of the advanced designs that are under development around the world, use uranium as the fuel. However, reactor designs that use thorium as the fuel are fully feasible, and several different such designs have been advanced over the years. Much of the excitement over using thorium relates to thorium’s relatively high earth abundance, including in countries like India which possess little uranium. Using thorium for a power reactor is fully feasible, although there is almost no operating experience with them beyond a very few experimental facilities. There is no reason to believe that a thorium reactor cannot achieve the safety, security and non-proliferation record of the best of the uranium-fuelled designs, if “done right,” while recognizing that many of the technical issues with both safety and non-proliferation differ in
important ways. In India, a program to develop a thorium-fuelled power reactor has been in place for some years. However, only the future will tell us whether this development program will succeed, both technically and in terms of cost.

International institutions to promote reactor safety and security: A fundamental principle worldwide is that the regulation of the safety of power reactors is a national responsibility. However, because there is a worldwide recognition of a fact that is often phrased as “a nuclear reactor accident anywhere affects nuclear power programs everywhere,” and because many power reactors are located near the border with another country, a number of international and multi-national institutions have arisen that work to promote nuclear reactor safety and security worldwide. Foremost among them, of course, is the International Atomic Energy Agency. One major IAEA initiative is the Nuclear Safety Convention, to which all countries with power reactors are signatories. The IAEA has for decades also developed principles for safety and security, international safety and security standards, guidance documents, and programs of assistance that have had important impacts. The IAEA also collects, analyses, and disseminates information about reactor safety and security issues, organizes conferences and other meetings to promote international cooperation among experts, maintains an incident response and information centre that can respond if needed when an accident or incident occurs, and provides several services to countries that request them to provide on-the-site advice and review of safety programs, safety practices, and regulatory-agency performance. All of the above provide vital assistance worldwide, although taking advantage of these services is entirely voluntary on the part of any individual country.

Another organization that carries out a set of similar programs in many of the same areas is the OECD’s Nuclear Energy Agency, although its programs are mostly restricted to the OECD’s own member countries. The NEA’s efforts have had great value. They have positively improved safety and security worldwide even beyond the borders of the NEA’s own member countries. A strengthened international safety regime would bring about tangible enhancement to safety of nuclear power worldwide and increase acceptance for an expanded role as part of future energy mix. One initiative that might provide greater worldwide benefit would be if participation could be made mandatory for at least some of the IAEA’s programs, such as those that do site peer-review visits to reactors worldwide to give advice and review of a site-specific program. Given the IAEA’s current structure, it seems difficult to see how to bring about such a change to mandatory participation, but there is little doubt as to the benefits, if something along these lines could be put in place.

4.2 Reactor Physical Security

The issue here is the potential vulnerability of a reactor installation to an outside attack, or to a malevolent act by an “insider” team, or some combination. The current approach to security emphasizes “guns, guards, and gates” along with intelligence and counter-intelligence systems. The obvious concerns are the adequacy of the external defences, the adequacy of the on-site security force and system, and the effectiveness of systems that screen employees to detect those with relevant skills and malevolent motivations. Recently, concerns with cyber-security threats have also come into prominence.
On balance, the general feeling on the part of the community of nuclear power experts and many others worldwide is that the current schemes used to achieve the desired security regime seem adequate, everywhere around the world. (Even in countries with other problems, the military tends to be strong and well organized.) There are always ongoing concerns, which revolve around the screening of employees and guards, especially in countries where corruption is an issue. Also of concern is the potential decline in vigilance due to complacency and the potential for political interference.

One issue that continually arises is how to know whether today’s physical security scheme is “adequate.” No objective definition is accepted by all. Several methods have been developed and used to assess the extent to which a given security scheme can protect against a given postulated threat. International technical forums and projects have worked on this issue for many years, and some convergence has occurred on the main issues and analysis approaches. However, disagreements persist on how to do this evaluation, and part of the problem is that the values brought to the evaluation by different countries inevitably differ, and probably always will.

4.3 Proliferation Issues

The issue here is the potential misuse of nuclear power reactor or fuel-cycle technology to make weapons usable material directly, or to extract it from a power-reactor or a fuel cycle facility by either a government or a non-governmental group for malevolent purposes.

Today, there is an international protocol to achieve the aims of deterring proliferation of nuclear weapons and weapons technology, under the Non-Proliferation Treaty, while fostering peaceful uses of nuclear energy including nuclear power. The treaty is enforced through a safeguards system administered by the UN’s International Atomic Energy Agency. The central aspects of this NPT protocol include inspections both planned (through safeguards) and unplanned (through the Additional Protocols that are not agreed to yet by all NPT members), monitoring both within and from outside a given installation or country, the availability of extensive training, the use of exercises to test the functioning of the system, and periodic reviews. Other institutions, such as the Nuclear Suppliers Group, also contribute significantly. A vital aspect of the overall international regime is a set of restrictions on the export of so-called “dual use” technologies which have both civilian uses and potential uses that could enhance the proliferation of nuclear-weapons capability.

For many years, major emphasis was placed on the issues of proliferation arising if power-reactor fuel is reprocessed so that plutonium is extracted for re-use, making it “available” in “weapons usable” form. The concern was mostly directed at government-sponsored reprocessing programs that are openly acknowledged. That emphasis has in the last decade or so been supplemented by emphasis on deterring the use by a government of uranium-enrichment technology, which can produce weapons usable highly-enriched U-235 (HEU) under the guise of enriching to lower enrichment levels to make LWR fuel. Both technologies
have dual use are permitted in principle under NPT if genuinely and demonstratively justified for a large nuclear power program and deployed transparently.

NPT has been relatively successful so far, but not fully. First, there are several examples in which a few members of NPT have developed dual use technologies under the pretext of a civilian national nuclear power program only to prove, or be suspected, to be otherwise (e.g. North Korea walking away on its NPT obligations and testing several nuclear weapons, and Iran widely suspected of aiming to develop at least a capability for nuclear weapons, especially because it initially planned and developed its enrichment program in secret). The second failure is evident in that several countries chose not to be party to NPT and went on to develop nuclear weapons, declared (India and Pakistan as well as South Africa), and undeclared (in the case of Israel). Another is the failure of the recognized nuclear weapons states under NPT to begin a credible program to systematically reduce, eliminate and renounce their arsenal of nuclear weapons.

Today, this concern about proliferation arising from openly acknowledged government-sponsored programs (whether a reprocessing program or an enrichment program) has been supplemented with a major parallel concern about possible clandestine government-sponsored programs, or about a program embarked upon by a sub-national group.

While theft of separated plutonium has always been an issue, theft of HEU has typically been of lesser concern because of its lesser availability -- although research and test reactors around the world that use HEU have always been a concern and remain so. Today, however, the theft of both separated plutonium and HEU are emphasized together as threats to peace.

The physical security aspects of this issue seem to be adequate – that is, adequate against theft by an unauthorized individual or non-governmental group. Less clear is the adequacy of the world’s ability to intervene if a sitting government proceeds, as government policy, down a path toward proliferation (meaning a path leading to the development of an actual nuclear weapon). This includes using a commercial nuclear power program as a “cover” for an illicit weapons program, or using an ostensible power-reactor facility (such as a low-enriched-uranium enrichment plant) for those ends. This set of issues has political ramifications that are beyond the scope of this essay.

4.4 Recommendations

From the above discussion, a few recommendations seem to emerge naturally. Some are for technical work, and some concentrate on institutions and policies.

Recommendations (technical)

A. Small (modular) reactors show great promise to enable the expansion of nuclear power in many electricity markets that are otherwise inaccessible to the larger LWRs. These smaller reactors are likely to be especially attractive in many developing countries, although not exclusively in them. To make these reactors a genuine option, an emphasis on technical
research and engineering development, and also on developing efficient means for regulatory agencies to review and approve the new technologies, is imperative. It should receive priority worldwide, as should identifying the most promising SMR designs and moving them toward prototype demonstrations.

B. Enhancing the training of technical personnel and developing technical infrastructure, especially in countries that today have little or no nuclear-power deployment and perhaps even little strong technical base at all, should be another worldwide priority.

Recommendations (policies and institutions)

C. A major barrier to widespread deployment of nuclear power is the set of “culture issues” that include corruption culture, safety culture, and the culture of institutional continuity and integrity. Policies that emphasize the positive attributes of these cultural issues, or discourage their opposite, are an urgent matter.

D. The need for an independent regulatory agency with authority and independence from politics cannot be overemphasized. No country without this should deploy nuclear-power technology. Policies, including policies in the developed world to provide assistance and mentoring, are a vital component of a successful worldwide nuclear power endeavour.

E. There is a need to strengthen the international safety regime, including, where feasible, making some current advisory services of IAEA mandatory.

F. In cases where policies are established to reduce the carbon footprint of the electricity grid, nuclear power should not receive discrimination in favour of renewables.

5. Economics of Nuclear and Renewables

New renewables (NR: wind; solar; modern biomass and biofuels; tidal, wave and ocean energy) are widely claimed to be clean, indigenous and sustainable sources of energy. Therefore, they are favoured by many governments and the public as a whole. However, their present contribution to global energy consumption is still limited (about 3% in 2013 and only about 10% even for heating) since their economics are not yet favourable. In most instances, they need to be supported by state subsidies and regulations. They suffer from high investment costs and, as a result of the intermittent and diffused nature of wind, solar, and tidal, relatively low-utilisation factors.

This section focuses on the economic aspects of nuclear power and new renewables for the generation of electricity. Incorporating new renewables into power grids poses challenges due to dispatching problems and potential needs for expensive transmission extension and/or grid reinforcement; issues with intermittency and prospects for energy storage as a solution are discussed in other sections.
Wider introduction of smart grids and the likely demise of nuclear in some OECD countries (in the short and medium term, at least) will enhance the future prospects for new renewables. However, their immediate future expansion will depend on continued subsidies, which are becoming difficult to sustain in present economic circumstances. Development of large energy storage facilities and carbon pricing could significantly enhance future NRs prospects as indicated earlier. Correspondingly, NRs, in spite of their popularity with some governments and sections of the public, are likely to face challenges which will slow their present rapid progress.

Nuclear power plants face different challenges and prospects, being now shied away from in many industrialised countries and having mixed prospects in developing economies. In many instances, they suffer from high initial costs, long lead times and often excessive construction delays. Nuclear power also faces challenging risks — investment as well as regulatory — although the wider diffusion of small modular reactors (SMRs), when developed and deployed beyond 2025, may reduce these risks. The challenges are compounded by safety and proliferation considerations and a lack of technical skills in many countries as discussed in an earlier section. In contrast to renewables, their share of global energy consumption is declining, though nuclear electricity generation will continue to grow in absolute terms. Nuclear power’s share of global electricity generation has declined from as high as 18% in 1990 to only 12% in 2013, — a percentage that is not likely to improve significantly in the near future.

5.1 The Economic and Financial Evaluation of Renewables and Nuclear

The levelised cost of electricity (LCOE) (DECC, 2013), is the traditional method for assessing and listing dispatchable generating facilities according to their annual costs, and it applies to assessment of the cost of nuclear. However, it does not directly apply to non-dispatchable technologies, like renewable, due to their intermittency. Developing the necessary algorithms for such a purpose, particularly in the case of wind energy, is not easy because of the difficulty in forecasting wind’s intensity and duration. For example, account needs to be taken of capacity factors achieved by wind energy developments. In the UK, it has been confidently claimed that onshore wind energy developments achieve a capacity (or load) factor between 20% and 50%, with an average attained of 30%. The official statistics demonstrate that for onshore wind energy developments in England, the rolling average capacity factor achieved to early 2014 has been barely 24%, and in 2010, nearly 60% of these developments failed even to achieve 20% — yet capital costs will be similar wherever wind energy developments occur onshore regardless of mean wind speeds impacting performance. Solar and tidal forms of energy suffer from the same problem to some extent.

5.1.1 Assessing the returns on investment in renewables

To assess the viability and economics of NRs (particularly solar and wind), it is necessary to compute the future stream of the electrical system cost with NRs and compare it with the system cost without the incorporation of NRs.
This also has to be weighted with the carbon saving and other intangibles of the NRs. The electric system cost does not only apply to generation facilities, but also to the transmission system extension and grid reinforcement as well, which can be substantial in the case of wind technologies. In most cases, the electric system cost per kWh delivered with the presence of NRs is going to be higher than in the absence of NRs. The extra cost indicates the extent of the subsidy (feed-in tariff) which needs to be provided, or increase in tariff to consumers to compensate, for these extra costs (NRs’ penalty). Calculating the present worth of system costs without NRs is straightforward. With the incorporation of NRs, there is a need for a more elaborate approach. Below we develop a simple, but effective, means to compute the financial and economic effect of incorporating NRs. We have, however, to distinguish between solar energy, which is relatively predictable in timing, duration and extent, and wind with its short term (if any) predictability in timing, duration and extent. In addition, we need to take account, in the case of solar, for the levels of direct and indirect solar variation which will vary between locations — generally higher in lower latitudes and lower in higher latitudes. Also, we need to differentiate if the investment is done by a regulated utility which can pass the extra cost of renewable electricity to consumers or it is executed by independent investors selling in the spot market. These need to comprehend fully the financial implications before committing themselves to a risky renewables investment.

The economic evaluation of power generating technologies should aim at evaluating their market value, that is, the revenue they generate to the provider. This particularly applies to NRs. The market value of NRs is lower than their LCOE due to integration costs. A new concept of ‘System LCOE’ has been developed. It is composed of generation cost plus integration costs. This new term system LCOE is the standard LCOE plus the indirect costs that occur at system level [Hirth (2013), Vithayasrichareon and Mac Gill (2013)]. The integration cost of NRs is additional system costs that are not direct generation cost of NRs. Integration costs of NRs have three cost drivers: variability, uncertainty, and location. All generation technologies have integration costs. This is true, but it is more specific and pronounced in NRs due to the variability and unpredictability in dispatching.

The three components of the integration cost (variability, uncertainty and location) mentioned above are shown in the Fig. 5.1 and are defined as follows:

a) Profile (variability) costs occur because wind and solar PV are variable. In particular, at higher shares this leads to increasingly inappropriate load-matching properties. Backup capacities are needed due to variability of NRs. The full-load hours of capital-intensive dispatchable power plants decrease while these plants need to ramp up and down more often.

b) Balancing (uncertainty) costs occur because renewable supply is uncertain. Day-ahead forecast errors of wind or solar PV generation cause unplanned intraday adjustments of dispatchable power plants and require operating reserves that respond within minutes to seconds.
(c) Grid-related (location) costs occur not only because NRs are mostly located far from load centres and large investments in transmission might be necessary, but also because of grid constraints and congestion management.

System LCOE is defined by adding the three components of integration costs to standard LCOE that reflect generation costs. Such integration costs vary from one system to another depending on the extent of penetration of NRs, location and the composition of the dispatchable plant in the generation system. They need to be computed separately for any national grid in order to compute the true market value of NRs. Therefore, the system costs of NRs can be significantly higher than their LCOE as demonstrated in Figure 5.1, though they do come down in the long-term, as the system adapts and integration options increase.

**Figure 5.1: System costs of new renewables**

![Diagram showing system costs of new renewables](source)


There are now many investors in NRs, ranging from regulated utilities to private investors in the spot market, and from large facilities and investments to individual households investing in small roof top PV installations. New and more advanced ways of investing in NRs are being developed: individual investors, leasing, net metering, etc. Therefore, it is not possible to deal with each case — but general and simple guidelines for assessment should be developed as indicated below.

The recent pace of change in the electric power sector has been little short of incredible, including significant increases in renewable generation in numerous countries prompted by rapidly falling prices just as electricity demand growth seems to have come to a virtual stand-still in many places, resulting in depressed wholesale prices and challenges of integrating growing amounts of intermittent renewable generation while maintaining grid’s reliability.

Recently (2014 -2015) there have been significant developments in the economics of renewable energy technologies (see Figure below). Both the cost of installation and production from both PV and wind installations has been significant. Recent contracts for PV,
in favorable sites, were less than 6 cents/kWh and still falling. The prices quoted by independent power producers (IPPs) in windy sites both in north and South America is as low as 4.25 cents/kWh. In both cases system costs can be significantly higher as already expressed above. Still these are significant developments which are likely to impact the economics of renewables and their contribution to power production. Their impact on system operation is also to be felt. Renewables must dispatch electricity, this can only be at the expense of other base load generation, mainly nuclear and large base load coal firing plants. Correspondingly the need for solid interconnections and meshing of the neighbouring networks are becoming increasingly crucial to absorb and dispense with sudden variation in renewables generation, particularly the difficult to predict wind.\(^6\)

**Figure 5.2 Falling Costs: MIT Study Estimates of the Average U.S. Prices for Residential and Utility-Scale PV Systems**

![Image](image_url)


### 5.1.2 The Economics of Nuclear Power

Nuclear’s global share as primary energy has been on a slow decline and is not expected to recover in the short to medium term despite a massive construction boom in China and a handful of other centrally-planned economies. This is in contrast to NRs. Hydro’s global share will remain flat while NRs show greater promise, albeit starting from a small base. (See Figure 5.3)

With increasing privatisation and liberalisation of the power generation sector, private investors are generally not interested in investing in nuclear without one or another type of government assistance to reduce the financial risk, due to its capital intensive nature, escalating construction costs, long lead times and possible high future safety risks.

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\(^6\) The discussion in this and the proceeding paragraph applies to countries that have an electricity industry and distribution system serving the bulk of its population.
It is mostly in centrally-planned power systems that nuclear is still finding some favour. Among the many reasons that are keeping private investors from investing in nuclear power is that it is difficult to know how much a given project is going to cost by the time the plant goes operational, or how long it will take to complete the project. This alone explains why so few are being built in the West. In centrally-planned economies, the cost of capital can be disguised, thus making it difficult to estimate costs across different economic systems.

**Figure 5.3: One Outlook for Renewable and Nuclear Energy (BP)**

Source: (BP, 2014)

There are currently only a handful of new reactors under construction in the US. The UK is pushing hard to get two new ones built — with some difficulty — and only two others are currently under construction in France and Finland, both behind schedule and over budget. Over the next decade, more reactors may be retired in the OECD than new ones built.

The nuclear industry has not succeeded in achieving the cost reduction through commercialization that has often characterized other new technologies. Several factors help explain this including more stringent regulations and standards, insufficient standardization and modularisation, uncertain regulatory environments and difficulties faced during construction. This is coupled with safety concerns, particularly those resulting from the three major accidents which nuclear plants have suffered since their inception: Three Mile Island (United States), Chernobyl (the USSR, now the Ukraine) and the more recent example of Fukushima (Japan).
Analysis of the economics of nuclear power must take into account costs and accidents that foreshadow the risks of future uncertainties. To date all operating nuclear power plants were developed by state-owned or regulated utility monopolies where many of the risks associated with construction costs, operating performance, fuel price, and other factors were borne by consumers rather than suppliers. Many countries have now liberalized the electricity market where these risks, and the risk of cheaper competitors emerging before capital costs are recovered, are borne by plant suppliers and operators rather than consumers, which leads to a significantly different evaluation of the economics of new nuclear power plants (MIT, 2003).

Because of the large capital costs for nuclear power and the relatively long construction period before revenue is returned, servicing the capital costs of a nuclear power plant is the most important factor in determining the economic competitiveness of nuclear energy. The investment can contribute about 70% to 80% of the costs of electricity. The discount rate chosen to cost a nuclear power plant's capital over its lifetime is arguably the most sensitive parameter to overall costs, as detailed below.

The industry consensus is that a 5% discount rate is appropriate for fossil fuel plants operating in a regulated utility environment where revenues are guaranteed by captive markets, and 10% discount rate is appropriate for a competitive deregulated or merchant plant environment. However, an independent MIT (2003) study used a more elaborate finance model distinguishing equity and debt capital, and had a higher (11.5%) average discount rate for nuclear

5.1.3 LCOE Comparisons

Both the US-DOE (EIA) and the UK publish estimates for cost of generation of nuclear and NRs. The competitiveness with fossil fuel plants depends on carbon pricing. If this is not included, as is the case in most centrally-planned power systems, there will be a significant gap between cheap generation utilizing cheap coal in modern coal firing plants and CCGT firing locally available natural gas on the one hand, and the more expensive nuclear and NRs on the other.

The following figures exhibit projected U.S. LCOE costs for new generation in both year 2020 and 2035 (EIA, 2013a). Note that countries like China and the UAE experience lower capital costs for new nuclear, and have a lower figure.
Figure 5.4: Levelised costs of electricity in the USA for the years 2020 and 2035 (U.S. cents per kWh)

Table 5.5: Levelised Cost of Electricity Generation Estimates, UK Department of Energy and Climate Change (2012 £ per MWh)

<table>
<thead>
<tr>
<th></th>
<th>CCGT</th>
<th>OCGT</th>
<th>Nuclear-FOAK</th>
<th>Onshore &gt;5 MW (UK)</th>
<th>Biomass Conversion</th>
<th>Offshore R2</th>
<th>Offshore R3</th>
<th>Large scale solar PV</th>
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<td>Pre-development Costs</td>
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<td>Fuel Costs</td>
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<td>0</td>
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<tr>
<td>CO2 Capture and Storage Costs</td>
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</tr>
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<td>Decommissioning and Waste Fund</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Total Levelised Costs (without carbon)</td>
<td>62</td>
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<td>90</td>
<td>101</td>
<td>108</td>
<td>113</td>
<td>120</td>
<td>158</td>
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<tr>
<td>Carbon cost</td>
<td>18</td>
<td>26</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>Total Levelised Costs (with carbon)</td>
<td>80</td>
<td>181</td>
<td>90</td>
<td>101</td>
<td>108</td>
<td>113</td>
<td>120</td>
<td>158</td>
</tr>
</tbody>
</table>

Source: DECC (2013)

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7 Coal plant costs include regulatory and environmental uncertainties (i.e. carbon pricing).

8 First Of A Kind
5.1.4 Cost of Nuclear Generation

The life-cycle costs of a project and its feasibility, for a given output, depend on three factors: (i) the investment cost, (ii) the operational costs and (iii) the discount rate utilised. Many planners think that the discount rate is the most important of these three factors. It greatly affects the whole economics of the project and the decision making, particularly in capital-intensive projects like those of the nuclear industry. In spite of its crucial importance in project evaluation, it is surprising how little effort project evaluators exert to research the proper discount rate needed for their project evaluation. Simultaneously, all the efforts in estimating investment and operational costs are rendered untrustworthy by an incorrect choice of discount rates.

The aim of a nuclear power program is to generate energy, and more explicitly electricity, at a cost that fits the economic needs of the country at issue. In practice, because the cost of reactor fuel is typically a modest component of electricity cost (seldom as large as 20%, typically 10% or so), and operating costs are typically in a similar range, the capital cost of building a power reactor is the major economic issue standing in the way of a major worldwide expansion of nuclear power.

This has led to an emphasis on capital cost as the major design figure-of-merit of the new large LWR reactors. A few years ago, it appeared that in the developed world the capital cost of these new LWRs was in a competitive range with other new baseload capacity. However, recent sharp declines in natural-gas prices (especially in North America but in some other locations as well) have made large-LWR capital costs less competitive. This is exacerbated to the extent that the subsidies or regulations aimed at reducing greenhouse gas emissions in the power sector are often not applied to nuclear energy (e.g., feed-in tariffs, clean energy standards, etc.).

The cost of constructing a new nuclear plant varies from one country to another, but appears to have increased over the last several years. Cost factors include location, availability of cooling water, seismic activity, labour and material costs and the cost of capital. Estimates of the cost of future nuclear power plants vary. According to EI Energy report, the average overnight capital cost (excluding interest during construction) of new nuclear plants in US and Europe is around 5300$/KW in 2014 (in 2014 $) and expected to stay level and then decline slightly to around 5000 $/Kw by 2030 and 4500 by 2050 (EINE 2014). On the other hand, there are a variety of cost studies, some of which project higher costs due to the inclusion of interest costs during construction or other factors, especially those associated with unanticipated delays. Moody’s Global (2009), in 2008, estimated the cost of nuclear plant in US to be around $7,000 per KW. Some existing projects tend to support the higher cost estimates. The cost of the planned Hinkley Point 1,600 MW reactor, albeit a First of a Kind, is estimated to be $13.7 billion (i.e. $8,300/KW), according to calculation by UK DECC. The strike price for this plant is expected to be $158.7/MWh, i.e. 15.4 cents/kWh. While this is double the UK wholesale electricity cost in 2013, it is in line with the subsidised cost of onshore wind energy developments in the UK, and two-thirds of the cost of OCGT. The UK government, in taking such a decision, is prompted by the need to comply with EU emissions’
regulations and the phasing out of existing nuclear plants. It is likely that future cost of similar design reactors will be significantly lower. The cost of nuclear power plants in some developing countries, particularly with centrally-planned power systems, government financing and less stringent regulations, is likely to be much less: below $5,000 per KW (Schlissel and Biewald, 2008).

One reason there is a controversy about estimated nuclear plant costs is that the initial estimates for Generation III+ power plants were often based on vendor estimates rather than actual experience (Kessides, 2010). These estimates might underestimate future nuclear power plant costs compared to estimates for other power technologies that are based on numerous actual projects and contracts. Generation III plant designs emerged in the 1990s. The cost estimates for these designs were typically in the neighbourhood of $1,000/kWe. As these designs have evolved, current U.S. and European cost estimates have grown to be several times higher. Plant cost estimates in the United States currently range from $2,500/kWe to $10,000/kWe. If the outlier cost estimates are deleted, current U.S. cost estimates are reported from some sources to be from $4,200/kWe to $6,600/kWe (Thomas, 2010). Other sources, such as the U.S. Energy Information Administration report overnight costs within this range ($5,500/kWe). It should be noted that overnight costs are not a good guide to the true cost of nuclear power plants as they take a long time to build, usually much longer than initially assumed, and financing costs can significantly add to the actual capital cost of a nuclear power plant.

Unfortunately, there is no assurance that cost escalation will not continue. An important factor behind these high estimated (and, in many cases, actual) costs to build nuclear reactors is the delay that these projects often face during licensing and construction that increases the capital burden, often at high interest rates. This is also a reason why the economics of nuclear power may be more favourable in countries such as Russia, China, UAE and South Korea where projects tend to stay on schedule.

5.1.5 Technology Learning

Predictions of future energy technology costs usually employ the concept of technology learning. The general principal is: for each doubling of capacity of a new energy technology, cost goes down by a fixed percentage (IEA, 2000). Since the nuclear industry is well established, additions to capacity would fall well short of any opportunity for further technology learning unless the Generation III and III+ designs were judged to be sufficiently different than Generation II reactors to be new technologies. Most estimates of future nuclear technology costs do not view them as such and do not anticipate significant cost reductions in Generation III reactors.

An analysis of the cost trajectory of the French nuclear reactor fleet indicates that construction costs, in constant dollars, have increased over time (Grubler, 2010). While this is consistent with U.S. experience, it may be surprising since the French reactor fleet is generally regarded as the most successful and well-managed nuclear power deployment, in part, by avoiding the
U.S. experience of building many different designs each requiring individual regulatory assessments and separate engineering design work.

Going forward, there may be reasons for nuclear reactor costs to systematically increase. About 60% of the cost of a nuclear reactor stem from on-site engineering as opposed to the major equipment items (reactor vessel, steam generators and turbines). Reactor heat-sink cooling is also an important cost component that has increased. In particular, environmental regulations to protect fish and other species have made it more likely that cooling towers would be required when reactors are located on rivers.

With high Asian economic growth that is not expected to lessen, the demand-supply balance for construction materials is likely to produce higher prices. Likewise engineering and labour costs are likely to increase with high economic growth. Compared to the opportunities to reduce the costs of manufactured products, large nuclear power plants appear to face the likelihood of higher costs, not lower costs.

5.1.6 Capital Cost Escalation and Other Risks in Liberalized Power Markets

Risks of cost over-runs are less likely to deter nuclear power plant investments in uncompetitive power markets or state-owned enterprises. A costly power plant in these markets will not necessarily have adverse consequences on investors as the higher cost can be averaged into the existing fleet of power plants. A private investor in an uncompetitive State-regulated power market would still receive the normal rate of return. A state-owned company likewise passes on the incremental costs to ratepayers or the government incurs higher electric subsidy costs.

A liberalized power market presents an entirely different picture to an investor. Delays and cost over-runs not only threaten to diminish their rate of return but put the investment itself at risk. This risk is compounded by five factors: 1) nuclear power has high capital costs per kilowatt of electrical generating capacity (kWe) compared to natural gas or coal power plants; 2) nuclear power has large economies of scale and require large investments for a unit of investment (1 gigawatt or more); 3) having high capital costs, nuclear power is more vulnerable to increases in material costs and construction delay; 4) construction delays are more likely due to uncertainties in the regulatory process, especially for new plant designs; and 5) because of potential public opposition to nuclear power, construction delays can also be caused by delays in issuing local permits, lawsuits and political pressure. Because of these risk factors, financing is often not feasible without government intervention to mitigate the financial risks. Equity financing is typically not an alternative to debt financing as it is difficult to ask shareholders to forgo dividends and accept risk that banks were unwilling to take.

Recognizing these barriers to nuclear power plant investments, the U.S. government established government subsidies and risk-sharing for nuclear power plants in the Energy Policy Act of 2005. These included production-tax subsidies for the earliest new nuclear plants, guarantees against regulatory delays and a loan-guarantee program to attract private
financing. While no new nuclear plants yet built have taken advantage of the production tax subsidies, the U.S. Department of Energy (DOE) has issued two loan guarantees for two 1.1 gigawatt Westinghouse AP1000 nuclear reactors at the Vogtle generating plant.

Like all of the several loan-guarantee applications DOE received, these new plants (Vogtle units 3 and 4) are being built at an existing nuclear plant site. The project sponsors include the Georgia Power Company. The Vogtle plants conditionally received $8.33 billion of DOE loan guarantees, or approximately $3,800/kWe capacity. The plants were initially estimated to have and overnight cost of $11.9 billion, or $5,400 per KWe capacity (Thomas, 2010). Prior to construction, the estimated cost, with financing, was $14.1 billion and has since grown to $16.5 billion, not including over $1.1 billion in possible litigation costs. The project is now 42 months behind schedule. In sum, a project that was originally expected to have an overnight capital cost of $5,400/KWe is now expected to have an actual cost of $8,000/KWe with the possibility of further delays and cost overruns as construction continues. Had the project not received Federal loan guarantees, the accumulation of additional financing cost would have been considerably larger.

The Vogtle experience is instructive since, as discussed in Difiglio and Wanner (2012), Vogtle enjoys significant economic advantages relative to power plants built in liberalized power markets. Typically, in liberalized markets, investors, not utility customers, accept the financial risk of cost over-runs and delays. Therefore, in addition to the Federal loan guarantees, Vogtle has lower-than-normal interest rates and a utility market regime that reduces financial risks to investors. Nonetheless, Standard and Poor’s downgraded the Outlook on Southern Power Company and Georgia Power’s credit ratings from “stable” to “negative (May, 2013) and other credit rating agencies have downgraded the credit rating of partners involved in the project including the Municipal Authority of Georgia bonds (Taxpayers for Common Sense, 2014). For U.S. nuclear power project that would not enjoy these advantages, the economic outlook is much more negative. For example, Moody’s Investors Service has characterized a decision to build a nuclear power plant as a “bet-the-farm” risk. “From a credit perspective, companies that pursue new nuclear generation will take on higher business and operating risk profile, pressuring credit ratings over the intermediate- and long-term...Of the 48 issuers that we have evaluated during the last nuclear building cycle (1965-1995), two received ratings upgrades, six went unchanged and 40 had downgrades...the average downgrade fell four notches” (Moody’s Global, 2009). It is notable that these credit downgrades affected utilities that were mostly operating in a state-regulated environment where regulators have effectively transferred the utilities’ risks to ratepayers. Moody’s concludes that utilities that pursue new nuclear power plants will experience credit downgrades and should: 1) rely on strategic partnerships; 2) increase reliance on equity financing; 3) moderate dividend policies to increase cash flow; and 4) adopt a “back-to-basics” focus on core electric utility operations. These recommendations are aimed at utilities

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9 The Georgia Power Company is fully regulated by the Georgia Public Service Commission. Competition is limited to customers with manufacturing or commercial loads of at least 900 kW.
that “can expect regulators to support the financial health of the utilities they regulate and will authorize recovery of investments and costs over a long time frame” (Moody’s Global, 2009). In a liberalized power market where power companies and investors would not enjoy such protections, the risk of credit downgrade would be much higher.

5.1.7 Load-Following: An Operational Cost Issue

Because a power reactor’s capital cost is such a large component of the total cost of electricity, it has seldom made economic sense to use such a reactor in a “load-following” mode — that is, in a mode in which its output would vary from hour to hour as the demand on the grid changes. However, deployment of large amounts of renewable electricity sources on a grid may make the desire for reactor load-following more important in the future. Besides the financial issues, there are also important technical considerations: frequent cycling of a reactor up and down in power can induce thermal and mechanical stresses on equipment for which some of them may not have been designed. It is definitely feasible to design a large power reactor to account for these technical issues, as the French have done, especially if the power excursions are limited to the 10% to 20% range for a modest fraction of the time (which would not affect overall economic viability very much.) However, for many of today’s existing large LWRs the technical feasibility of significant load-following, especially if required on nearly a daily basis, has not been convincingly demonstrated yet. This option requires technical evaluation on a case-by-case basis. But going forward, new reactors can certainly be explicitly designed for this capability.

5.1.8 Countervailing Factors Supporting Nuclear Economics

The analysis suggests that nuclear power plants will be difficult to finance in liberalized power markets without government intervention to help mitigate the financial risks. If nuclear power plants built with government support or those built by state-owned power industries prove that nuclear power plants can be reliably built at a competitive cost, power plant economics will be a significant positive factor for the nuclear industry, especially taking into consideration national commitments to reduce greenhouse gas (GHG) emissions. If costs continue to increase over the estimates being used by the IEA and EIA, power-plant economics become a significant negative factor for the nuclear industry that may not be offset by pricing CO2 emissions.

These findings do not apply to reactor projects in many countries outside of the OECD, especially in Asia and the Middle East. Nuclear power is estimated to enjoy a more favourable cost advantage than in the United States, Europe or Japan. In addition, private financing is less important in many Asian countries and delays due to licensing problems are less likely. Given the high electricity demand growth expected in Asia, more competitive costs, and government support, it is not surprising that over 60% of currently-planned nuclear reactors are in Asia.
5.1.9 Small Modular Reactors

The myriad financial challenges associated with nuclear projects that can exceed $10 billion have increased interest in the idea of deploying the proposed new smaller (modular) designs. If these were available, capital investments could be made in smaller-sized investment packages – capacity would be added as needed by building additional small reactors one-by-one on a given site. These features would be beneficial for both the developing and OECD economies.

The smaller (modular) reactor designs hold out a promise of lower costs due to factory fabrication, simpler operating features, and simpler, less capital-intensive design features. They also have the promise of being safer, and also requiring less safety equipment. The issue with these new smaller (modular) reactor designs is that, until they go into production, their potential cost advantages will not have been demonstrated. This is a classic “chicken-and-egg” dilemma, of course. How it will play out is still for the future.

5.2 Subsidies

Subsidies are an integral feature of the economics and costing of both NRs and nuclear. These subsidies are usually driven by two considerations: the first, “green” features with no carbon emissions during production; the other, that they provide a measure of local energy security being not dependent on imported fossil fuels or depletable resources.

5.2.1 Subsidies of renewables

Subsidies to NRs, mostly in OECD countries, take many forms both direct and regulatory. They are mainly in:

- Capital subsidies and loan guarantees to manufacturers.
- Feed-in tariffs (FiT) to consumers. These provide financial encouragement to convert small electricity consumers (mainly households) into producers.
- Production tax credits (PTC) for investors.
- Renewable portfolio standards (RPS) that ensures that a segment of electricity production goes to NRs (mandatory targets).
- Tradable energy certificates.
- Priority in dispatching, guarantee to access transmission lines and long term contracts.
- Carbon pricing and taxation.

Feed-in tariffs (FiT) are generally considered to provide the best inducement towards encouraging investment in NRs particularly to individual domestic suppliers. Feed-in tariffs are a generic class of polices that guarantee a set payment for electricity production from certain sources that feed the grid. This provides home owners as well as many establishments with an incentive to invest in solar panels, with a secured return on their investment. In 2004, the German government, which was in the forefront of such subsidy providers, guaranteed investors almost 60–70 cents per kilowatt-hour (kWh) they generate for the next two decades.
from photovoltaic generation (PV). This compares most favourably with German retail prices of 21–24 cents per kWh. Germany was not the only country to adopt FiT; similar practices were adopted by many European countries leading to expansion of uneconomical individual and community PV generation. However, such a bonanza cannot go on as market realities and economic hardships have begun to dawn. Recently, Germany decided that solar PV incentives will fall to 19.5 cents per kWh for smallish installations, 16.5 cents for installations up to 1 MW, and 13.5 cents for larger installations with gradual cuts of 0.15 cents per kWh per month.

The cost of solar panels, particularly rooftop systems has been dropping recently, particularly due to the reduction of the cost of Chinese panels. In Germany, the cost was around 2,900 euro per kW in 2010, this dropped to around to 1,900 euro in 2012. This was mainly due to the drop in the cost of manufactured panels which recently went down from 1,000 euro per kW to less than half of that. Yet it should be realised that the cost of labour, connections and other infrastructure did not significantly drop. These now constitute more than half cost of the system and are not likely to improve significantly in the future.

Subsidies for PV facilities have, from their inception until 2012, generated over 100 billion euros to consumers in Germany, despite the fact that PV plants only account for 3 per cent of electricity generation in Germany. Correspondingly, the cost of this huge subsidy increased the bill of German households by around 25 per cent between 2007 and 2011, putting a large burden on low income and seniors in the country. The domestic tariff in Germany is now 25.3 euro cents (32 US cents) per kWh, one of the world’s highest. Taxes and FiT account for almost half of this. Many wind energy investors now claim that they can produce electricity at a cost comparable to that of the national grid. This may be true in abstract terms, but it ignores system effects, the multiple restrictions and other expenses, particularly new transmission investments, grid reinforcement and dispatching restrictions, associated with such generation, some of these are already mentioned and further detailed below. What is important is system cost, how much (positively or negatively) is the system affected by the introduction of the NRs. These costs do not yet allow wind energy to provide competitive electricity without subsidy in one form or another of the many incentives mentioned above. Solarbuzz, a solar market research and analysis firm, provides data for solar electricity costs in the US range from 28.91 cents per kWh in sunny climates to a very high 63.60 cents per kWh in cloudy ones. This is many times the 11–12 cents per kWh cost of grids utilising fossil fuels or nuclear generation.

There is also the issue of what we mean by costs. Where modern biomass or biofuels undermine ecosystems, biodiversity, agricultural land and water availability (with knock-on effects on food supplies and prices), as explained in a later section, it surely behoves policy makers to heed a broad definition of costs.

The fact remains that most NRs, without governmental subsidies and intervention cannot compete, in most cases, with traditional thermal power generation practices and facilities. No new private NRs investment would venture into the market without support or encouragement of some form or another. With the present global economic challenges, future NR projects
may not continue to enjoy the type of governmental favours of the past. The market future of NRs is challenging to new investments, and needs careful assessment as detailed below. With the increasing amount of variable-output NRs in the network, there is a need also to increase flexible generation. This can be not only in the form of hydroelectric plant or pump storage schemes if they exist, but also in the form of rapidly dispatchable single cycle gas turbines and diesel generation which can rapidly respond to load variation.

The WEO 2013 (IEA, 2013a) reckons that in 2011, renewables excluding large hydro received an estimated $88 billion in subsidies in various forms, up 24% from 2010, of which $64 billion went to electricity and the remainder to biofuels (Figure 5.6). Solar PV received more than any other renewable energy technology for electricity generation ($25 billion), followed by wind ($21 billion) and bioenergy ($15 billion). In the new Policies Scenario, total future subsidies to renewables will grow to about $185 billion in 2020 and reach almost $240 billion per year by 2035. Support provided to bioenergy for power generation continues to grow over time, reaching $69 billion in 2035, exceeding that received by any other technology. The amount received by solar PV grows rapidly in the medium term, reaching $77 billion in 2027, before falling to $58 billion in 2035, as retired installations are replaced by new less expensive capacity. Onshore wind power receives more support each year until around 2020, before falling to $14 billion by 2035, as this technology becomes increasingly competitive. Biofuels receive $24 billion in 2011, increasing to $46 billion in 2020 and $59 billion in 2035, with the vast majority going to conventional biofuels in 2035.

**Figure 5.6: Subsidies paid out, and anticipated, to new renewables (excluding hydro) in US $ millions (2013)**

While subsidies to NRs in the power sector increase in total, they decline on a per-unit basis as the cost of NR technologies fall and electricity prices increase, mainly due to higher fossil fuel prices and the introduction — in some regions — of a carbon price.
5.2.2 Subsidies to Nuclear Power

Nuclear power benefits from various forms of government support and subsidies involving liability limitations, preferential financing rates and export credit agency subsidies. However, the most important subsidies to the nuclear industry do not involve cash payments. Rather, they shift construction costs and operating risks from investors to taxpayers and ratepayers, burdening them with an array of risks including cost overruns. This approach has remained remarkably consistent throughout the nuclear industry’s history and distorts market choices that would otherwise favour less risky energy investments. Nonetheless, there are many examples of governments providing or subsidizing electric power.

5.3 Advanced / Next Generation Technologies

We have already explained that the nuclear industry has not been able, for many decades, to reduce the cost of nuclear facilities. On the contrary, these have been increasing over time due to the rising cost of materials and difficulty of financing coupled with increasingly stringent regulations prompted by recent nuclear accidents and public awareness. Learning over the last few years did not assist in reducing the cost of nuclear due to lack of modularisation, standardisation, streamlining of regulations, and procurement/construction process. Therefore the answer to nuclear’s future lies in dealing with the above, and answering the following cost considerations:

- Scale effects: Can the increase in the size of the plant lead to a reduction in the construction costs per MW installed? Alternatively, can the widespread diffusion of small modular reactors (SMRs) reduce construction costs per MW installed?
- Modularization: Can the building of more components in factories and less on site (for large plants or SMRs) reduce construction time and cost?
- Standardization and cumulative experience: Can capital cost reductions be achieved in standardising plant designs and constructing similar plants in large series?
- Regulation: Can the regulatory framework reduce the risk of cost overruns while providing adequate safety levels?
- Procurement and competition: Can improved competition and procurement contracts result in significant cost reductions (D’haeseleer, 2013)?

5.4 Challenges to System Integration of Renewables and Nuclear

As discussed above, one of the main challenges to NRs and nuclear is their integration in the power generation systems. If the contribution from NRs is small, say less than 10%, these problems are manageable. However, when their penetration assumes significant proportions then these pose serious challenges to system operation and cause an increase in system costs.

5.4.1 Examples of Estimated System Costs

Many countries have enacted official targets for renewable power share for their grids, and others are considering them. US states are doing so as well. This is leading to increasing
shares in a number of jurisdictions. Consequently, the challenges for grid operation caused by the intrinsic character of the intermittent nature of wind and solar are being faced by real world grid operators. Further, since these targets are typically still higher for future years, various planners have been engaged to forecast future operations and their costs.

The following are some costs calculated by the OECD NEA. They are presented with strong caveats in the original source. They are included here to be illustrative of the fact that these costs are believed to be real and significant. Further, they vary by power system.

**Table 5.7 Grid-level system costs in selected OECD countries ($/MWH)**

**Finland**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Nuclear</th>
<th>Coal</th>
<th>Gas</th>
<th>Onshore wind</th>
<th>Offshore wind</th>
<th>Solar</th>
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<tr>
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<td>30%</td>
<td>10%</td>
<td>30%</td>
<td>10%</td>
<td>30%</td>
</tr>
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<td>0</td>
<td>0.06</td>
<td>0.06</td>
<td>8.05</td>
<td>9.7</td>
</tr>
<tr>
<td>(adequacy)</td>
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<td></td>
<td></td>
<td></td>
<td>9.68</td>
<td>10.67</td>
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<td>Balancing costs</td>
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<td>0</td>
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<td>Grid connection</td>
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<td>0</td>
<td>0</td>
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<td>and extension</td>
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<tr>
<td>Total grid-level</td>
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<td>17.79</td>
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**France**

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**Germany**

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(Source: OECD NEA (2012))

These are rather heroic calculations given the paucity of sources (consequently the uncertainties are large), but they do indicate plausible effects. They illustrate the influence of
back up and grid costs. They show the relatively benign impact of nuclear power on system costs compared to renewable power. They illustrate large differences among different countries. Back-up costs for renewables tend to increase in direct proportion to the renewable capacity (MW) that needs back up and the increased capacity adds proportional MWh. However, balancing costs increase because more spinning reserve capacity is required at lower load factors. As penetration increases, grid reinforcement and extension costs increase because the grid must be extended farther afield to find suitable renewable sources, and outer reaches of the grid must be reinforced to carry the increased load. As a side note, backup and balancing is less costly in the United States because the usual back-up power, natural gas, benefits from lower natural gas prices than most other countries.

A further inference can be suggested from these results: it is that the marginal system costs will generally increase with increased penetration of renewables essentially because of their intermittency and tendency for remote locations.

In addition to marginal system cost per MWh, there is another critical metric: marginal cost per ton of CO2 emissions reduced by increased deployment of renewables. After all, that is a primary policy driver for renewable targets.

The state of California has set ambitious goals for renewable penetration: 33% by 2020, not including hydro. Even more has been considered (up to 51% in a legislative proposal) for the future. The 33% level is thought to engender an implicit cost of carbon reduction of $50/ton. A number of power generators commissioned a recent study to investigate the problems and costs associated with increasing that target up to 50%. As the following table shows, the resulting estimates are $340/ton for 40%, and a lowest cost $403/ton for 50%. However, the Diverse Scenario is based on assumed flexibility benefits occasioned by 5000 MW of storage or advanced demand response. Recent trends are that increased renewable capacity has come in the form of large solar. Extending this yields $636/ton.
5.5 Conclusions

Both renewables and nuclear face significant economic challenges. The costs associated with renewable technologies have consistently been higher than those for building fossil-fuelled power plants, although renewables costs (especially solar PV) are decreasing. Furthermore, renewables cost estimates may not fully include systems integration costs. For nuclear, the capital costs remain a major challenge; the cost of financing new nuclear plants is very high in many countries, owing to investors’ fears about time, technology, regulatory, and safety risks. These issues may not be as large for state-owned companies or regulated markets for which utilities have ready access to inexpensive capital, and this partly explains why enthusiasm for nuclear reactors is much stronger in many developing countries than in the United States or Europe. Learning could help decrease costs for both types of technologies, but the track record for learning-by-doing in the nuclear sector is not good (though this may change with small modular reactors if they can be fabricated by manufacturing processes).

Both nuclear and renewables receive subsidies that vary by country and region. Some subsidies are direct, like feed-in-tariffs for renewables, while others shift risks from utilities to customers or taxpayers.

The following recommendations would help establish a better accounting for the costs of nuclear and renewables, and could help support cost reduction of both:
1. Comparisons of nuclear and renewables costs should account for systems integration and differences in capacity factors.
2. In order to estimate nuclear costs, more attention should be given to the sensitivity of the estimated cost to the discount rate, as the discount rate greatly affects the cost of production. Studies of the technical issues that may impede using a nuclear reactor in “load-following” mode are important and should be given high priority.
3. Priority should be given to new reactor technologies like SMRs and regulatory reform in order to reduce nuclear capital costs.

6. Electricity Storage

A central challenge for grid operators, described in detail in previous sections, is matching electricity supply to demand. The challenge increases when more of the electricity supply is composed of intermittent renewable resources, and the trend is up for renewables on many nations’ electricity grids. Besides this operational challenge, intermittent renewables pose market challenges for baseload resources. For example, at night when the wind blows strongly and electricity demand is low, prices are suppressed, but nuclear units generally cannot power down. If more renewables lead to more sustained price suppression, baseload units have trouble recovering their costs (Renewable Analytics, 2013).

Several system options could help balance electricity supply and demand given different mixes of intermittent, baseload and load-following generation capacity. One alternative is to match each renewable installation with full backup capacity (typically natural gas) such that all the combination of renewables and back-up is reliable and dispatchable. This, however, would increase the cost of renewable generation and reduce the environmental benefits of renewables. A second option is to build substantial transmission capacity, so a drop in renewable electricity generation in one area (e.g. due to clouds over solar panels) could be compensated for by electricity production in another region. In the U.S., studies have shown that 45% penetration of renewables is achievable with the current transmission system (IEA, 2011), and as much as 80% renewable penetration can be achieved by expanding transmission capacity, including increasing the number of ties between the Eastern and Western grids and building transmission backbone lines to bring Midwest wind to the coasts (Mai, T., R. Wiser, D. Sandor, G. Brinkman, P. Denholm, DJ Hostick, N. Darghouth, A. Scholsser, and K. Strzepek, 2012). Smaller grids, however, may not have sufficient capacity or geographic diversity to accommodate sudden, large shifts in supply. Furthermore, U.S., cost and permit issues are major barriers to achieving significant transmission capacity expansion. A third option for managing intermittency is to increase cycling of baseload plants, but this can be challenging and costly, especially for nuclear power. Demand response (DR), or contracting with consumers to reduce demand when the grid is short on supply, is yet another option to ensure a supply and demand match; large DR potential remains in many countries and has relatively few drawbacks, other than challenges with consumer acceptance and eventual limitations for how much DR the system can sustain.
An important additional option to integrate varied generation sources, match electricity supply and demand, and allow generation sources to dispatch power at a profit is electricity storage. In theory, if electricity storage could be deployed widely, grids of any size could sustain a wide range of profiles of intermittent and baseload power. Storage systems enable arbitrage of renewable generation, in which power is bought at times when demand is low, power is cheap, and renewables are generating, and then sold back when power prices are high. They can also provide ancillary services to the grid. At the consumer level, they can provide backup power and help maximize use of distributed generation systems. Storage, however, is currently costly, and most market structures worldwide do not favour its adoption because they do not allow remuneration for the flexibility benefits storage provides. Because neither storage nor the other options described above are without drawbacks, integrating high levels of renewables with baseload power may require a combination of strategies to meet multiple objectives. Among these strategies, energy storage is of particular interest because storage systems are flexible, may be carbon-free, and are scalable. However, high costs are currently a barrier.

The next section gives an overview of grid-scale storage technologies in various stages of development and deployment. Following sections discuss existing energy storage installations, valuing energy storage on the grid, and R&D efforts on storage. The emphasis throughout this report is on large storage systems that have the ability to provide grid-level renewables integration services, including electricity arbitrage and ancillary services like frequency regulation.

6.1 Overview of Selected Storage Technologies

Cost estimates can be challenging for storage technologies, as costs vary widely by geography (especially for pumped hydro and compressed air systems) and are hard to estimate for emerging technologies. Table 6.1 provides an overview of technology costs, and each is discussed further (with references) below.

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10 Note that storage can provide a wide range of grid services on many timescales, and some systems can provide more than one type of service. For purposes of this study, we focus on grid-scale storage with the ability to provide electricity arbitrage and regulation services, as these are of especially high importance for grid integration of renewable and baseload sources.
### Table 6.1 Summary of Storage Technology Costs*

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<th>Technology</th>
<th>Cost/kW (power)</th>
<th>Cost/kWh (storage)</th>
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</tr>
<tr>
<td>Compressed Air</td>
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<td>$125/kWh</td>
</tr>
<tr>
<td>Flywheels</td>
<td>up to $4000</td>
<td>$200-$500</td>
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<tr>
<td>Lead-Acid</td>
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*Note that these are published cost estimates for utility-scale installations in the U.S. from EPRI, BNEF, and peer-reviewed papers as of May 2014. Between May 2014 and May 2015, several companies have announced sales of battery systems available at lower cost; these examples are discussed below.

#### 6.1.1 Pumped Hydroelectric

Pumped hydro is the most mature, widely-deployed energy storage technology. Pumped hydro facilities include high and low water reservoirs, typically with elevation differences in the hundreds of meters range. During periods of electricity storage or “charging,” water is pumped from the lower to the higher reservoir, and then when electricity is needed, the water flows from the high reservoir to the lower through a hydroelectric turbine. According to the Electricity Storage Association, these processes lose very little electricity, reaching round-trip efficiencies as high as 80%. The major challenges for pumped hydro include dependence on geography and public concerns about environmental degradation where new reservoirs are created.

Current cost estimates for storage technologies vary by country and can vary by location within countries – especially for pumped hydro storage. EPRI estimates U.S. pumped hydro costs at $2500-$4300/kW (power) and $420-430/kWh (storage) for small facilities with capacities less than roughly 5500 MWh, and $1500-$2700/kW and $250-270/kWh for facilities up to 14000 MWh (EPRI 2010a). The national hydropower association reports slightly lower capital costs for pumped hydro (NHA, 2010).

The potential for building new pumped hydro varies by country as well. In the US, DOE and Oak Ridge National Laboratory are surveying potential for new facilities. Elsewhere, over 60 pumped hydro projects are under construction, most in Europe, China, India, and Japan (NHA, 2010). The potential for pumped hydro could be large, even in Europe: Gimeno-Gutierrez and Lacal-Arategui (2013) indicated the possibility for a ten-fold increase in storage capacity, and MacKay (2009) estimates up to 400GWh of potential in the UK. However, realizing this potential will likely require overcoming environmental challenges for specific geographies. In addition, in some regions, the economics for new pumped hydro facilities may be at issue, as more demand-side management and solar deployment shaves peak electricity prices and reduces arbitrage opportunities for storage plants. Switzerland has good examples
of both. Following the decision to discontinue nuclear, the Swiss government published ambitious plans for increased hydro – which were immediately opposed by the cantons. Plans for increasing the capacity of pumped storage at the Grimsel have been put on ice because of the cheap midday wind energy flooding in from Germany.

6.1.2 Compressed Air Energy Storage

Compressed air energy storage systems (CAES) pump air underground into geologic formations or (more rarely) into above-ground vessels and pipes. When electricity is needed, the air is released, heated, and expanded by natural gas to drive a turbine. Advanced CAES technologies include those that take advantage of electricity production during the compression phase, and those that recycle flue gas in order to minimize natural gas burns. Although CAES faces twin challenges of limited geography and greenhouse gas emissions, it is the third-most widely deployed storage resource. The IEA in conjunction with the International Renewable Energy Agency estimates CAES capex costs at $800 - $1000/kW with cheap, natural underground storage (IEA-ETSAP and IRENA, 2012), EPRI estimates costs up to $1250/kW and $125/kWh (EPRI, 2010b), and Wesoff (2011) estimates $1500/kW.

6.1.3 Flywheels

Flywheels are low-energy, high-power storage devices typically used for maintaining power quality and to provide black start capacity. Flywheels consist of rotors on electromagnetic bearings that increase spin speed while charging, then maintain spin with minimal frictional losses as an energy storage mechanism. When electricity is needed, the rotors generate electricity as they slow. Challenges include materials fatigue and limits on the system energy density; until flywheels can store more energy, they may not be a primary technology choice for peak-shifting applications needed to integrate intermittent renewables. IEA/IRENA estimate flywheels to cost up to $4000/kW for MW-sized systems, and a Lawrence Livermore National Laboratory study pegs storage costs at $200-$500/kWh (IEA-ETSAP and IRENA, 2012).

6.1.4 Batteries

Batteries consist of electrochemical cells, historically with an aqueous electrolyte and solid negative and positive electrodes. When charging, positive ions flow from the positive to the negative electrode while electrons flow in the opposite direction; these flows are reversed during discharge. In order to provide grid support services, batteries should be able to store significant amounts of energy at low cost (though unlike for consumer electronics and vehicles, grid-scale batteries may be large). For peak-shifting applications, grid-scale energy storage systems comprising batteries should be high-powered (e.g. MW-scale), able to respond to grid needs appropriately, and possess long cycle lifetimes. In general, batteries may be separated into sealed or flow designs. Lead-acid, lithium-ion, and sodium-sulphur technologies have, to date, been the most prominent battery chemistries for grid-scale storage, yet cost, durability and/or safety challenges remain.
Lead-acid batteries are generally considered the most mature of rechargeable battery
technologies. Though they are deployed in smaller numbers than lithium-ion for grid support
applications, they appear extensively in automobiles, telecommunications, and other systems.
Challenges to expanded production and use of lead-acid for grid applications include battery
toxicity, high costs, and low cycle life. EPRI estimates costs for commercial, advanced lead-
acid batteries at $1700 - $1900/kW for 200 MWh, 50 MW systems, and up to $4900/kW for
250 MWh systems with twice the cycling life. Costs per kWh nearly double for the larger,
longer-cycle life system, from about $450/kWh to about $950/kWh (EPRI, 2010b).

Over the last few years, grid penetration of lithium-ion batteries has increased significantly.
Lithium-ion batteries include a range of different chemistries, but all continue to face residual
challenges with safety (e.g. reactivity and flammability) and cost. Both of these factors
become more of an issue when the batteries are scaled from everyday applications in personal
electronics devices to grid-scale energy storage systems. Bloomberg estimates lithium-ion
battery capex costs at $850/kWh for hour-scale price arbitrage applications (Bloomberg,
2013a). This particular discussion does not address residential-scale applications of storage, but in
principle, if residential storage were widely deployed and grid-connected, the storage network
could assist in balancing utility-scale renewables and baseload power. Therefore, the recent
announcement by U.S. company Tesla in that it would sell residential lithium-ion battery
systems for $350/kWh could be significant. The cost is significantly lower than for other
residential systems, due to Tesla’s intention to build a large manufacturing facility taking
advantage of economies of scale. But whether Tesla or its competitors achieve significant grid
penetration depends on the demand for residential battery systems, which may not be high
even at these lower price points. (Warshay, 2015). Tesla has also suggested it will offer
utility-scale applications of its technology at $250/kWh, offering some of the lowest costs Li-
ion batteries available.

Sodium-sulphur batteries have been developed and deployed primarily in Japan. They
generally consist of a high-temperature molten sulphur positive electrode and liquid sodium
negative electrode separated by a solid, sodium-conducting ceramic. Because of the
abundance and elemental nature of the battery chemistry, these systems have the opportunity
for low cost; however, safety and cycle life challenges remain. EPRI estimates Sodium-
sulphur battery costs at $3100 - $3300/kW and $520 - $550/kWh (EPRI, 2010b). To address
safety and improve on cost, an analogous high-temperature molten Na/NiCl₂ has been
developed and is entering early stages of commercial deployment.

Flow batteries separate the power and energy function of a battery by storing charge in
solution (typically aqueous) electrolytes that are flowed over a stack of electrochemical cells
for power generation and storage. Higher power requires a larger stack of cells, while higher
energy requires a larger tank of electrolyte. The benefit of this power/energy separation is
typically achieved at the expense of energy density; flow battery systems are typically 2-5X
larger than sealed battery systems. Vanadium redox batteries are, so far, the most widely-
deployed flow batteries and utilize a single electrolyte for both the positive and negative battery active material. Advantages of vanadium redox flow batteries include long cycle life and relative safety. The high cost of vanadium limits the potential for this flow battery chemistry; EPRI estimates the cost of a 250 MWh vanadium redox battery at $3100 - $3700/kW and $620 - $740/kWh (EPRI, 2010b).

Recent announcements by vanadium flow battery companies indicate further cost reductions may be imminent. Eos Energy Storage introduced a grid-scale zinc hybrid cathode battery with an aqueous electrolyte in January of 2015. The stated cost for the Eos system is $1000/kW or $160/kWh, making it the least expensive on the market. Through partnerships with utilities, Eos intends to deploy up to 1MW of storage capacity in the U.S. in 2015. Another company, Imergy, has announced vanadium flow batteries available for $500/kWh. Whether these costs are achieved in near-term projects remains to be seen.

6.1.5 Hydrogen

Hydrogen energy storage systems are virtually negligible in terms of grid deployment; SBC estimates less than 2MW capacity is installed worldwide (SBC, 2013). Nonetheless, hydrogen fuel cells have the potential to provide significant amounts of electricity balancing for intermittent renewables. Most hydrogen in the U.S. is produced by steam reformation of hydrocarbons, but clean grid-scale battery technologies typically focus on hydrogen production from water. They operate by converting water into hydrogen and oxygen during charging (either through electrolysis, biological or catalytic processes), and they recombine hydrogen and oxygen in order to produce electricity. These systems have been developed for over 50 years, primarily for space applications but with an eye towards automotive. One major advantage is that hydrogen systems can store energy for long periods of time, but a major drawback is the low efficiency with which hydrogen conversion occurs. Sandia National Labs estimates current hydrogen systems to cost about $1150/kW for 6 hours of storage (Schoenung, 2011).

6.2 Existing Storage Facilities

By far, the most widely-deployed storage technology is pumped hydro, owing to its historical cost effectiveness compared to other storage technologies. Pumped hydro, however, is limited by geography; it requires two large reservoirs with a significant altitude difference between them. Research is underway on using seawater and/or underground reservoirs to minimize the environmental footprint, but these options are likely to be significantly more costly (IEA, 2013d).
Flywheels represent the next largest segment of the storage market; the installed capacity is mostly composed of two half-gigawatt scale projects in Europe. Compressed air energy storage has significant presence in the U.S. Japan has the largest sodium sulphur battery installation, at 34 MW, and the U.S. leads on installed capacity of lithium-ion batteries. Thermal energy storage, often associated with buildings, represents a growing market segment.
to shift electricity demand (IEA, 2013d). Because thermal storage is often used in this demand-response-like manner, it is not depicted on the charts above or discussed further here.\textsuperscript{11}

Several nations and regions worldwide have adopted policies to increase storage deployment. California passed a bill requiring utilities to procure 1.3 GW of electrical and thermal storage by 2020 in order to mitigate grid disruptions that may result from its 33\% renewable portfolio standard (GreenBizz, 2013). Japan and Germany have both begun subsidize storage systems at the consumer level, to enhance operation of distributed PV systems (Wilkinson, 2013).

Forecasting even near-term electricity storage deployment is very difficult because the market structures and storage service opportunities vary widely, and the potential for cost reduction by storage technology is unclear. The IEA examines three storage deployment scenarios in its 2014 energy storage technology roadmap, showing a large increase in deployed energy storage by 2050 under a 2C GHG emissions target, and an even larger increase if aggressive storage cost reductions are achievable. This work clearly illustrates the value of activities that are directed towards reducing the cost of energy storage technologies.

\textbf{Figure 6.3 Three 2050 Electricity Storage Deployment Scenarios (IEA); including a scenario in which warming is limited to 2 degrees C (2DS), a “breakthrough” scenario in which storage costs come down substantially, and an “EV” scenario with high EV penetration.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.3.png}
\caption{Three 2050 Electricity Storage Deployment Scenarios (IEA); including a scenario in which warming is limited to 2 degrees C (2DS), a “breakthrough” scenario in which storage costs come down substantially, and an “EV” scenario with high EV penetration.}
\end{figure}

\textbf{SOURCE: (IEA, 2014)}

\textbf{6.3 Valuing Storage in Electricity Markets}

Ultimately, storage will only achieve high levels of penetration if it can compete for service provision in electricity markets. Markets are set up to value electric capacity and the generation that traditional power plants provide, but they do not generally value the high level of uncertainty and intermittence of renewable resources. This has led to a focus on battery technologies, which offer the highest capacity factor and can be deployed on a large scale in the near term.

\textsuperscript{11} Note, however, the significant exception of thermal storage coupled with concentrated solar power systems, rendering CSP a dispatchable renewable technology.
of flexibility storage can provide. In some cases, regulatory decisions prevent storage systems from participating in ancillary service markets.

One way for storage systems to make money in electricity markets is with arbitrage, storing electricity from the grid when it is cheap and selling it back when it is expensive. Predicting precisely when to buy and sell, however, is difficult. A Bloomberg analysis determined that buying and selling at set times, i.e., buying at the 4th hour of the day and selling at the 12th, would yield nearly 30% less revenue than the perfect strategy in the German day-ahead market between 2008 and 2012 (Bloomberg, 2013b). In general, Bloomberg found that participation in the German ancillary services market was more economical than arbitrage. Besides providing arbitrage or ancillary services, a third way for storage systems to obtain market revenues is to receive capacity market payments, as PJM is currently considering in the U.S.

Rather than allow storage to compete in electricity, ancillary service, or capacity markets (or some combination), a different option involves valuing energy storage based on a regulated, cost-of-service or willingness-to-pay model. Regulators could ensure a rate of return for storage developers that could include valuation of avoided costs, like the ability for storage to obviate the need for additional transmission. Under a rate-recovery system, storage could be treated alongside transmission, and this may become possible in the U.S. FERC is currently creating accounting standards to facilitate rate-basing of storage assets in 2015 (Bloomberg, 2013a).

The particular combination of market and non-market alternatives most conducive for storage will vary depending on the particular needs of each grid and the existing market dynamics. Bloomberg’s analysis of the market competitiveness of storage in Germany, North America, and the UK shows very few, but varying applications for which lithium-ion or sodium-sulphur batteries are economic. In Germany, only the provision of primary control reserve generated a positive IRR. In North America, arbitrage is profitable in some regions of Ontario, and economic opportunities exist for storage applications elsewhere (DOE, 2013a), especially if battery costs come down and storage becomes eligible for capacity payments. In the UK, the only currently profitable application for lithium-ion batteries is deferral of transmission upgrades (Bloomberg, 2013c). In general, storage systems are otherwise too expensive.

As alluded to above, the storage technologies most likely to achieve commercial success are those which can provide more than one service, “stacking” the payments they can receive (Kaun and Chen, 2013). The U.S. Department of Energy classifies technologies according to whether they can definitely, potentially, or never supply various electricity services. Table 6.4 describes commercial and in-development technologies and lists the renewable integration-related services they can provide.
### TABLE 6.4: Technologies and Energy Services

<table>
<thead>
<tr>
<th>Service</th>
<th>Peak-shifting (arbitrage)</th>
<th>Energy smoothing and shaping</th>
<th>Ancillary services (e.g. frequency regulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timescale</td>
<td>hr.+</td>
<td>min. to hr.</td>
<td>sub-minute</td>
</tr>
<tr>
<td>Technology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumped Hydro</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressed Air</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flywheels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-Acid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li-ion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Batteries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Solid box = can provide, Hashed box = potentially provide, Empty box = cannot provide

**SOURCE:** [DOE (2013b), SBC (2013)]

From the perspective of maximum opportunity for service provision, battery technologies are attractive because they can provide all three types of services. They are also more attractive than other listed technologies because they tend to be more scalable (for example, they are not bound by reservoir sizes and can be made quite small), and thus have applications at the distribution and consumer level. This larger market depth for batteries may mean they have more opportunities to come down the cost curve.

Lazard (2014) calculates the LCOE of batteries, and determines the range to be $265 - $324/MWh for lead-acid at the low end and NaS at the high end. But Lazard also notes the costs may come down as low as $168/MWh by 2017; at that point, they may be competitive with other generation technologies (Lazard, 2014).

The next section examines research, development and demonstration priorities that could enhance the ability of storage systems to provide a range of services at low cost.

### 6.4 Development of Advanced Electricity Storage Technology

Much of the R&D focus on storage is and should be on attaining cost-competitive systems. This means developing storage solutions with low per-kW power and per-kWh storage capital costs. DOE has a near-term target of achieving costs below $250/kWh, and a long-term target of achieving capex under $150/kWh. DOE estimates that achieving a levelised cost of 10 cents/kWh in the long term will make storage solutions economically scalable without subsidies; for reference, the levelised cost of storage for lithium-ion is currently on the order of 10 times that (EPRI, 2010b). Other research targets include reaching low O&M costs.

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12 DOE lists these as “can potentially provide”
related to achieving high efficiency, high energy density, high cycle life, and low capacity fade, among other parameters. Each of the technologies discussed so far faces different challenges achieving low cost targets.

Safety and environmental issues are also of importance to potential storage investors. Battery technologies, for example, contend with some safety and reliability issues, and some battery research focuses on reducing safety risks and/or demonstrating the reliability of battery systems. Compressed air energy storage presents environmental challenges because it typically requires a natural gas system to heat expanding air. New technologies, however, may obviate the need for a gas heat source. Table 6.5 describes the primary focus of R&D for each of the storage technologies.

**TABLE 6.5: R&D Thrusts by Storage Technology**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Primary R&amp;D Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped Hydro</td>
<td>Cost of underground/seawater reservoirs to remove geographic dependence &amp; mitigate environmental harms*</td>
</tr>
<tr>
<td>Compressed Air</td>
<td>Adiabatic and isothermal processes to avoid use of gas to heat air upon decompression; artificial reservoirs to remove geo. dependence</td>
</tr>
<tr>
<td>Flywheels</td>
<td>Materials cost; flywheel stability</td>
</tr>
<tr>
<td>Lead-Acid</td>
<td>Improve cycle life and depth of discharge</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Find lower-cost materials for the negative electrode; increase energy density &amp; cycle life; confirm safety; scale-up from small, cylindrical to large-format, prismatic cells for energy storage applications</td>
</tr>
<tr>
<td>Molten Salt</td>
<td>Improve durability/ manufacturability of ion-conducting separator; improve corrosion resistance; alternative chemistries to reduce operating temperature, improve safety</td>
</tr>
<tr>
<td>Flow Batteries</td>
<td>Improve specific energy and cycle life; alternative chemistries to lower system cost</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Improve efficiency of oxygen reactions while reducing cost of oxygen electrodes</td>
</tr>
</tbody>
</table>

**SOURCES:** [DOE (2013b), SBC (2013)]

Two promising, very early-stage battery technologies aim to address some of the challenges listed above. Lithium-air batteries could be a substitute for Li-ion, as they replace the cathode with oxygen and obviate the need for a cathode structure. Challenges with the designs remain, however, because the cathode degenerates due to encroaching humidity (SBC, 2013), and Li-air’s reliance on oxygen electrochemistry means it suffers from efficiency challenges similar to those encountered by hydrogen batteries. Other flow battery chemistries may also be of interest; EPRI estimates, for example, that zinc-bromine batteries could cost as little as $1450 - $1750/kW, or about half the cost of vanadium redox systems (EPRI, 2010b). Liquid metal batteries provide a second alternative to conventional molten salt batteries: the cathode, anode, and electrolyte are all liquid metal layers, separated due to their different densities. Research on liquid systems focuses on developing materials that can be kept at lower temperatures and sustain higher voltages (Wesoff, 2014a). The manufacturing, scale-up, and putative cost
reduction of conventional, small cylindrical Li-ion batteries and systems comprising them is another interesting development (Wessoff, 2014b).

The U.S. and other countries are devoting substantial resources to storage technology development. The U.S. government spent about $1.3 billion on storage initiatives between 2009 and 2012, of which the majority went through DOE programs and roughly 25% through the Department of Defence. DOE programs have included basic research, storage demonstration programs under the American Recovery and Reinvestment Act, energy storage “hubs,” and ARPA-e storage projects aiming to develop new solutions and make them market-ready.

The European Electricity Grid Initiative mapped storage RD&D projects in Europe and found nearly $1.72 billion spread across nearly 400 projects. About 1/5 of the funding for these projects came from the EU, and the remainder came from national governments. The survey showed that Europe is betting heavily on batteries and thermal storage, especially non-centralized storage systems. Geth, Kathan, Sigrist and Verboven (2013) noted this funding largely applied at an early R&D stage, and that in the next few years, the EU may implement increasing numbers of follow-on demonstration projects. Japan continues to fund efforts toward demonstration and deployment of battery systems as well, leading the world on NaS.

Another frontier for storage technology research includes the use of electric vehicles (EVs) to provide grid services. Plug-in vehicles could provide frequency regulation and fast-response reserve power, competitive with spinning reserves. Some vehicle technologies could provide peak-shifting services useful for integrating intermittent generation sources. One study estimated that if wind supplied half of 2005 U.S. electricity generation (700 MW), 23% of the vehicle fleet could provide the needed firm backup capacity in the form of fuel cell cars with collective storage capacity of 1190 GWh (Kempton and Tomić, 2005). Similar studies have demonstrated promise for EV support of wind integration in the UK and in Germany (Loisel, Pasaoglu and Thiel, 2014).

Despite this promise, deployment of grid-connected vehicle systems remains minimal worldwide. A major issue is cost; the German study noted that due to battery degradation, battery-powered electric vehicle owners could have difficulty recouping costs in the primary ancillary services market (Loisel, Pasaoglu and Thiel, 2014). Another challenge includes developing a business model that is workable for grid operators and attractive for consumers. Grid operators will want maximum flexibility to use vehicle storage resources, while drivers need to be assured their cars will charged and available when needed.

The U.S. government is engaging in research to reduce these barriers to EV/grid systems. The Department of Energy has funded vehicle-to-grid demonstration projects, including one in the PJM territory with early results establishing revenue for grid-enabled vehicle owners of about $5/day (Shepard and Garther, 2013). The California ISO has developed a vehicle-grid integration roadmap as part of its Zero Emission Vehicles (ZEV) initiative, and the Department of Defence pledged $20 million in 2013 toward establishing grid-enabled plug-in
electric vehicles on military bases. Navigant estimates that more than 250,000 grid-enabled of vehicles will be sold worldwide by 2022 (Shepard and Garther, 2013).

Deciding where countries should focus storage R&D efforts requires understanding which technologies are most likely to compete based on the services they can provide, and which technologies are closest to commercial maturity. Environmental and social impacts are important considerations as well, especially as nations move to internalize emissions costs.

At this stage, no single technology stands out as being clearly most worthy of RD&D support. Pumped hydro and compressed air storage are the most mature and cost-effective, but both come with geographic limitations and environmental drawbacks. They should be deployed as cleanly and widely as possible, and research should continue on options to mitigate the challenges associated with both technologies. Batteries remain expensive, so research should focus on ways to bring costs down (including by improving performance parameters like efficiency and shelf-life). Battery configurations relying on earth-abundant materials should be top priority. Otherwise, the suite of battery systems receiving support should remain broad and include advanced, less-mature designs, until more clarity emerges about which technologies will compete best on cost. Electrochemical storage, including flow batteries and hydrogen systems, should remain a focus as well. Scientists have examined electrochemical storage solutions for decades, and while smaller-scale storage and mobility applications have taken centre stage and a large amount of the hydrogen funding at least in the U.S., renewed focus should rest on inexpensive conversion processes for grid-scale electricity storage.

6.5 Conclusions

Electricity storage can provide vital grid services needed for integrating renewable and nuclear generation. Worldwide deployment is still relatively small and dominated by pumped hydro, but that picture may change with sustained R&D investment and electricity market reforms to ensure low-cost storage solutions can provide value. To that end, we recommend entities with regulatory jurisdiction or the ability to provide research support do the following:

1. Create a level playing field, allowing storage to participate in provision of all market services for which it is qualified,
2. Support deployment of mature storage technologies as widely as possible (especially pumped hydro), by characterizing resources to identify those with the lowest environmental impact and highest potential to help integrate baseload and intermittent generation, and
3. Continue to fund research, development, and demonstration projects across a wide range of advanced energy storage technologies, including grid-enabled electric vehicle systems.

7. Environmental Impacts of Nuclear and Renewables

There have been many studies on the environmental aspects of nuclear power generation and of renewable energy sources, for two particular reasons:
1) Nuclear energy production involves a series of processes from uranium mining through to final waste disposal, all of which are major engineering activities. These commonly require the production and assessment of an official Environmental Impact Assessment (EIA) before they can be licensed. Large scale use of renewables such as in wind farms or solar power plants also requires an EIA.

2) Nuclear energy production is a controversial subject in most countries, resulting in an active debate on the associated environmental issues, and on their impacts relative to alternative means of producing electricity. Increasing controversy also surrounds the environmental impacts of renewables as aggressive programmes to increase their market penetration have led to growing local opposition in some countries.

Most often in the current energy debate, the comparisons that have been made are between nuclear and fossil fuels or between renewables and fossil fuels. Given the widely acknowledged high impact of fossil fuels, both on human health and on potential climate change (Lynas, 2014), the more interesting comparison is between nuclear energy production and the use of other low carbon alternative energy sources such as hydropower, solar, wind and biomass.

In this section we consider the environmental impacts of nuclear and renewables in terms of a wide range of actual and potential impacts. We begin by using the literature data to summarise, as quantitatively as is feasible, the impacts of the different technologies in terms of their materials and energy requirements, their emissions during operation, their health effects during operation, the accident risks, and the associated waste streams. Recent studies referenced below provide important information for such comparisons, although challenges remain in gathering reliable data and in appropriate normalization of the impacts. We follow up these sections with some more anecdotal evidence on selected impacts that are either particularly topical or are important but less commonly addressed. These include impacts of wind turbines on persons and on bird life, the underestimated problems with biomass, and concerns about biodiversity reduction. Finally we address the public attitudes towards both renewable energy technologies and to nuclear power. The energy policies of many countries are perhaps more strongly influenced by public and political perceptions of available technologies than they are by rational assessment of the actual benefits and drawbacks.

The most transparent approach to comparing all such environmental impacts from various electricity production methods is within a Life Cycle Analysis (LCA) in which all impacts, including costs, are assessed and summed throughout all stages. These types of analyses were extensively studied within the ExternE Project of the EU which ran through to 2005. The website established for this project remains updated to include references and results for subsequent work up to the present. (ExternE, 2014). This includes links to the NEEDS project (Lecointe et al, 2007) which extends the nuclear power plant studies to include estimates for newer reactor technologies that may be implemented up to 2050.

Many of the figures given in the texts below for nuclear power and for renewable technologies are based on LCA analyses, often making use of the Ecoinvent database produced in Switzerland (Ecoinvent, 2014). A large database was also assembled for the recent IPCC report on climate change (IPCC, 2014) and results from this comprehensive document are also included below.
7.1 Resource Requirements

7.1.1 Materials

The principal materials concerns with wind and solar energy technologies relate to the use of “rare earth” materials. The US Department of Energy (US DOE, 2011), and others, have identified neodymium, dysprosium, terbium, europium, and yttrium as substances which wind turbines and solar panels are currently dependent. Shortages in the short to medium term have been identified; these are likely to impact on the availability and cost of these materials. Particular concerns have arisen about the role of China which controls a large proportion of rare earth supplies.

The proportion has been estimated at over 90% of the world total production of rare earth metals (REM). Recently, China has cut its exports for the second time due, it is claimed, to environmental concerns (Rudarakanchana, 2015). This has stimulated those economies with the greatest demand for critical materials – the EU, the USA and Japan – to seek the implementation of a strategy which would encourage new mining activity, focussed R&D, and other actions (including efforts to offer EU experience in the field of environmental protection as part of trade agreement arrangements with China) to help offset reliance on China (Baldi, Peri and Vandone, 2014).

A top capacity wind turbine may use 2000kg of neodymium-based permanent magnet material. Not all wind turbines use permanent induction generators (that currently require neodymium); some use Tesla induction generators that do not require rare earth magnets, but the latter require variable pitch control and, if HVDC transmission becomes a widespread reality, permanent induction generators are likely to be given preference.

Thin film solar cells, while still a small segment of the solar market, draw on three other “critical” (but not rare earth) materials – gallium, indium, and tellurium. Indium and tellurium are already exceptionally scarce. Issues related to the materials employed in the various power generation technologies relate, not just to the quantities of different elements but also to their toxicities, especially if toxic elements eventually land up in waste streams. This aspect is dealt with in section 7.6.
Figure 7.1: Critical raw materials content of renewable resources

<table>
<thead>
<tr>
<th>Application</th>
<th>Component</th>
<th>Critical raw materials content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind and hydropower plants</td>
<td>Permanent magnets of synchronous generator</td>
<td>Neodymium, dysprosium, praseodymium, terbium</td>
</tr>
<tr>
<td></td>
<td>Corrosion-resistant components</td>
<td>Chromium, nickel, molybdenum, manganese</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>Transparent electrode</td>
<td>Indium</td>
</tr>
<tr>
<td></td>
<td>Thin film semiconductor</td>
<td>Indium, gallium, selenium, germanium, tellurium</td>
</tr>
<tr>
<td></td>
<td>Dye-sensitized solar cell</td>
<td>Ruthenium, platinum, silver</td>
</tr>
<tr>
<td></td>
<td>Electric contacts</td>
<td>Silver</td>
</tr>
<tr>
<td>Concentrating solar power (CSP)</td>
<td>Mirror</td>
<td>Silver</td>
</tr>
<tr>
<td>Fuel cell-driven electric vehicles</td>
<td>Hydrogen fuel cell</td>
<td>Platinum</td>
</tr>
<tr>
<td></td>
<td>Electric motor</td>
<td>Neodymium, dysprosium, praseodymium, terbium, copper</td>
</tr>
<tr>
<td>Biomass to liquid (BL)</td>
<td>Fischer-Tropsch synthesis</td>
<td>Cobalt, rhenium, platinum</td>
</tr>
<tr>
<td>Electricity storage</td>
<td>Redox flow rechargeable battery</td>
<td>Vanadium</td>
</tr>
<tr>
<td></td>
<td>Lithium-ion rechargeable battery</td>
<td>Lithium, cobalt</td>
</tr>
<tr>
<td>Electricity grid</td>
<td>Low-loss high-temperature super-conductor cable</td>
<td>Bismuth, thallium, yttrium, barium, copper</td>
</tr>
</tbody>
</table>

There have been considerable efforts to portray the scope for deploying advanced materials for "sustainable energy" (Dusastre, 2011), and there has been great interest in the use of graphene for solar cells.

Renewable power sources also require significant quantities of conventional materials such as concrete. For the case of wind turbines, a 300MW installation using 152 wind turbines of 2MW each required 930,000m$^3$ of concrete (Lafarge, 2012). For a 1000MW plant, this implies that 310,000 m$^3$ of concrete would be required.

In nuclear power plants, the only material for which the availability of resources has been discussed is the uranium fuel itself. The world's present measured resources of uranium at prices around 1.5 times present prices, if used only in conventional reactors, are estimated to last for about 90 years (WNA, 2015), but uranium is ubiquitous and recovery even from sea water may become economically feasible. More practically at present, if uranium were used in breeder reactors in a closed fuel cycle the available resources could last 50 times longer. Nuclear power plants also require large quantities of steel and concrete, which together comprise over 95% of the material inputs (Peterson, Zhao and Petroski, 2005). The data of these authors imply that construction of older nuclear power plants with a 1000 MWe capacity required around 45’000t of steel and 100’000 m$^3$ of concrete. However, they show that the evolutionary Generation III plants—EPR and ABWR—use approximately 25% more steel and 70% more concrete than older LWRs. Other sources quote differing figures for a 1000 MWe plant, with estimates for steel ranging from 35’000 to 70’000t and for concrete up to 350’000m$^3$ (White and Kulcinski, 1999). Specific figures for a Swiss PWR given by Dones et al (2007) are 40’000t for steel and 170’000 m$^3$ for concrete. It is apparent that the concrete needed per MW capacity is higher for wind power than for nuclear. If the normalization is to GWe years rather than maximum power, then the comparison looks even less flattering for wind power, given its lower average availability.
7.1.2 Water Use

Water usage by power plants is second only to that required by agriculture, but the major part of the water used for cooling a plant is returned to the river or sea from which it is taken. The figures given by the US Nuclear Energy Institute (NEI, 2014) for water use by a nuclear plant normalise to 1500 l/MWh (e) for once through cooling and 2700 l/MWh (e) for a plant with wet cooling towers. For a specific example (the 1000MWe Leibstadt plant in Switzerland), the required cooling water throughput is 32 m$^3$/s and the losses from evaporation amount to 1m$^3$/s. The nuclear plant requirements are stated to be 2 to 4 times lower than for geothermal or solar-thermal power plants. The highest water usage is by hydropower plants which can lose 17000l/MWh(e) due to evaporation from reservoirs. The IPCC WG III report on renewables (IPCC, 2011) gives a comprehensive overview of water usage, as illustrated below.

Figure 7.2 Power Plant Water Consumption
7.1.3 Land Use

Hirschberg and Dones (2014) estimate that, for operation of nuclear power plants, the necessary land requirements correspond to only 0.6 m$^2$/GWh(e). The Swiss figures, given for hydro power and large solar, are respectively 49 and 1275 m$^2$/GWh(e). They point out, however, that solar panels on existing buildings need no additional land areas. Mackay (2009) states that wind farms need around 500 times as much land as a nuclear plant. This figure is in broad agreement with that of the NEI (2014) which estimates that wind farms need 300 times the area to produce the same output as a nuclear plant. The SBC Energy Institute (SBC, 2014) gives land use figures for the plant itself and also for all indirect land use. In normalised units m$^2$/GWe, these are for nuclear power 50/120; for photovoltaic 329/463 and for wind 1500 to 3200.

A further contentious point, however, is the potential for long-term loss of land use. This can be large for a major nuclear accident, as evidenced by Chernobyl and Fukushima. It can also be large for a dam; the extreme case is the Three Gorges dam in China which will eventually have a 660km long reservoir with an area of 630 km$^2$ and a capacity of 18GW.

7.3 Emissions

7.3.1 CO$_2$ Emissions

Mackay (2009) estimates that building a 1GWe nuclear power plant results in CO$_2$ emissions of 300’000 t CO$_2$. For a 40 year plant lifetime, this corresponds to around 1g CO$_2$/kWh(e). This is much lower than the figures that he gives for fossil fuels (400g CO$_2$/kWh(e)). For the total CO$_2$ emissions for all stages of the fuel cycle MacKay quotes an IPCC estimate of 40g CO$_2$/kWh(e). The Austrian study by Wallner et al (2011) points out that below a certain ore concentration the life cycle emissions become dominated by the ore preparation; for a low concentration of 0.013%, the value given is 288g CO$_2$/kWh(e).

In general, however, nuclear power and all of the renewables considered result in much lower greenhouse gas emission than do fossil fuels$^{13}$. This is illustrated clearly by the figure below which is based on IAEA data.

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$^{13}$ The figures for wind and solar are somewhat dependent upon whether aluminium is used in the construction of wind towers or solar plants. The association of sulphur hexafluoride with aluminium, a so-called greenhouse gas having a Global Warming Potential in excess of 3’000 times an equivalent volume of carbon dioxide, makes this a potentially important consideration.
The IPCC 5th Assessment Report (IPCC, 2014) also quotes CO₂ emission data confirming that nuclear energy is among the lowest carbon forms of generation similar to wind turbines at 12g CO₂/kWh(e). Hydro and solar have emissions of 24g CO₂/kWh(e) and 28g CO₂/kWh(e) respectively. Biomass has much higher total emissions of 220gCO₂/kWh(e). For comparison, coal is at 920gCO₂/kWh(e), gas at 490gCO₂/kWh(e) and fossil fuels with CCS at 160-220gCO₂/kWh(e).

### 7.3.2 Toxic Emissions

All energy technologies also produce air pollutants at some points in their life cycle. These include particulates, nitrous oxides, sulphur dioxide and volatile organic compounds. Nuclear and fossil fuels also result in some radioactive releases. At the local and regional levels, air quality can be severely affected by carbon monoxide, and sulphur and nitrogen oxides. Per GWh(e) generated, solar thermal emits larger volumes of carbon monoxide (285 kg) than natural gas (190 kg) or oil (110 kg). Solar PV has been estimated to release 263 kg of nitrogen oxides and 731 kg of sulphur oxides per GWh(e) electricity generated, and wind energy 71 kg and 137 kg respectively (Hirschberg, 2007). The data gathered from numerous sources by the IPCC, show clearly that the SO₂ and NO₂ emissions per GWh(e) generated by fossil fuels and biomass far outweigh those from nuclear power and all other renewables. Nuclear
power plants release radioactive gases such as Kr-85 and Xe-133 and I-131. These can result in very small doses to persons.

7.4 Effects on Health

Systematic studies of the effect of energy production on health were begun at Brookhaven National Laboratory in the early 1970s and at Lawrence Berkeley Laboratory soon thereafter. More recently, Canada’s Atomic Energy Control Board studied the overall risks of 11 energy sources and found that total risk per unit of energy output of wind came third (after coal and oil), and was then followed by solar PV in fourth place, solar thermal in fifth, solar space heating in sixth, and hydro seventh. Nuclear and finally natural gas offered the lowest risks in this survey. Man-days lost per unit of energy output, though lower than for coal and oil, were not inconsiderable – with wind and solar PV taking the next highest slots. A 1991 IAEA study found somewhat similar rankings, with fossil fuels (coal, oil, and gas) posing the highest mortality risks, followed by renewables and finally nuclear (Haddad and Dones, 1991). Based on ExterE data, Starfeld and Wikdahl (2011) produced the chart below comparing deaths per KWh from various sources.

Figure 7.4 Deaths per KWh by Primary Energy

![Deaths per KWh by Primary Energy chart]

Source: Starfeld and Wikdahl (2011)

The main cause of human fatalities in the solar PV sector arises from falls incurred by solar rooftop installers, and there have been estimates of these up to 150 per year worldwide. In the wind energy sector, human fatalities have been rising as the number of turbines installed has risen. In the USA 99 fatalities were reported as having occurred in the recent past (East Country Magazine, 2012). A UK source reported that there were between 157 and 166 wind
energy-related accidents annually between 2011 and 2014 at least 1,660 since the 1980s, and 151 fatalities, of which over 60 were not engaged in the industry (CWIF, 2014). These figures are considered to be only "the tip of the iceberg". For example, in December, 2011, the UK’s main wind energy industry association, RenewableUK, reported that there had been 1,500 accidents over the previous five years, although claiming these had resulted in only four fatalities and about 300 injuries. The industry association’s then Director of Health and Safety further claimed: “No members of the public have ever been injured or harmed in the reports we have received.” Nevertheless, there have been numerous near misses due to blades falling off, small turbines collapsing (one in a school playground), and ice shear (TDT, 2011). In Germany there were 880 ice shearing events alone between 1990 and 2003; 94 in 2005; and 27 in 2006. Many of the operational accidents have been transport-related.

Of course, public interest focuses primarily not on impacts of normal operation, but rather on potential consequences and probabilities of accidents. These are treated in the following section. But in the long run, given pressures of world population increase and land and water stresses, it is arguably modern biomass and biofuel developments which pose the greatest threat to sustainable development among the new renewables.

7.5 Accidents

In this section, we have in mind the potential impacts of earthquakes, tsunamis, volcanic eruptions, land slips, flooding and hurricanes. These potential impacts can have a bearing on some forms of new renewable energy operations as well as on nuclear. In particular geothermal, hydro and wind energy operations can be severely affected. Note, however, that fossil plants and systems are not without the propensity for accidents as well. Coal mine accidents and natural gas pipeline explosions claim many lives, and major earth events affect fossil systems as well as nuclear and renewables.

There has been much discussion in the recent past as to whether geothermal activities, like fracking for shale gas, can trigger earthquakes – or less severe earth tremors. The subject is hotly debated between those who consider such activities can trigger earth tremors, and those who dispute the contention – usually on two grounds, that earthquakes measured on the Richter scale have a far greater magnitude than any human activity is likely to cause, and because although drilling does not cause earthquakes, using cool liquids against hot rocks can sometimes cause minor tremors. The geothermal industry, which world-wide has over 10,000 MW installed capacity, would claim their operations do not pose a significant threat to humans or the environment. Earthquakes and flooding could, of course, adversely affect their operations.

Dam failures of those built for irrigation purposes have a long history. Those built for hydropower have a somewhat shorter one. About half the failures that have occurred in
recent decades were the result of heavy rainfall and resultant flooding - such as Banqiao-Shimantan, China, in 1975; Machuchu – 2 in India, in 1979; Shakidor, Pakistan, in 2005; and Kopru, in Turkey (where the dam’s diversion tunnel seal also failed), in 2012. Some 30 percent of failures are due to structural issues – the hydropower dam at Gleno, Italy, in 1923; Teton, Idaho, USA, in 1976; and Campos Novos, in Brazil, in 2006. No estimates of human fatalities match those at Banqiao-Shimantan, in Henan province, in which 171,000 people died. In excess of 1,800 people died as a result of the failure of Machchu-2 in 1979, since then, there have been only three cases where fatalities exceeded 100.

Hurricanes and strong winds more generally can cause wind turbine towers to collapse, blades to be spun off, turbines to catch fire, and ice shear to spread wider – potentially to areas where human life and property may be threatened. However, engineering solutions including providing the ability of wind towers to yaw can significantly reduce the risk of wind tower damage. The US National Academy of Sciences has looked into the potential for tower buckling, and found it high relative to other locations in Galveston County, Texas, and in Dare County, North Carolina.

Most energy sources and facilities are, of course, liable to be affected by earthquakes, strong winds, tidal waves, and other causes of flooding. From offshore oil and gas rigs to inadequately protected nuclear plants, and even coal mines let alone solar or wind power or biomass/biofuels, these facilities are not risk-free or able to withstand all possible natural disasters. Stefan Hirschberg has reported that in the period 1969-2000, hydropower was responsible for the highest number of fatalities among all forms of energy in non-OECD countries if the very high number of deaths following the Banqiao/Shirmantan dam accident is included. Even when this accident is excluded fatalities rank equal second, with non-OECD including China for coal, to those in the LPG sector ranked highest.

The IPCC (2011) report again presents relevant data. Results are presented for severe accidents with 5 or more fatalities since these tend to attract most public attention and to influence political actions most strongly. The authors give fatality rates normalized to the electricity generation in GW-years, and they estimate maximum consequences for a single accident of a specific energy technology. Coal has by far the highest fatality rate (especially in China) and hydropower and nuclear have the lowest of the large technologies. Hydropower can, however, have large numbers of fatalities due to dam failures. All other renewable energy technologies have low fatality rates and low maximum consequences, the latter because of their distributed nature. The authors point out, however, that other types of risks should also be considered and give as examples induced seismicity from enhanced geothermal systems and the risk of ship collisions with offshore wind turbines. The extract below from the IPCC report illustrates the fatality rates for nuclear and renewables:
7.6 Wastes

Because of the enormously higher energy density in nuclear fuels, nuclear power plants produce much smaller quantities of wastes than do fossil plants. But the more relevant comparison here is with renewable energy systems which are often thought to produce little or no wastes. Again the most objective comparison normalizes the wastes produced to the electricity generated.

A 1000 MWe light water reactor generates around 200-350 m$^3$ low- and intermediate- level waste and about 25 tonnes) of used fuel per year, or about 1’500 tonnes of used fuel over an assumed 60-year plant lifetime. (A coal fired plant of the same size produces about 400’000 tonnes of ash). While the total volume and mass of nuclear wastes produced per year is relatively small, it is the radiotoxicity and heat of nuclear waste that determines the relative burden in managing it. Nuclear waste requires isolation from the biosphere and sufficient spacing and cooling, so is per-tonne more expensive to manage than wastes from renewables. Rhodes and Beller (2000) state that a 1000MWe solar electric plant generates 6’850t of hazardous waste from metals processing over a 30y lifetime, and a 1000MWe solar thermal plant would generate 435’000 t of manufacturing waste of which 16’300t would be contaminated by heavy metals.

Disposal of the wastes produced from electricity production is a high profile issue in the case of nuclear power. Despite the fact that geological disposal is widely recognised by the technical community as a suitable and safe approach, there is often strong public and
political opposition to specific disposal projects, based primarily on the high toxicity and long lifetimes of the most active wastes. Around 5% of the 1500 tonnes of used fuel from the lifetime of a large reactor contain consists of highly radioactive fission products and plutonium; the rest is uranium which can be recycled into fresh fuel. The energy produced over the lifetime is around 50 GWe years, giving a specific spent fuel inventory of 30 tonnes per GWe year or a highly toxic waste inventory of around 1.5 tonnes per GWe year.

On the other hand, solar modules contain some potentially dangerous materials which do not decay with time. There is little awareness of the problems of dealing with wastes from solar power production because the panels are produced largely in China and not in the other countries where solar power is promoted. The potential problems in China are huge (Nath, 2010); however, even in California around 20’000t of hazardous waste were produced by solar companies between 2007 and 2011 (Dearen, 2013). One of the most obvious examples is the use of cadmium in the manufacture of thin film solar panels. This is attractive because of their lower cost than silicon-based solar. However, elemental cadmium is very toxic, although the compound used CdTe may be less so. In the USA, Cd containing cells are acceptable; in the EU, although Cd is acknowledged as carcinogenic, it is widely forbidden – but exceptionally allowed in solar cells since promoting renewables is judged to be more important (EU Directive 2011/65/EU). A quantitative comparison with toxic nuclear wastes is of interest. The large Desert Sunlight Solar Farm in the Mojave Desert in the USA has 8 million solar panels, each with around 6g of Cd. This implies that the Cd inventory for the 550 MWe peak capacity plant is around 40 tonnes. Unless all this Cd is recycled after the 25y plant lifetime, the toxic waste inventory per GWe year is around 6 tonnes, assuming 50% availability.

7.7 Public Attitudes

Few robust general statements can be made about public attitudes to either new renewables or nuclear power. In both cases, there are strong proponents and the bitterly opposed. However, it is very clear from public polling that there is a fundamental difference in public attitudes to renewable energy sources and to nuclear power. The data below from 2011 (Wallard et al., 2012) illustrate this clearly:

**Figure 7.6 Public Attitudes towards Nuclear and Renewable Power**

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Public Support (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar power</td>
<td>97</td>
</tr>
<tr>
<td>Wind power</td>
<td>93</td>
</tr>
<tr>
<td>Hydroelectric power</td>
<td>91</td>
</tr>
<tr>
<td>Natural gas</td>
<td>80</td>
</tr>
<tr>
<td>Coal</td>
<td>48</td>
</tr>
<tr>
<td>Nuclear energy</td>
<td>38</td>
</tr>
</tbody>
</table>

(IPSOS Data from April 2011)

Source: Wallard et al., 2012
7.7.1 Attitudes to Renewables

Public attitudes towards modern biomass and biofuels have been influenced by loss of traditional forests, reduced diversity of agricultural crops grown, concerns about impacts on wildlife, and the activities of environmental pressure groups. In general environmental pressure groups have been opposed to modern biomass and biofuel development on rational grounds. The same is not true for wind energy development and operation, large hydropower schemes, or estuarine barrages. In each of these cases, there are strong emotional issues involved in the argumentation. Support is normally high for solar PV at a small scale, but the acceptance of large area solar parks has not been widely tested.

Performance claims for renewables have been shown to be exaggerated (Jefferson, 2012). Negative impacts of wind energy developments on residential property prices, sleep patterns for some people, and visual outlooks are not regularly discussed. Atif Ansar and colleagues (Ansar et al., 2014) have noted that for large hydropower schemes: “Much of the data in existing literature are drawn from surveys and interviews of dubious validity. At times, interest groups, seeking to promote a particular kind of scale or technology, also report distorted data.” Their first recommendation was: “Create transparency on risk profiles of serious energy alternatives, from not only the perspective of financial cost and benefit, but also the environmental and social impacts – hard evidence is a counter-point to experts’ and promoters’ oft-biased inside view.”

In the case of estuarine barrages for tidal power, there have been statements such as: “The most detailed work … carried out on the Severn has suggested that birds may actually benefit in most cases to a (sic) barrage being present.” Speakers at a tidal power conference covering estuarine barrages in the Bay of Fundy managed to avoid any reference to birds (until challenged from the audience), and time has proved them incorrect in their assessment of fish mortality at Annapolis (Clare, 1992).

Concern at challenges which may be posed by enhanced near-surface global warming also affects attitudes and support for new renewable energy developments in many quarters.

Public attitudes at the local level may also differ sharply. Many may find wind turbines aesthetically pleasing, while others do not. Some may be deeply disturbed by their visual intrusion, on historic assets or fine landscapes, while others may be indifferent. Some may have residential properties at risk of price falls, or are among those who suffer loss of sleep pattern due to aerodynamic modulation from wind turbine blades. Some may see job opportunities arising, or other financial benefits (farmers where wind turbines are located, for example), while others are concerned their vacation homes will be blighted (such a polarity has emerged in various European countries, including Finland and the UK). There are also many examples of public acceptance growing over time among those living in close proximity to wind turbines, solar ‘parks’, and nuclear plants. There has even been reported an “inverse NIMBY” (Not In My Back Yard) syndrome where those with wind energy developments in their “backyard” strongly support the technology (Warren et al., 2005). As Charles Warren and his colleagues point out, the media may often give disproportionate attention to vocal minorities – in this case those opposed to wind energy developments. But
vocal minorities often demonstrate that they are more closely in touch with the local realities of costs and subsidies, impacts on residential property values and potential health impacts, and more sensitive to landscape impacts. Nevertheless, as Matthew Cotton and Patrick Devine-Wright have written:

“The NIMBY label is problematic, as it is often used by proponents of development projects as a means to discredit all forms of project opposition, regardless of its motivation, and wrongly characterizes local people as worried, irrational, ignorant of scientific and technical facts, and selfishly unwilling to support projects that benefit the broader society.

Even if one were to accept this characterization of citizens opposed to the siting, NIMBYism is neither irrational nor necessarily unethical” (Devine-Wright, 2011a).

There is a growing body of evidence that local people are frequently well-informed about a technology, its likely performance in the intended setting, and the wider implications of its usage. There is also growing recognition in the literature of the importance of a sense of place attachment, something which due to familiarity over time is more deeply entrenched in rural dwellers. Thus landscape values and historic assets may be more highly valued by a higher proportion of rural dwellers than urban dwellers. There may be significant differences in emotional attachment between individuals, wherever their location (Lynne and Devine-Wright, 2014) There also appear to be significant differences between countries when it comes to rural countryside protection concerns – stronger in England, for example, than in The Netherlands or in Germany (Devine-Wright, 2011b).

Beginning to emerge among the general public in some relatively prosperous countries, however, is an even more profound concern. This is that a “dominant faith that renewable energy alternatives exist in abundance, and all we need to do is to shift them, and then our energy and climate change problems can be solved, and we can go on enjoying affluence and growth forever” (Trainer, 2013). In light of the above, and given the significant economic challenges faced by countries that have adopted high penetrations of intermittent renewables (including Germany and Spain), this view deserves a long and hard look.

Thus even the aspiration of those who believe that the last remaining hope, on technical potential grounds, of meeting these challenges is solar energy has been challenged. That hope was, and for some still is, the use of concentrating solar power, with ultra-high voltage direct current transmission (CSP+UHVD). This has the technical potential to meet the demand for energy services not just in Europe (the Desertec concept) but throughout Africa, as well as in the Americas and Asia. Proponents have had their optimism undermined by political and social turmoil in North Africa, the differing perspectives of European countries (especially between France, Germany and Spain), and failure to press forward determinedly with this technology (which has been around since 1912) in the USA.
7.7.2 Attitudes to Nuclear Power

It is interesting to study the fluctuations over time in public support for or rejection of nuclear power. There have been many studies over the decades since nuclear power was introduced which have discussed the public attitude to this energy source and, in particular, have analysed the reasons for the acknowledged anxieties of the public concerning radiation. Some have asserted that the nuclear bombing of Hiroshima and Nagasaki, Japan, near the end of WWII, has coloured public perceptions since then.

Others (Weart, 1988) claim that, even before then, there was an inbuilt fear of a hazardous agent that one “could not see, touch, taste or smell”. It has also been claimed by von Hippel for example in GEA (2012), that “one abiding concern has been the connection with nuclear weapons”. However, the weapons connection today seems more of an argument for specialists than for the general public. The potential for high consequence accidents influences people more than do the arguments that probabilities of these are very low; the risks imposed on individuals by others are less acceptable than voluntary risks that they take upon themselves and the potential for long-term and wide-spread contamination of land causes concern.

Nevertheless, support for nuclear energy increased slowly in many countries, with the strongest support often being in countries with significant numbers of nuclear plants. In numerous countries, however, there has long been extremely active opposition to nuclear power, the most pronounced examples being Germany, Austria, Italy and Australia. The safety-related arguments have alternated between concerns about power plant operation and radioactive waste disposal. Currently, in western countries moving to expand or introduce nuclear power, an additional major controversy is related to the cost of nuclear energy relative to the (subsidized) costs of wind or solar power.

In the first decade of this century, additional powerful arguments leading to increased support for nuclear were the need for expanded base load electricity in developing countries and also the growing fear of catastrophic climate change due to CO2 emissions from fossil fuel plants. Countries like China, India and South Korea developed massive expansion plans. Countries like the UK and the USA have been, mainly for economic reasons, ambivalent about nuclear new build. Countries with ageing plants such as Switzerland and the Netherlands started planning for newer generation plants. Even in Germany, the Government reversed plans for shutting down nuclear and agreed to extend plant lifetimes.

Then in March 2011, an unprecedented large earthquake and resulting tsunami led to the Fukushima Daiichi plant in Japan losing on-site electrical power for so long that three reactor cores melted, hydrogen explosions wrecked the upper part of the reactor buildings where the spent fuel pools were, and widespread radiation releases resulted.

Unlike in the Chernobyl disaster decades before, this plant was of the same design as western reactors, the media coverage was intense and the nuclear consequences (which did not
include any radiation induced deaths to members of the public) were accompanied by massive loss of human lives and of buildings due to the huge wave that swept inland. Since the Fukushima accident, there have been a number of studies and public polls aimed at assessing the public and political impacts. Questions have also been raised about the level of defences (e.g. height of containing walls to prevent incursion of tsunami driven water in an area known to be close to a tectonic plate) and quality of maintenance somewhat removed from reactor design issues.

The immediate impacts were naturally very negative. Rapid political decisions in Germany and Switzerland (taken before any proper assessment of public attitudes – and shortly before upcoming elections) led the governments of these countries to announce that they would renounce nuclear power. A WIN-Gallup International Global Poll within a month of the accident recorded the views of over 24000 persons in 42 countries. 52.7 percent favoured the use of nuclear energy before the accident, and only 45.4 percent favoured it after the accident (Younghwan et al, 2013), with the sharpest decrease in support (28%) being, as expected, in Japan.

In some countries, however, the dip in acceptance was short-lived or absent. In the USA, the 57% who favour nuclear power just one year after the accident was identical to the percentage measured just before the Fukushima incident (Newport, 2012). Equally striking are the results from the UK (Poortinga et al, 2013). The figure below shows that support for nuclear has remained rather constant throughout the Fukushima phase. In fact, the proportion wanting to phase out nuclear power (immediately or gradually) decreased from 50% in 2005 to 40% in 2013. It also shows, interestingly, that support for new renewables, solar and wind, although still much higher, has been reducing as their implementation has been spreading. Other countries where national nuclear support continues to be strong include China, Finland, India and South Korea.
It is interesting to speculate whether government support in these countries is a reason for the higher levels of public support or whether the greater public support makes it easier for governments to propose expansion.

7.8 Additional Issues

7.8.1 Wind Power

For some people the incidence of aerodynamic (or amplitude) modulation of wind turbines can cause sleep disturbance, and hence health problems, at distances up to 1.5 kilometres from their nearest turbine (Bowdler, 2008; Stigwood, 2009; and Pedersen and Persson, 2007). This is not turbine noise as such, but air disturbance (the swish-swish noise of blades turning) (Hanning, 2009). Hanning’s paper reports on acoustics experts and doctors’ case histories. At the March, 2014, Institute of Acoustics meeting held in Newport, U.K., examples of amplitude modulation and its impacts were provided from the USA, Sweden and Australia, as well as the UK. Concerns and complaints have continued to be reported, and it was therefore somewhat surprising that an MIT study funded by the European Wind Energy Association and its Canadian counterpart found there were "no clear or consistent
associations between noise from wind turbines and any reported harm to human health”. (December 4, 2014)

One consequence of the above phenomenon may be loss of residential property values. Wind energy developments can reduce residential property values by over 10% where located within 2 kilometres of the nearest turbine – in some cases resulting in properties becoming unsaleable (Gibbons, 2013). Often linked to these effects are the occasional impacts of aerodynamic modulation mentioned above, and visual impacts (on picturesque landscapes and in relation to historic assets). A number of cases have been reported where wind development has caused severe problems such as in Lincolnshire, UK (Gibbons, 2013). Whether such problems are representative of typical wind energy developments is not well known. For example, some studies have found a relatively weak statistical relationship between wind developments and changes in property values (Hoen, et al, 2013; Laposa and Mueller, 2010; Hinman, 2010; and Heintzelman and Tuttle, 2012). More research about the impact of wind farm development on property values is needed.

7.8.3 Hydropower and Solar

On a much larger scale from time to time, especially in some developing countries, are the impacts of large hydropower schemes resulting in displacement of population, loss of agricultural land, unemployment, and consequential economic and social upheaval, as Atif Ansar and colleagues have suggested (2014). To date of only limited significance are the complaints from some aircraft pilots and passengers of the near blinding glare of the Sun’s reflection off solar mirrors placed in the Mojave Desert on the California/Nevada border.

7.8.4 Impacts on Bird Life

The concern that modern biomass and biofuel developments will compromise biodiversity has led to increased interest in the study of bird life. This is because birds are an interesting indicator of biodiversity, being high in the food chain, sensitive to monoculture expansion, more mobile than most other groups, and therefore likely to respond to and reflect environmental quality on a broader scale than mammals or terrestrial insects. Hence they are often considered to be good indicators of wider ecosystem health (Gregory, 2005; Bateman, 2013).

There is a vast literature on the impacts of loss of biodiversity and of human-erected structures on bird species and mortality. Although bird mortality is strongly linked to windows and other parts of buildings, passing traffic, and domestic cats, there is also strong evidence that wind turbines have been the cause of large numbers of bird fatalities. Fatalities appear to be increasing with the growing height of towers and to blade tip.
In the USA and elsewhere bird fatalities are higher around migration routes, especially down the western and eastern sides of the continent. In Canada also, the placing of wind energy developments along bird migration routes has been strongly condemned – such as on the peninsula in Prince Edward County, on the eastern shore of Lake Ontario. In Australia a wind energy development in North-West Tasmania has been responsible for the deaths of endangered wedge-tailed eagles.

There has been strong criticism of poorly conducted site surveys – even when, for example, the UK’s Royal Society for the Protection of Birds (RSPB) has had an involvement (for example, the Moorsyde Environmental Statement near Chillingham, Northumberland). Fewer site visits have been made in such instances than a proper survey would have required, there has been notable under-recording of bird fatalities, and faulty claims that the site was not on a bird “flyway” (Windbyte, 2014). This is despite the RSPB claiming: "We insist that wind farm proposals are subject to rigorous environmental assessment before development is permitted", and acknowledging that: "Some poorly sited wind farms have caused major bird casualties, particularly in Tarifa and Navarra in Spain, and the Altamount Pass in California". (RSPB, "Wind Farms", December 3, 2014) In Denmark the authorities are accused of having bulldozed plans through to place seven 250-metre high wind turbines between the Thy National Park and the Veljerne RAMSAR site, which some estimate is Europe’s largest breeding ground for migratory birds. There are also instances, however, where concerns about bird species have caused the planned expansion of wind energy developments to be abandoned – as in the case of the offshore London Array, where the proximity of a significant red-throated diver colony was a major factor in 2014.

Efforts to reduce casualties have arrived at the following conclusions. A prior environmental assessment should be carried out to ensure wind energy developments are not placed on or close to bird migration routes. Start-up wind speeds should be increased from 4 metres per second to 5.5 metres per second (this has been found to result in little loss of overall wind turbine performance – in load/capacity factor terms). A radar look-out for the approach of large numbers of birds has also been recommended, although research findings suggest a poor link between number of birds in the vicinity of turbines and fatalities (Manuela, 2008). Stopping wind turbines within three minutes of the sighting of the approach of birds has been estimated to reduce fatality rates of griffon vultures by up to 50 percent.

It is not just bird fatalities that have given cause for concern. In 2010 420 wind turbines in Pennsylvania killed more than 10,000 bats according to the State Game Commission. At Tug Hill Plateau in New York State there are 195 wind turbines, with bat fatalities estimated at close to 60 per turbine per year. At Canada’s Ontario Wolf Island Eco- Power Centre there were nearly 2,000 bird and bat deaths in the first eight months of the wind development’s operation, with 33 bird species involved and five bat species – bat fatalities accounted for 1,270 of that total number. Then in December, 2013, a study from the University of Colorado at Denver appeared which concluded that: “well over 600,000 bats may have been killed at wind energy facilities in 2012.” (Hayes, 2013). Bat fatalities due to wind turbines have been reported in many European countries.
To date little action has been taken against wind energy developers and operators to
discourage placing turbines where bird and bat fatalities arise. In the USA, however, there
are environmental laws which can be applied to discourage this under the Migratory Bird
Treaty Act. Duke Energy was fined $1 million in November, 2013, when eagles died at Top
of the World and Campbell Hill wind energy developments outside Casper, Wyoming. Since
then Exxon Mobil have been fined under this Act for bird fatalities at US oil production
fields; and PacificCorp for electrocuting 232 Golden Eagles and other migratory birds on
power lines in Wyoming, so the problem is not confined to wind turbines.

Two other forms of new renewable energy have attracted adverse criticism on grounds of their
impact on birds. On February 12, 2014, The Wall Street Journal published an article headed:
“The $2.2 Billion Bird-Scorching Solar Project”. This related to the large solar thermal (CSP
or concentrating solar power) project in the Mojave Desert on the Nevada/California border.
Dozens of birds have died there in recent months apparently because of the heat emitted from
the tower-based structures (as opposed to the more traditional, though still grossly under-
exploited, parabolic mirrors). US Federal wildlife investigators visiting the BrightSource plant
at Ivanpah Dry Lake, California, reported an average of one bird igniting in midair due to the
solar plant every two minutes. These dead, or dying, birds, are called "streamers" and whereas
BrightSource estimate the fatalities at 1,000 per year, the Centre for Biological Diversity
estimates the figure at 28,000 (Syracuse.com, August 18, 2014).

The other form is estuarine barrages. These have been under discussion since Thomas
Fulljames proposed a barrage across the Severn Estuary, between England and Wales, in
1849 (it is now the site of the Severn Bridge). The most widely known example in existence
is near St. Malo, in North West France, where an estuarine barrage runs across the La Rance
River. M. Rodier, of the developer Electricite de France, has stated that “The total closure of
the estuary between 1963 and 1966 during the construction of the plant caused the almost
complete disappearance of the original species.” (Rodier and Clare, 1992) Subsequently,
Canada has closed its Annapolis barrage in the Bay of Fundy due to concerns about bird and
fish mortality, and not proceeded with earlier plans for the Minas and Cumberland Basins,
and Shepody Bay, for the same reason (Jefferson, 2008). In 1999 the Cardiff Bay Barrage, in
the Severn Estuary between Wales and England, was completed. The loss of inter-tidal
mudflats (access to which is essential if wading and some other bird species are to survive,
as they need to access the invertebrates there) led to almost all the Common Shelduck and
shorebirds that used the Bay to be greatly reduced. Some initially used nearby sites, but this
proved unsustainable. Only two major studies have been published, both with the same lead
author (Niall Burton, of the British Trust for Ornithology, 2000 and 2006), and focused
mainly on the Redshank (Tringa tetanus). Although this species has relatively high site-
 fidelity, there are numerous other species which exhibit site-fidelity but which have not been
studied. It is known that weight loss and lower survival rates have resulted at nearby
settlement areas. This all raises the issue of whether objective assessments have been carried
out and, if not, why not. There have also been ongoing concerns of anglers about the impacts
of the barrage on fish. On March 18, 2015, in his Budget Speech, the UK’s Chancellor of the
Exchequer announced that negotiations were opening for a tidal lagoon at Swansea Bay. The
would-be developers are seeking £168 per MWh (nearly US$ 248) for 35 years, supported
by a (electricity consumer) subsidy of around £92 MWh ($136) per year. The proposed site includes the Blackpill Site of Special Scientific Interest; the Burry Inlet Special Protection Area; and would threaten one bird species (the sanderling) where it occurs in nationally important numbers; and several other species currently present in regionally important numbers (e.g. the ringed plover, the dunlin, the great crested grebe, and the oystercatcher).

7.9 Conclusions and Recommendations

In setting preferences for the choice of electricity generation systems, many aspects have to be considered and, as Hirschberger and Dones (2014) point out in their comprehensive evaluation of systems, no single system performs best under all criteria. For the health and safety and environmental aspects discussed in this Chapter, renewables and nuclear energy both outperform by far fossil fuel sources. The relative advantages and drawbacks of renewables and nuclear are perceived or weighted differently by different technical, public or political stakeholders. Large hydropower is in many aspects superior, but opportunities for its use are often limited by topography and land use conflicts. The new renewables, solar and wind, can supply plentiful but dilute energy; they use large amounts of special materials and can require substantial tracts of land. Biomass can contribute, but the impacts on food production and on biodiversity need to be taken more into account. For nuclear power, the major hurdles are the fear of low-probability, high-consequence accidents and concerns about radioactive waste disposal. All these feed into the further hurdle that costs are high and uncertain. In practice, the dogmatic positions taken by extreme supporters on renewables or of nuclear power may serve only to prolong and increase the use of cheap fossil fuels, despite the acknowledged higher risks associated with these. An “all of the above” approach encouraging the use of all energy sources that have low output of carbon and other emissions appears to be the most rational approach.

Key conclusions and recommendations include:

- In the absence of carbon-capture-and storage, the negative environmental impacts of fossil fuels are so pronounced compared to those of renewables and of nuclear power, that electricity generation strategies should be based on reducing fossil fuel usage by promoting all low carbon technologies over the highest- carbon technologies – where they can be soundly located and ideally with the consent of any local populations.

- Sound analysis of actual and potential technical options should inform energy policymaking, yet in some significant cases is overlooked. Energy policies of many governments in those cases appear to be based on subjective judgements of risks, influenced by powerful energy lobbies of all kinds, and/or designed primarily to appeal to the public.
- Life cycle analyses of energy systems are the most promising approach to developing objective criteria that can aid future decision making. Unfortunately, too little attention is paid to this approach by decision makers.

- The strongest proponents of both nuclear and renewables tend to have an overly optimistic view on the ability of their favoured technology to provide all of the low carbon electricity that is required.

- Nuclear power faces special challenges because of the widely recognised “radiation phobia” in the public. The scientific community in general, and the nuclear industry in particular, have not been very successful at responding to emotionally based public fears with rationally based science data. The greatest public concern about nuclear power is the potential for high consequence accidents, even if their estimated frequency is very low. The ultimate disposal of long-lived wastes also continues to be a concern for the public in most countries.

- The environmental impacts of some renewable electricity sources may be underestimated by the public. Examples include:
  - The hazards of large dams
  - The requirements for rare and toxic materials
  - Failure to consider their efficacy in terms of power density, EROI, sound location (in relation to wind, solar, land and water availability).

- Limitations on sustainability posed by the environmental and human impacts of energy technologies should be factored in to policies that support certain technologies over others.

8. Nuclear Fusion: Status Report and Future Prospects

The number of conceivable non-fossil candidates that could replace the current massive use of fossil fuels is very limited: essentially renewables and nuclear fission at the moment. A third option for use in the future is nuclear fusion. It is still in the development phase, but has particularly valuable environmental and safety advantages and virtually inexhaustible resources. This chapter discusses the current status of worldwide fusion research, resources, safety, environmental and economic aspects of fusion energy.

8.1 Principles

Replicating the fusion reaction in the sun would be a first possible approach to realize fusion on Earth. However, the p-p reaction in the sun essentially converts 4 protons into a Helium-4 (^4He) nucleus containing 2 neutrons. This reaction requires thus the conversion of protons into neutrons, implying a weak interaction with a very low probability and therefore not suited for an economical process on earth. A much more ‘simple’ solution is offered using hydrogen isotopes, already containing the necessary numbers of neutrons and protons from the start, thus resulting in a reaction where essentially a rearrangement of the nuclides takes place, with
a $10^{24}$ times higher reaction rate than the p-p process in the sun. From all possible reactions involving H isotopes, the least difficult fusion reaction is the one between the hydrogen isotopes deuterium (D) and tritium (T):

$$\text{D} + \text{T} \rightarrow ^{4}\text{He} (3.5\text{MeV}) + \text{n} (14.1\text{MeV})$$

To produce sufficient fusion reactions, the core temperature of a D-T plasma has to be about 150-200 million C.

The reaction products are very energetic (one 3.5 MeV Helium particle and one 14.1 MeV neutron). This energy will be converted into heat in a blanket that surrounds the reactor, extracted by a cooling system and converted into steam to produce electricity using conventional technology. As about one million times more energy is released from a fusion reaction compared to an average chemical reaction, this then explains why so little fuel can produce so much energy: when burnt in a fusion reactor, the deuterium contained in 1 liter of sea water (about 30 mg) will produce as much energy as burning 250 liters of gasoline.

**8.2 Status of Magnetic Fusion Research**

There exist presently two approaches to realise nuclear fusion on earth: inertial and magnetic fusion. Magnetic fusion uses magnetic fields to confine the fuel. Three classes of devices in use are tokamaks, stellarators and reversed field pinches and many devices exist around the globe. Strong magnetic fields are used to keep the hot particles away from the walls of the confinement device. This method uses the property of charged particles to follow a helical path around magnetic field lines (caused by the Lorentz force) and possible movements perpendicular to the field are thereby highly restricted. The interested reader can find a wealth of additional information in Cook (2001).

Inertial fusion consists of micro-explosions of small fuel pellets by means of powerful lasers or particle beams. Confinement of the fuel is based on the inertia of the pellet fuel mass, which resists the natural expansion when it is heated to thermonuclear fusion temperatures. To achieve sufficient fusion reactions in this short time requires a compression of the fuel to a density of about 1 kg/cm$^3$, a 10000-fold increase over the original density and about 100 times the density of lead or 1000 times that of water (Tabak and et al, 1994). This approach is being investigated in far fewer countries largely because of the relation of target physics and design to military programs. This is also the reason why some aspects of inertial fusion research remain classified in several countries.

Substantial progress has been made in magnetic fusion in the last decades. Three generations of magnetic devices (mainly tokamaks) led to a 10000 times better performance (characterized by the value of the fusion triple product – density times temperature times confinement time) in the last 40 years, approaching now reactor conditions (Wesson, 2004).

First large scale fusion experiments took place in the early 1990s. Several MW of fusion power have been released in a controlled way in deuterium-tritium experiments in JET (Joint European Torus, Culham, UK) and TFTR (Tokamak Fusion Test Reactor, Princeton, USA). Peak values of about 16 MW have been obtained on JET in 1997 corresponding to values for
the power amplification $Q_{DT}$ (i.e. the ratio of the power released from deuterium-tritium fusion reactions to the power applied to heat the fuel) close to 0.7. A summary of what has been achieved in high power D-T experiments is shown in Fig. I. In addition, ion temperatures up to 45 keV, which is about 30 times higher as that in the centre of the sun, have been achieved in Japanese tokomak JT-60U (Japan Atomic Energy Agency, Naka Fusion Institute, Naka, Japan) (Ishida and et al., 1997).

Magnetic fusion research has thus now arrived at the point where large amounts of fusion energy can be produced in a controlled way. The next step is to maintain a steady power output from fusion reactions in long pulses. To make this possible, superconducting coils for the magnetic fields will have to be used allowing in principle unlimited pulse lengths (evidently, as long as the coils are cooled below 4K). The use of superconducting coils has been very successfully demonstrated e.g. in Tore Supra (CEA-Cadarache, France) and the Large Helical Device LHD (National Institute for Fusion Science, Toki, Japan). Both machines have record length pulses at relevant plasma parameters in hydrogen and deuterium plasmas: 6 minutes and 30 seconds on Tore Supra in 2004 (Bucalossi and et al., 2005) and 54 minutes on LHD in 2007 (Mutoh and et al., 2007).

Magnetic fusion research entered a new era in 2005 with the international agreement (28 June 2005) on the construction site of ITER at Cadarache (close to Aix-en-Provence in France). Seven large nations are participating in the project: Europe, Russia, India, China, Japan, South Korea and the USA. Construction started in August 2010. First low fusion power experiments are projected for 2023, with high performance fusion plasmas around 2030 and pulse durations of 400s and longer, producing up to 500 MW of fusion power. In addition, Europe and Japan have launched a joint project called “Broader Approach” for exploring the next step device after ITER, which should be a first prototype of a fusion power reactor, producing power for the grid, and is called DEMO. The “Broader Approach” includes three research projects (JAEA, 2014):

a) the Engineering Validation and Engineering Design Activities (EVEDA) for the International Fusion Materials Irradiation Facility (IFMIF), a dedicated laboratory to be built in the near future to test candidate first wall materials / alloys for a future fusion power reactor (Knaster and et al., 2013)

b) the International Fusion Energy Research Centre (IFERC) in Rokkasho, close to Aomori, in Japan, for DEMO design and R&D (Nakajima and et al., 2012)

c) an upgrade of the tokamak JT-60U, termed JT-60 Super Advanced or JT-60SA (Kamada and et al., 2013)

Progress in inertial fusion progress has also been impressive. The National Ignition Facility in the US (NIF, Livermore, California), hosts one of the most powerful laser systems in the world. The NIF laser system consists of 192 individual beamlets that deposit the huge energy needed for the compression of the pellet in one thousandth of a billionth of a second. NIF was completed in 2009 and a recent important milestone has been reached on this facility (Hurricane and et al., 2014). The European counterpart to NIF is the Laser Megajoule (LMJ), an experimental ICF device being built near Bordeaux, France by CEA, the French nuclear science directorate. Laser Mégajoule is the largest ICF experiment being built outside the US
and uses a series of 240 laser beam lines, organized into eight groups of 30 beams. GEKKO XII is a high-power 12-beam laser system at the Institute for Laser Engineering in Osaka, Japan in use since 1983. The Osaka group has proposed a new concept, called fast ignition, using a Petawatt laser, and is now promoting this as the FIREX project (Azechi and et al., 2013).

Future plans in high power short pulse laser systems are ELI (Extreme Light Infrastructure) in Europe and GEKKO EXA in Japan. Both systems are intended to deliver the extreme energies in pulses that are thousand to one million times shorter than in NIF.

8.3 Fusion Fuel Resources

**Deuterium**, a non-radioactive isotope of hydrogen is extremely plentiful as it can be obtained from ordinary water (about 30 g from 1 ton (Friedman, 1953)) with cheap extraction techniques using conventional technology. Complete burning of deuterons and the first generation fusion products (T and $^3$He) results in the overall equation:

$$6D \rightarrow 2^4\text{He} + 2H + 2n + 43.3 \text{ MeV}$$

The amount of deuterium in seawater on earth is estimated at $4.6 \times 10^{13}$ tons, equivalent to a potential energy production of about $5 \times 10^{11}$ TWyr, i.e. 10 billion times the current world consumption per year.

**Tritium** is the radioactive isotope of hydrogen. It decays to $^3$He by emission of an electron:

$$T \rightarrow ^3\text{He} + e^- + 18.7 \text{ keV}$$

with the rather short half-life of 12.3 years. The quantities available in nature are not sufficient for technical applications and tritium will be produced in-situ using from a blanket containing Li compounds, according to the reactions:

$$^{6}\text{Li} + n \rightarrow ^4\text{He} \ (2.05\text{MeV}) + T \ (2.73\text{MeV})$$

$$^{7}\text{Li} + n \rightarrow ^4\text{He} + T + n - 2.47 \text{ MeV}$$

Thus the real consumables in the D-T fusion process are D and Li, while T is an intermediate product burned in the fusion reaction.

**Lithium**, like deuterium, is a widely available element. Estimated reserves of natural Li are about 29 million tons in known ore deposits and brines (Evans, 2008) and about 200 billion tons dissolved in sea water (0.1-0.2ppm) (Evans, 1978), equivalent to about thousand to a million times the current yearly energy consumption.
8.4 Safety Aspects

8.4.1 Inherent and passive safety

First, the amount of fuel available at each instant is sufficient for only a few tens of seconds, in sharp contrast with a fission reactor where fuel for several years of operation is stored in the reactor core. Second, fusion reactions take place at extremely high temperatures and the fusion process is not based on a neutron multiplication reaction. With any malfunction or incorrect handling the reactions will stop. An uncontrolled burn (nuclear runaway) of the fusion fuel is therefore excluded on physical grounds. Even in case of a total loss of active cooling, the low residual heating excludes melting of the reactor structure (Cook, 2001).

8.4.2 Minimal Radioactivity

The basic fuels (D and Li) as well as the direct end product (\(^4\)He) of the fusion reaction are not radioactive. However, a fusion reactor will require confinement and control of radioisotopes since it has a radioactive inventory consisting of (i) tritium and waste contaminated by tritium and (ii) reactor materials activated by the neutrons of the fusion reaction. Studies (Cook, 2001) indicate, however, that an adequate choice of the latter can minimise the induced radioactivity such that recycling should become possible after some decades to a century. Thus, radioactivity does not have to be inherent to nuclear fusion, in contrast to nuclear fission where the fission reaction itself leads to dangerous long-lived radioactive products.

The tritium cycle is internally closed, and the total tritium inventory in the fusion power plant will be on the order of a few kg. An evacuation of the public might not even be needed in case of an accident if a proper detritiation system is implemented. Special permeation barriers will have to be used to inhibit discharge into the environment of tritium diffusing through materials at high temperature (Cook, 2001). As tritium is chemically equivalent to hydrogen, it can replace normal hydrogen in water and all kinds of hydrocarbons. It could thus contaminate the food chain when released in the atmosphere. The absorption of tritium contaminated food and water by living organisms is a potential hazard. However, possible damage is reduced owing to the short biological half-life of tritium in the body of about 10 days.

8.4.3 Reduced proliferation risk

The operation of fusion reactors is not accompanied by the production of fissile materials required for nuclear weapons. Only a significant modification of the fusion reactor - the introduction of a special breeding section containing fertile material - would make the production of weapons grade fissile materials possible. However, the presence of such a section (in an environment where none at all should be present) could be easily discovered by qualified inspectors (IFRC, 1990).
8.5 Environmental Aspects

8.5.1 Environmental pollution?

The primary fuels (D and Li) and the direct end product ($^4\text{He}$) are not radioactive, do not pollute the atmosphere, and do not contribute to the greenhouse effect or the destruction of the ozone layer. Helium is in addition chemically inert and indispensable for superconducting applications. There are no problems with mining (Li) and fuel transportation. No ecological, geophysical and land-use problems exist such as those associated with biomass energy, hydropower and solar energy.

Measures for tritium containment and detritiation of substances contaminated with tritium will have to be taken. During normal operation the dose for the public in the neighbourhood of the plant will only be a fraction of the dose due to natural radioactivity.

8.5.2 Dangerous waste?

An important advantage of fusion is the absence of direct radioactive reaction products, in contrast to fission, where radioactive waste is unavoidable since the products of the energy releasing nuclear reaction are radioactive.

Adequate disposal of radioactive waste is especially difficult if the products are volatile, corrosive or long-lived. The neutron-activated structural materials of a fusion reactor would not pose such problems and because of their high melting point and their low decay heat, will not necessitate active cooling during decommissioning, transport or disposal. Studies (Cook, 2001) show that over their life time, fusion reactors would generate, by component replacement and decommissioning, activated material similar in volume to that of fission reactors but qualitatively different in that the long-term radio toxicity is considerably lower (no radioactive spent fuel).

Fusion could be made even more attractive by the use of advanced structural materials with low activation as e.g. vanadium alloys or silicon carbides. These materials offer in principle the prospect of recycling in about 100 years after the shutdown of the reactor as the radioactivity would fall to levels comparable to those of the ashes from coal-fired plants (Cook, 2001) (which contain always small amounts of thorium and other actinides). As already discussed above, there is a large research programme set up jointly between the EU and Japan to prepare the experimental investigation of properties of candidate alloys, with the IFMIF/EVEDA program.

8.6 Economic Aspects

It is obviously difficult to estimate with any useful precision the cost of a system that will only be put into service several decades from now. In comparison with other energy sources, environmental and safety-related advantages and the virtual inexhaustibility of the fuel sources should be taken into account, as well as the evolution of the cost of electricity based
on (exhaustible) resources. It is difficult at this point of time to estimate the likely cost of a commercial fusion power plant. Investment costs (reactor chamber, blanket, magnets, and percentage of recirculating power...) will probably be higher than current power plants, but the fuel is inexpensive and abundant. On the basis of present knowledge, technologically sophisticated power plants will probably have an electrical output larger than 1 GW to be economic. The fast neutrons produced in the D-T reaction could be used to produce fissile material in fusion-hybrid breeder reactors. This complementary role for fusion might improve system economics compared with pure fusion systems; however, it would increase societal concerns related to safety, environment and weaponry.

![Graph showing fusion power development in the D-T campaigns of JET and TFTR](image-url)

**Fig. 1** Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines) (Jacquinot and JET Team, 1999).
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