Economics of Nuclear and Renewable Electricity

Energy Science Coalition

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1. Introduction

Nuclear energy arose as a ‘spin-off’ from nuclear weapons. Its use grew rapidly during the 1960s, nurtured by huge subsidies and the belief that nuclear electricity would soon become ‘too cheap to meter’. According to the International Atomic Energy Agency, at the end of 2009 there were 438 operating nuclear power reactors in the world, total generating capacity was about 371 gigawatts (GW) and annual generation about 2600 terawatt-hours (TWh). Since 2005 the number of reactors, installed capacity and annual generation have all stabilised.[1] The contribution of nuclear energy as a percentage of total global electricity has declined rapidly through the 2000s, falling to 14% in 2007.[2,3] Concerns about hazards and unfavourable economics have stopped the growth of nuclear energy in all but two Western countries, Finland and France. In the USA, no orders for nuclear power stations placed after 1978 have been completed and all plants ordered after 1973 have been cancelled. However, there is still growth in nuclear energy in several other countries, notably China, Russia, India and South Korea. The general decline in global nuclear energy is likely to accelerate as many aging reactors are retired over the next 15–20 years. Lack of growth is already affecting the economics of nuclear energy, because there are declining numbers of manufacturers of key components and of nuclear engineers and technicians[4].

Table 1: Countries with the highest percentage of nuclear energy generation, 2009

Country	Share of electricity (%)	Reactors under construction
France	76	1
Slovakia	56	2
Belgium	54	0
Ukraine	47	2
Sweden	42	0
Slovenia	42	0
Switzerland	39	0
Armenia	39	0
Hungary	37	0
South Korea	36	5
Bulgaria	33	2
Czech Republic	32	0

Source: Schneider et al. Nov.-Dec.2009[3]. The present author has omitted Lithuania, because its only operating nuclear power station was shut down in late 2009.

The principal nuclear power countries, in terms of percentage of electricity supplied, are shown in Table 1. For comparison, Japan has 25%, the USA has 20%, the UK has 13% and China and India each have 2%. The principal nuclear electricity generation countries, with 2008 generation in TWh, are USA (809), France (418), Japan (241), South Korea (144) and Germany (141).

This paper addresses the economics of nuclear energy and its alternatives. It commences from the fundamental value-laden position that, in the face of global climate change from greenhouse gas emissions, new conventional coal-fired power stations should not be an option. This position is based on the assessment by leading climate scientists that all coal-fired power stations without carbon capture and storage should be phased out by 2030.[5] While conventional coal-fired power stations are still being built in some countries, there is a growing social movement against them, many orders have been cancelled and investors are losing interest, especially as carbon prices are being introduced or foreshadowed in several countries and states or provinces within countries. Therefore, the choice of new electricity generation technology is not between nuclear and coal, but instead is between nuclear and a combination of energy efficiency and renewable energy, with gas playing a transitional role as back-up.

The paper is written for an international audience, while giving brief indications of how the general results may be applied to Singapore as a particular case. The paper first summarises, in section 2, the technological status of various low-carbon electricity generation technologies, a necessary prerequisite to any economic analysis. If a technology is still at the R&D stage or the early demonstration stage, there is little basis for any credible economic estimates. Then section 3 examines nuclear energy economics, as far as it can be determined, for semi-commercial (generation III) and commercial (generation II) nuclear technologies. Section 4 reviews the economics of the non-fossil alternatives, energy efficiency and renewable energy, again focusing on semi-commercial and commercial technologies. Section 5, the conclusion, summarises the answers to the questions posed by the workshop organisers.

2. Status of electricity generation technologies

Various nuclear power and renewable electricity (RElec) technologies are currently at different stages of development and commercialisation, as shown in table 2. The boundaries between the different stages are somewhat fuzzy, progression between stages is not always smooth and some technologies (or types of technologies) fail on the pathway to the commercial stage. Nevertheless, this classification shows which technologies are ready for rapid expansion to the commercial stage, or are already there, and can be costed.

2.1 Commercial stage

'Commercial' is not defined here in terms of economic competitiveness, because this depends on government policies, such as a carbon price, a renewable energy target or feed-in tariffs. Such policies can be seen as means of compensating clean technologies for the failure to include the environmental, health and social costs of fossil fuels in the latter's prices. So 'commercial' describes an optimised system in mass production that can be ordered and installed at a fixed price. Included in this category are generation II nuclear power (although the commercial classification is debatable since, even after 50 years of experience, very few systems have been successful constructed on time and within budget[6]); biomass combustion; conventional PV based on silicon crystals or amorphous silicon; conventional geothermal and tidal; and, on the demand side, solar hot water and many energy efficiency technologies.

2.2 *Precommercial stage*

This stage has strong input from production engineers and involves limited mass production. Although some further evaluation and optimisation of design may still be required, this stage allows approximate cost estimates to be made.

For example, two different types of concentrated solar thermal power station (trough and central receiver systems) are in the precommercial stage in Spain and the USA. Also one type of thermal storage being used in Spain (molten salt) is precommercial. Since several hundred megawatts (MW) of these technologies are operating successfully and several thousand MW are under construction and being planned, these technologies are precommercial and are on the brink of being commercial. However, there is less experience with several alternative collector systems (eg, Compact Linear Fresnel and big dishes) and alternative storage systems (eg, graphite blocks; dissociation of ammonia into nitrogen and hydrogen), and so these are considered to be still at the demonstration stage. While the existing Spanish systems could be mass-produced in many countries, they could ultimately turn out to be slightly less efficient than some of the alternatives that are being developed elsewhere. Concentrated solar thermal power stations still need optimisation of various features and the whole system to make them fully commercial. This is very likely to happen within a few years. Generation III nuclear power stations are at the precommercial stage, because of the absence of any operating experience and the huge cost overruns with the Areva reactors under construction in Finland and France.

Table 2: Global status of electricity supply and energy efficiency technologies

Stage of development	Explanation of stage	Technology
Research & development	Experimental technology or systems on laboratory or small field scale; not designed for mass production	Novel PV; some advanced batteries; coal+CCS; integral fast reactor with pyroprocessing; nuclear fusion
Demonstration	Only a few medium-scale units exist; designed with future mass production in mind	Wave; ocean current; advanced batteries other than those in 'R&D'; some fast neutron reactors (GenIV); hot rock geothermal; solar thermal electric other than those in 'precommercial'
Precommercial	Limited mass production; some optimisation of design still required	Solar thermal electric (trough and central receiver) with thermal storage; off-shore wind; micro-scale CHP; trigeneration; GenIII nuclear
Commercial	In large-scale mass-production. 'Commercial' does not necessarily mean 'economically competitive with dirty coal power', since competitiveness is determined by government policies (eg, on carbon pricing).	On-shore wind; conventional PV; biomass co-firing and direct combustion; landfill gas; large and small hydro; conventional tidal; large-scale CHP; conventional geothermal; 1st generation biofuels; GenII nuclear; conventional coal and gas power; many energy efficiency technologies

Note: CCS is carbon capture and storage; PV is solar photovoltaic; CHP is combined heat and power; Gen is generation.

Source: the author's adaptation of Foxon 2005[7].

2.3 Demonstration stage

This stage shows how the concept would work on a larger scale than R&D, while considering some of the design requirements of future mass production. Economic estimates made on technologies at the demonstration stage have a wide range of uncertainty. At the demonstration stage are fast neutron reactors, hot rock geothermal, wave power, ocean current power and second-generation biofuels based on lignocellulose. Fast neutron reactors have been stuck at the demonstration stage for decades as a result over poor performance, fires, partial meltdowns, other breakdowns and enormous costs. The MIT report considers that they will not be commercial before 2030, if ever[8].

2.4 Research and development (R&D) stage

This stage is to prove the concept. Therefore the technology used in this stage has very little resemblance to the final product that could enter the market. There is no credible basis for any serious economic assessment of technologies in the R&D stage. At this stage are some novel types of photovoltaic cells, generation IV nuclear reactors (eg, integral fast reactor and thorium reactor systems), some types of advanced batteries, and carbon capture and storage. Although fast neutron reactors are at the demonstration stage, the integral fast reactor, which has an experimental type of system for reprocessing spent fuel called pyroprocessing, is still at the R&D stage. South Korea is planning R&D on the integral fast reactor with pyroprocessing to last until 2028[9].

2.5 Implications

Technologies at an early stage (R&D; demonstration) cannot simply be rushed into mass production without substantial risks of technological failure, financial losses and, in some cases, major environmental and health hazards. The technologies of greatest interest for rapid development are those at the pre-commercial and commercial stages, together with some of the simpler technologies that are performing well at the demonstration stage.

Generation IV nuclear power stations (eg, integral fast reactor; thorium breeder system; pebble-bed reactor) are still at the R&D stage, while fast reactors with conventional reprocessing are still at the demonstration stage. It could be 2030 before they are commercially available. With the possible exception of the pebble-bed reactor, they are more complex than existing generation II reactors and are therefore likely to be even more expensive. Reprocessing of spent fuel would certainly add substantially to cost. No credible economic estimates are possible for these systems at their current early stages of technological development.

Generation III reactors (eg, Areva European Pressurized Water Reactor; Westinghouse AP1000) are under construction in several countries and can at best be considered as semicommercial. Experience with construction of the Areva EPR in Olkiluoto, Finland, outlined in section 3.4, does not give grounds for confidence that this reactor will be commercial soon. Four AP1000 reactors have been contracted to China and two are under construction. China has also signed a contract with Areva for two of its reactors.

However, China does not readily provide verifiable information about costs and performance.

Even the current generation II nuclear power stations have long planning and construction periods[10]. For countries that do not already have nuclear energy, the first power station and associated infrastructure could take 15 years to plan, build and commission. This in turn leads to high levels of interest during construction (IDC). This is another reason why nuclear energy is so expensive. Generation II and III nuclear power stations are huge construction projects.

In contrast, most of the improvements in efficiency of energy use and several of the renewable energy technologies have very short construction periods. For example, large wind farms, solar power stations and small bioenergy plants can be planned, approved and installed in less than two years. This is because most of the components of RElec systems can manufactured and site works are a minor part of the process. Exceptions are large-scale hydro-electric and conventional tidal power stations.

The following RElec technologies are likely to have low potential in Singapore: concentrated solar thermal power (because of the prevalence of diffuse instead of direct sunlight) and wind power (because of limited resource). The grid could only accept a small nuclear power station. Technologies of potential rapid growth in Singapore are energy efficiency; solar hot water; cogeneration and trigeneration fuelled by natural gas or gaseous and liquid biofuels; solid biomass combustion (or gasification followed by combustion); solar photovoltaics based on flat collectors; and geothermal heating and cooling. For the longer term, the potential for geothermal electricity and marine technologies (wave and ocean current) may deserve further investigation. International transmission links within the ASEAN region could also play a valuable role, especially for trading renewable energy.

3. Nuclear economics

3.1 Limited economic data

A report to the UK Sustainable Development Commission points out difficulties of obtaining objective data on the economics of nuclear power:

> There are few sources of data on the costs of future nuclear power that relate directly to UK circumstances…The problematic category is capital costs, where there is no recent European or North American experience. Examination of the limited number of published capital cost estimates that apply directly to the UK shows that all appear to derive from studies originally designed to apply to other countries *and from vendors of reactor systems*.[11] (my italics)

It is risky to accept manufacturers' estimates of capital costs and to sign a contract that does not specify a fixed cost, yet that is what some purchasers do.

Other problems arise because some studies fail to identify the discount rate used to convert capital cost in dollars per kilowatt ($/kW) into a levelised cost of electricity in cents per kilowatt-hour (c/kWh); some studies address new or modified types of reactors that are only in the design stage and have not been built; some studies do not specify the year of the currency; most studies do not reveal whether they assume that a single reactor or a batch of identical reactors is ordered; and few studies take into account the costs of waste management and decommissioning. Comparisons between countries are confused by changes in currency exchange rates. Costs are sensitive to all of these assumptions. The only countries where detailed data are available on the costs of nuclear energy are the UK and the USA, discussed below.

3.2 Method of levelised costs

How do we go from a capital cost expressed in \$/kW to a cost of energy expressed in c/kWh? A standard method for various electricity sources, with various capital costs, lifetimes, capacity factors (average power output divided by rated power) and discount rates, is the levelised annuity formula[12]:

$$\textit{Cost of energy in c/kWh} = \frac{\textit{100 x capital cost in \$/kW x R}}{\textit{(8760 x capacity factor)}} + \textit{(operating cost in c/kWh)} \qquad [1]$$

where 8760 is the number of hours per year and R is the capital recovery factor, which is determined by the discount (real interest) rate and lifetime of the power station. For example, if we take a discount rate of 0.08 (8% per year) and lifetime of 30 years, then R becomes 0.089. If the nuclear capital cost including interest during construction is \$6000/kW, the operating cost (fuel + operation + maintenance) is 2 c/kWh and the capacity factor is 0.8, then the cost of electricity becomes 9.6 c/kWh. However, for a capital cost of \$8000/kW, the midrange value of estimates by Wall St and independent consultants (see section 3.3), the cost of energy increases to 12.2 c/kWh. More precise calculations would have to consider the details of financing, for example, the proportions of debt and equity, for each power station.

3.3 Nuclear economics in the USA

Despite huge subsidies (see section 3.7), the USA has not had a new nuclear power station for over 30 years. This has been attributed primarily to poor economics[13], although the accident at Three Mile Island in 1979 and the anti-nuclear movement may have played roles.

In 2003, a pro-nuclear study, *The Future of Nuclear Power,* by an expert interdisciplinary group from the Massachusetts Institute of Technology (MIT), ignored the UK experience and even much of past US experience, making several optimistic assumptions about future capital and operating costs. With an assumed 'overnight' capital cost (defined below) of US\$2000/kW, a capacity factor[14] of 85% and a lifetime of 40 years, it found the estimated cost of electricity from a hypothetical new nuclear power station to be US 6.7 c/kWh[15], increasing to US 7.5 c/kWh for a capacity factor of 75%. Although the report stated that financing was done under market conditions, the interest rate chosen to repay the debt was surprisingly low at 8% nominal or 5% real, giving an advantage to nuclear power in comparison with fossil fuels.

In 2007, in a study sponsored by nine vendors and purchasers of nuclear power stations, the Keystone Center, estimated the costs of electricity from hypothetical new nuclear power stations in the US to have risen to 8.3–11.1 US c/kWh. The increases came mainly from increased capital costs to a range of US$3600–4000/kW[16]. Shortly afterwards a study by Harding estimated capital costs at US$4300–4550/kW in 2007 US dollars[17]. In 2008, Moody's estimated $7500/kW[18]. A 2009 study by CA Severance estimated $7400/kW. Severance identified large escalations in the capital costs of hypothetical new nuclear power stations in the USA. Taking into account interest as well as price escalations during construction, Severance set out all his assumptions explicitly and found that the projected capital cost could be as high as $10,500/kW and nuclear electricity generation costs could be in the range US 25–30 c/kWh[19], comparable to electricity from solar photovoltaic (PV) power stations. Some of these results are summarised in Table 3 and Figure 1. This figure shows a clear trend of overnight capital cost escalation in real terms among nuclear power stations through the 1980s and into the 90s, while the studies listed in Table 3 suggest rapid cost escalation during the 2000s. Lovins attributes these to 'severe manufacturing bottlenecks and scarcities of critical engineering, construction, and management skills that have decayed during the industry's long order lull'[20].

Table 3: Nuclear power capital cost escalation, USA, 2003–2009, selected studies

Study or actual reactor	Capital cost (US$/kW)
Ansolabehere et al. (2003) MIT	2000 + IDC
Keystone Center (2007)	3600–4000
Harding (2007)	4300–4550
MIT (2009) update	4000 + IDC
Moody's (2008)	7500
Severance (2009)	7400 with no further escalation; 10,500 assuming current escalation rate continues
Olikiluoto 3 reactor, Finland, under construction	5188 so far

Note: IDC is interest during construction. References are cited in the text

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As shown in figure 1, overnight cost estimates by Wall St and independent analysts range from $6000 to $10,500/kW, much higher than those of early consultants and utilities. Actual capital costs, including IDC and costs escalation, will be even higher. Assuming conservatively that these additional costs add 15% to overnight costs[21] lifts this capital cost range to $6900–12,075/kW. Keeping the same assumptions as in section 3.2 gives a cost of energy range of 10.8–17.3 c/kWh.

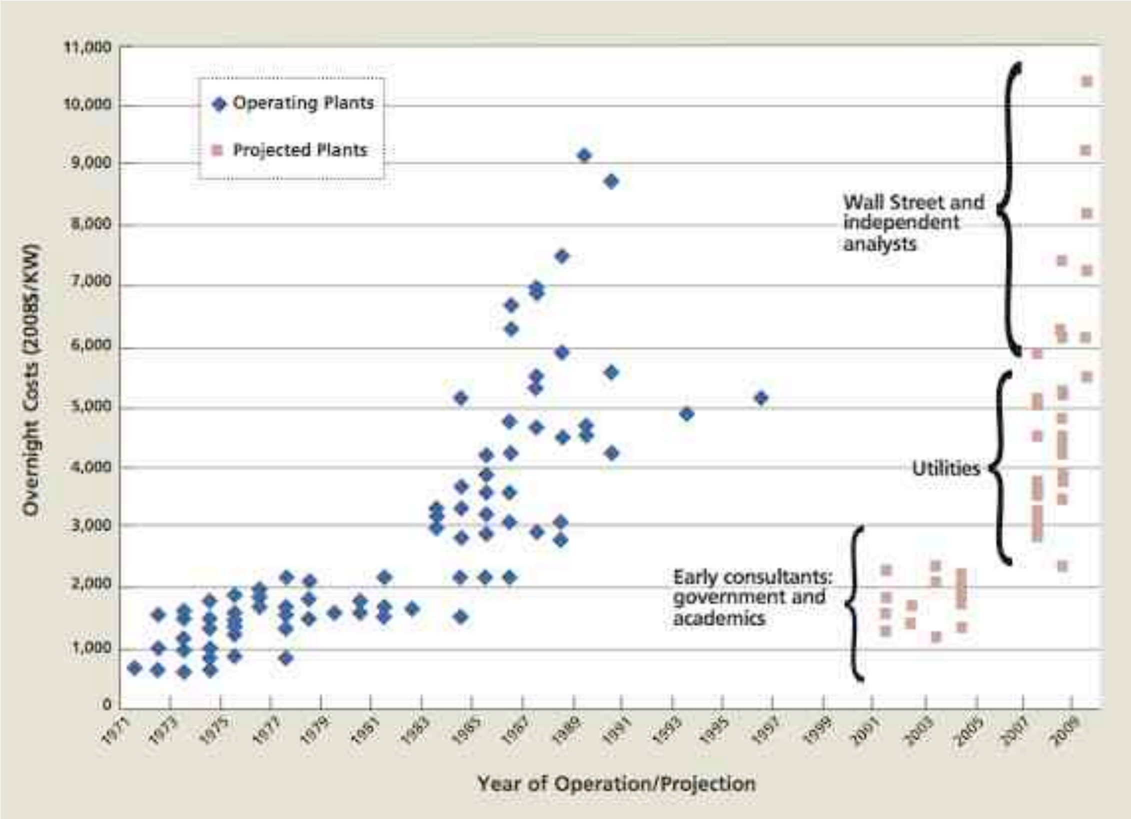

Figure 1: 'Overnight' capital costs for operating and new US nuclear power stations

Source: Cooper 2009[22], reviewing numerous studies.
Note: 'Overnight' cost does not include financing costs, dominated by interest during construction (IDC), and cost escalation during construction. For nuclear power, the full capital cost may be 15–50% higher than the overnight cost.

In recent years, operating costs in the USA have been quite low, around 2 c/kWh, but this is partly because high capacity factors have been finally achieved after decades of poor performance and partly because the government assumes responsibility for the disposal of spent fuel for the nominal fee of 0.1 c/kWh.[23]

3.4 Nuclear economics in the UK

The British experience has characterised by several changes to the types of reactor ordered, leading to consistently high costs. The last British nuclear power station to be built, Sizewell B, ended up with a capital cost of £2500/kW adjusted to 2005 British currency[24]. This demonstrates the financial risks involved.

In recent years operating costs have been 3–4 p/kWh (US 4.5–6 c/kWh), much higher than in the USA, because much spent fuel was reprocessed in the UK.[25]

As recently as 2003, the British White Paper on Energy stated that 'the current economics of nuclear power make it an unattractive option for new generating capacity'[26]. However, UK's electricity generation system is now mostly owned and controlled by French and Germany utilities – EDF, E.ON and RWE – some of which have large involvements in nuclear energy. So it is likely that their influence is responsible for the recent change in the UK government's position towards acceptance of more nuclear power stations.

3.5 Nuclear economics in Finland

Finland receives special mention here, because one of only two[27] nuclear power stations under construction in a western country in 2010 is the Olkiluoto-3 reactor in Finland. This is Areva's so-called generation III+ reactor. The nuclear industry has claimed that the commencement of this project demonstrates that nuclear energy is competitive in under market conditions. But independent commentators point out that the power station is being built by a consortium that includes a 40 per cent share by the government of Finland and that it will sell its electricity to members of its own consortium. Therefore it will not operate under conditions of a competitive market and so it can obtain finance at interest rates far below market rates. Construction commenced in 2005 and by late 2009 it was more than three years behind schedule and its capital cost, including interest during construction, had escalated by at least €1.7 billion.[28]

3.6 Misleading presentations of nuclear economics

Claims by the industry that nuclear energy is cheap in countries other than the UK and USA are often unverifiable bottom-line results or 'justified' by analyses with hidden assumptions that are highly favourable to nuclear power, for example:

Because nuclear energy has a high capital cost and low operating cost, choosing an unrealistically low interest or discount rate[29] can make nuclear energy look much less expensive. This is illustrated particularly clearly by the first comparative electricity generating cost study published jointly by the International Energy Agency and the OECD Nuclear Energy Agency, both widely regarded as pro-nuclear. With a realistic discount rate of 10% real per annum, there were no countries out of 18 studied where nuclear energy was cheaper than either coal or gas. However, when an unrealistically low 5% real discount rate was chosen, nuclear energy was claimed to be the cheapest in 5 out of 18 countries.[30] Even the results for a 5% discount rate could be over-optimistic, because the data are supplied to the OECD by the nuclear industry itself and are not open to objective verification. Nuclear power economic studies generally choose unrealistically low discount rates. Incidentally, the 2010 report in this IEA/NEA series includes a carbon price of $30/tonne to boost nuclear economics relative to fossil fuels. Furthermore, it attempts to make European wind power look much more expensive than it really is by using data from Switzerland, a country that has harsh climatic conditions for wind power, very few megawatt-rate wind turbines and no wind farms larger than 4 MW.

Another means of disguising the high annualised capital cost of nuclear energy is to chose accounting methods (eg based on historical costs) that shrink the capital cost component. This device was used in the UK in the years before electricity industry restructuring[31].

Making over-optimistic assumptions about operational performance, as measured by capacity factor of the nuclear power station, is another method. Nuclear proponents often choose as typical the year with the highest capacity factor (average power divided by rated power), instead of averaging the capacity factor over the lifetime of the station. An omission from most studies is the opportunity cost of land forming the exclusion zone around the nuclear power station and other nuclear facilities.

When comparing coal and nuclear power as potential competitors for base-load operation, the nuclear industry often assumes that coal is operated as intermediate-load (that is, for less time per year) while nuclear is base-load, thus assigning a lower capacity factor to coal. This is obvious inappropriate when considering different energy technologies as competitors for base-load (24-hour) power.

Ignoring the huge subsidies from government to nuclear energy also makes the technology look less expensive.

3.7 Subsidies to nuclear energy

Varying in quantity and type from country to country, these subsidies include R & D, uranium enrichment, decommissioning, waste management, stranded assets paid by ratepayers and taxpayers, limited liabilities for accidents and loan guarantees. Subsidies entail that risk is not properly allocated in the market and the true economics of nuclear energy is masked[32]. Comprehensive quantitative data on subsidies are incomplete and difficult to obtain.

In the USA, subsidies are estimated to have accumulated over the 50-year period 1948 to 1998 to about US$74 billion[33] or around US$100 billion in 2006 currency. Another report found subsidies to US nuclear power to be about $9 billion per year in 2006.[34] In the 2000s the G.W. Bush government allocated loan guarantees worth many tens of billions of dollars[35]. In 2010 the Obama government allocated an additional $8.2 billion in loan guarantees for two new proposed nuclear power stations.

In Germany, a recent study commissioned by Greenpeace found that total (direct + indirect) subsidies from 1950 to 2008 amounted to 165 billion euros (US$235 billion).[36]

When the UK electricity industry was privatised, the British Government had to impose a levy on electricity prices, called the Fossil Fuel Levy, to subsidise nuclear electricity through the Non-Fossil Fuel Obligation (NFFO). In the 1990s this subsidy peaked at £1.3 billion per year[37], equivalent to a subsidy of 3 p/kWh, making the total cost of nuclear power at that time about 6 p/kWh (9 c/kWh). In addition, the UK Nuclear Decommissioning Authority has estimated that the cost of decommissioning existing nuclear power stations to be about £70 billion. In 2006 the UK Chancellor announced that Treasury had increased this estimate to £90 billion[38].

There is also some discussion on subsidies within the EU on the WISE/NIRS website[39].

3.8 Checklist for governments

Governments considering a nuclear power station as a possible future option are advised to consider the following issues:

- Realistic assessment of the capital and operating costs of the power station, plus the costs of associated infrastructure.
- Extreme caution about signing a contract with a supplier that declines to specify a fixed cost.
- Management of high-level nuclear wastes.
- Decommissioning the power station at the end of its operating lifetime.
- Sources of uranium.
- Is there a suitable location in a geologically stable region at least several metres above current sea-level with access to a high-voltage transmission line and sufficient land for an exclusion zone?
- Either a source of vast quantities of cooling water or provision of additional funds for air cooling the reactor.
- Security against terrorism.
- Back-up for periods of forced outage.
- Education and training of staff for operation and maintenance. In particular, can a culture of safety be created?
- Have safer alternatives been considered properly?

4. Alternatives to nuclear energy

At present nuclear energy is only used to generate electricity. Globally, most electricity is generated by burning coal, followed by natural gas. So, until electric vehicles become prevalent, nuclear energy cannot be marketed honestly as part of the solution to peak oil.

The alternatives to nuclear energy, that may be economically feasible and low in environmental impact, are:

(i) measures that reduce the demand for electricity, such as efficient energy use, energy conservation and solar hot water;
(ii) renewable sources of electricity of low to moderate cost;
(iii) natural gas, especially cogeneration and trigeneration plants, combined with renewable energy;
(iv) transmission lines from neighbouring countries with excess power to sell.

4.1 Reducing electricity demand

The wide range of technologies and measures for improving the efficiency of energy use are the cheapest and fastest to implement. This approach can yield large electricity savings and very large savings in primary energy at zero or negative net costs. Negative energy efficiency costs are well established and result from market failures, such as split incentives between landlords and tenants, and transaction costs that could be easily removed by appropriate government policies, such as restructuring energy utilities to become energy service providers[40],[41]. In substituting for base-load thermal power stations, every unit of electricity saved substitutes for about three units of primary energy at the power station. If the primary energy is the chemical energy stored in coal, the reduction in greenhouse gas emissions is substantial. Furthermore, the economic savings from efficient energy use can pay for a large proportion of the additional costs of low-carbon electricity supply. [42,43]

In each of many regions, several base-load power stations (both coal and nuclear) are operated between midnight and dawn solely to heat water via electric resistance heating. Substituting solar, gas and electric heat pump hot water, together with some additional grid-connected gas and renewable power during the daytime, could significantly reduce the demand for base-load electricity and enable some existing base-load power stations to be retired and proposed new stations to be delayed or cancelled.

All the measures mentioned in section 4.1 are generally much less expensive than nuclear electricity.

4.2 Renewable electricity supply

These are listed in order of increasing cost. The technologies are described in more detail elsewhere.[44,45,46]

- Hydro-electricity, both large-scale and small-scale. It should be noted that large-scale hydro generally has large environmental impacts and may also displace large numbers of people from their land. Hydro-electricity based on large dams flooding large vegetated areas can produce greenhouse gas (methane) emissions similar in impact to the CO_2 emissions from an equivalent coal-fired power station.
- Wind power at suitable sites. In South-East Asia, there may be some limited potential on coastal sites, but very low potential inland.
- Bioenergy, in particular, burning organic residues to generate electricity and heat. Cogeneration and trigeneration are efficient forms of energy generation from biomass (see section 4.3). There is large potential for bioenergy in South-East Asia.

The above three sources are commercially available and at suitable sites are generally less expensive than nuclear energy as shown in table 4.

Another commercially available source of renewable electricity is solar photovoltaic (PV) power, which is still expensive for urban/suburban residential and commercial use, although it is often the most appropriate electricity source for small-scale uses in locations remote from the grid and for a wide range of niche uses everywhere. Prices will be much lower within a decade, as the recent advances made in laboratory (e.g. thin films; crystalline silicon on glass; Sliver cells) enter the market on a large-scale. In doing the economics of PV installed at the point of use, it should be noted that it competes with the *retail* price of grid electricity, not the wholesale price. The retail price can be 2–4 times the wholesale price. This means that residential PV is already close to being economically competitive in southern Europe and several other countries with high insolation (sunlight levels) and high retail prices of grid electricity.

Concentrating solar thermal electricity is rapidly expanding from a small base in the USA and Spain. In the USA a first generation solar thermal power station of 354 megawatts electrical (MWe) has been operating for over 20 years in the Mojave Desert, with 70% of its output from the Sun and 30% from natural gas back-up. At the time of writing (March 2010) several smaller second generation solar thermal power stations are also operating. In Spain at least 181 MWe of generation II solar thermal power plant is operating and about 800 MWe is under construction in 2010. Some stations have thermal energy storage of up to 7.5 hours of full capacity in molten salt and a power station with 16 hours of storage is under construction. In principle, 24-hour storage is feasible and solar thermal power can be operated either as base-load, intermediate-load or peak-load, depending on the amount of storage installed and electricity prices at various times of day. Since solar concentrators only focus direct sunlight, these systems are less efficient in capturing sunlight in moist tropical areas where much of the sunlight is diffuse.

Conventional geothermal power has been operating for decades in volcanic regions such as the Philippines, Iceland and New Zealand. Indonesia has much untapped potential. However, on a global scale conventional geothermal power is limited geographically. A much larger potential source is known as hot rock, enhanced or engineered geothermal power, in which wells are drilled 3–5 km down into rocks that have been heated for millions of years primarily by the decay of traces of radioactive elements. Currently, electricity is being generated from hot rock geothermal power at small prototype power stations, each rated at 1–6 MWe, in France and Germany, and at a 19 MWe demonstration plant in Nevada, USA[47]. A 25–50 MWe demonstration plant is planned to be operational in Australia in December 2013[48]. The potential for both conventional and hot rock geothermal power could be explored further in South-East Asia.

Other technologies, still at the demonstration stage, that have some potential for coastal regions, are ocean current power and wave power.

4.3 The role of gas

On the pathway to a renewable energy future, gas is a valuable transitional fuel, both as a source of electric power in its own right and as a back-up or partner to renewable energy power stations. 'Gas' means both natural gas and coal seam methane.

If gas is used on its own to generate base-load electricity in a combined-cycle power station, its greenhouse gas emissions from operation are typically about 400 g/kWh, compared with 800–1400 g/kWh for coal and 13–40 g/kWh for the full life-cycle emissions from RElec sources. In a greenhouse-constrained world, this level of emissions from gas is still problematic. Much lower greenhouse intensity can be obtained by capturing the waste heat from gas combustion for residential and industrial heating and cooling. These systems are known as cogeneration (combined heat and power) and trigeneration (combined heat, power and cooling). Further reductions in emissions can be achieved by substituting for some or all of the gas with gaseous and liquid biofuels produced in an environmentally sustainable manner: eg, biogas from wet organic wastes; first generation ethanol produced from sugars; second generation ethanol produced from lignocellulose; and biodiesel produced from oil seeds. It must be emphasized that there is no environmental advantage in producing biofuels by clearing native forest, a method that actually results in higher greenhouse gas emissions than burning fossil fuels[49].

Gas is also a very suitable back-up or booster for solar hot water, solar thermal electricity and wind power.

Gas is an excellent substitute for all the principal uses of oil (transport fuel, power generation and feedstock for petrochemicals. Considering that the world is close to the peak in oil production[50], gas will become scarcer and more expensive over the next several decades. Fortunately, biofuels can be used in existing technologies for combusting oil and gas with only minor modifications.

4.4 Regional cooperation by transmission links

Energy resources – whether they be fossil fuels, uranium or renewable energy sources – are not distributed uniformly over the planet. Hence cooperation by international trading can lead to mutual benefits. The European Wind Energy Association has recommended the development of an off-shore trans-Europe electricity transmission 'super-highway' that would be particularly valuable for increasing the penetration and distribution of wind power[51]. In a separate scheme, a consortium has been formed to investigate the possibility of generating vast amounts of solar and wind energy in North Africa and transmitting it by undersea cable into the European grid[52].

There may also be potential for electricity trading in the ASEAN region to distribute more widely the region's large hydro-electric and geothermal potential.

4.5 Economics of the renewable energy

As in the case of nuclear power, there are big variations in the costs of RElec by country and by site within country. However, for large-scale non-hydro RElec, planning and construction periods are generally short (2–3 years), IDC is generally low and so the 'overnight cost' is generally quite a good first approximation to the capital cost.

Table 4 summarises estimates made in 2008 by the US National Renewable Energy Laboratories (NREL) for the 'overnight' capital costs of various RElec and other technologies expressed in 2006 US dollars per kilowatt of rated capacity[53]. The results for each technology are averages over several studies. To make the comparison more meaningful, the table also gives the overnight capital costs in US dollars per average kilowatt generated, which takes capacity factors into account. Even in this case care must be taken in making comparisons: for instance, base-load plants can only be compared with other base-load plants; fuel costs are substantial for gas-fired generation; interest during construction (not included in the table) can be very high for nuclear and large hydro, and very low for wind and solar; renewable electricity prices are generally declining in 2009–20010, while nuclear prices are increasing. On the basis of table 4 and known fuel, operation and maintenance costs, nuclear is already more expensive than many demand reduction technologies and measures, landfill gas, wind, conventional geothermal, and base-load biomass combustion of agricultural and forestry residues.

Table 4: 'Overnight' capital costs of new RElec and other electricity generation technologies in $/rated kW and $/average kW generated

Technology	**Overnight capital cost** ($/kW rated)	**Capacity factor**	**Overnight capital cost** ($/kW av)
Gas turbine, open-cycle	875	0.1	8750
Gas, combined-cycle, intermediate-load	930	0.5	1860
Gas, combined-cycle, base-load	930	0.8	1163
MSW Landfill gas	2056	0.8	2570
Hydro, peak-load	2343	0.1	23,430
Hydro, intermediate-load	2343	0.5	4686
Coal, pulverised fuel	2749	0.8	3436
Wind onshore	1679	0.3	5597
Wind offshore	2879	0.45	6398
IGCC	3052	0.8	3815
Geothermal, conventional	3201	0.8	4001
Biomass, base-load	3294	0.8	4118
Biomass, intermediate-load	3294	0.5	6588
Solar thermal, no storage	4550	0.2	22,750
Nuclear	4933	0.8	6166
Solar PV, no storage	5578	0.2	27,890

Notes: Overnight capital costs (column 2) are averages over several studies summarised by NREL[53]; they are in 2006 US$; capacity factors (column 3) depend on operational strategy and location and are from the author who has estimated lifetime averages which are less optimistic than NREL's figures for all technologies; column 4 = column 2 divided by column 3.

In 2010, Clean Edge, the research and publishing firm devoted to clean-tech, reported that big reductions had occurred through 2009 in typical installed market prices of wind power (from $1900/kW to $1700/kW) and solar PV (from $7000/kW to $5120/kW, with some utility scale projects as low as $3000/kW)[54].

Based on these and other data, Table 5 gives the author's estimates for ranges of values for the prices of energy for various technologies from very good US sites in 2010 and projections for 2020. Much of the variation in prices is due to variations in siting and size of installation.

Table 5: Cost of energy from RElec ordered in 2010 and in 2020 (projected)

RElec technology	Cost of energy in 2010 (c/kWh)	Cost of energy in 2020 (c/kWh)	Comment
Energy efficiency	-4 – 0	-2 to +4	Large economic potential, provided market failures addressed
Landfill gas	2–4	2–4	Tiny resource
Solar hot water	4–6	3–5	
Wind (on-shore)	7–11	5–8	
Biomass residue combustion	8–16	8–12	
Geothermal (conventional)	4–6	4–6	Geographically limited resource
Geothermal (hot rock)	n/a	8–12	Large resource; cost will decline post-2020
Wind (off-shore)	15–25	8–12	
Solar thermal	20–30	10–15	With thermal storage
Solar PV (power station)	20–30	12–20	
Solar PV (residential)	30–50	15–25	Competitive with some projected retail electricity prices in 2020

Sources: The author, based partly on Diesendorf 2007, Cooper 2009, NREL 2009 and Clean Edge 2010.
Notes: Fixed 2010 US currency; discount rate 8% real.

5. Conclusion

Since there is negligible operating experience with generation III and IV nuclear power stations , there is no basis for estimating their economics. We are left with generation II.

Despite 50 years with huge accumulated subsidies, the true economic costs of generation II nuclear energy are consistently far higher than admitted by proponents, who use misleading presentations to hide its very high capital costs. The vast majority of nuclear power stations built to date have been over time and over budget. Furthermore, since 2003 the estimated capital cost of new nuclear power stations has escalated much more rapidly than the capital cost of renewable electricity, with one recent estimate of the projected cost of new nuclear electricity being comparable with that of solar PV power stations.

At a midrange 'overnight' capital cost of $6000/kW, nuclear electricity cannot compete economically with efficient energy use, solar hot water, landfill gas, conventional geothermal power, cogeneration fuelled by gas, on-shore wind power at high-wind sites or bioelectricity from agricultural and forestry residues. By 2020, the retail price of nuclear electricity delivered to residential consumers may not be able to compete with residential PV electricity in many countries or with concentrating solar thermal power at sites with a high level of direct insolation. Furthermore, it's possible that other promising alternatives that are still at the demonstration stage – hot rock geothermal power, ocean current power and wave power – could also be less expensive than nuclear energy by 2020.

Because nuclear power stations are gigantic construction projects with very limited prospects for mass production of large components, the rapid growth of nuclear energy is impossible. Embarking upon a nuclear energy program entails very large economic risks and potential losses of billions of dollars per reactor compared with a mix of energy efficiency, renewable energy and gas.

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