

Comparing the Economics of Nuclear and Renewable Sources of Electricity

Mark Diesendorf¹

¹Institute of Environmental Studies
University of New South Wales
Sydney, NSW 2052, Australia
m.diesendorf@unsw.edu.au

ABSTRACT

This paper reviews recent studies on the economics of nuclear energy and compares the results with the economics of several sources of renewable electricity. It finds that the costs of nuclear energy have been escalating very rapidly since 2002. The lowest cost renewables, appropriately sited, are already competitive with nuclear. Several more expensive renewables could be competitive with nuclear by around 2020. Furthermore, most renewable energy technologies are capable of much faster growth than nuclear energy, provided effective government policies are implemented now.

Keywords: economics, nuclear energy, renewable energy, technology status

INTRODUCTION

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 (Hansen et al. 2008; Hansen 2009). 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, states and provinces. 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.

Since climate mitigation is an urgent issue, this paper focuses on electricity generation technologies that are likely to be widely available over the next 15 years. If a technology is still at the R&D stage or the early demonstration stage, it is very unlikely that it could meet this criterion and there is little basis for any credible economic estimates. Hence this paper first reviews the technological status of various nuclear and renewable electricity generation technologies and then examines the economics of nuclear and renewable sources of electricity that are beyond the demonstration stage and are either commercial or precommercial (as defined in Table 1).

STATUS OF TECHNOLOGIES

Various nuclear power and renewable electricity (RElec) technologies are currently at different stages of development and commercialisation, as shown in Table 1. 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.

Tab. 1: Global status of electricity supply 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; some advanced batteries; 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 molten salt thermal storage; off-shore wind; 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, feed-in tariffs).	On-shore wind; conventional PV; biomass co-firing and direct combustion; landfill gas; large and small hydro; conventional tidal; conventional geothermal; 1 st generation biofuels; GenII nuclear

Note: PV is solar photovoltaic; GenII is generation II, representing existing commercial nuclear power stations.

Source: the author's adaptation of Foxon et al. (2005).

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 have been stuck at the demonstration stage for several decades. It could be 2030 before they are commercially available, if ever. The types of generation IV reactors listed above are more complex than existing generation II reactors and are therefore likely to be even more expensive. Reprocessing of spent fuel is rarely carried out for generation II reactors on account of its high cost, but would be essential for fast reactors, adding substantially to the latter's cost. No credible economic estimates are possible for these systems at their current early stages of technological development.

Generation III reactors (eg, Areva's European Pressurized Water Reactor; Westinghouse's AP1000) are under construction in several countries and can at best be considered as precommercial. Experience with construction of the Areva EPR in Olkiluoto, Finland, does not give grounds for confidence that this type of reactor will be commercial soon. 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 (Hollinger 2008; World Nuclear News 2009).

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 of generation II nuclear power stations have long planning and construction periods (Kooimey & Hultman 2007). 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 payments during construction (IDC). This is another reason why nuclear energy is so expensive. 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 2–3 years. This is because most of the components of RElec systems are manufactured and site works are a minor part of the process. Exceptions are large-scale hydro-electric and conventional tidal power stations.

NUCLEAR ECONOMICS

Limited economic data

A report to the UK Sustainable Development Commission (MacKerron et al. 2006) 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*. [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 of nuclear stations do.

Problems of interpreting the limited data 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.

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, the nuclear industry often chooses low interest or discount rates in its economic analyses. This makes nuclear power

station costs look much less expensive than they are in a market situation. The sensitivity of the results to discount rate is illustrated 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 an appropriate discount rate for a risky investment of 10% real per annum, there were no countries out of the 18 studied where nuclear energy was cheaper than either coal or gas. However, when a low 5% real discount rate was chosen, nuclear energy was claimed to be the cheapest in 5 out of 18 countries (NEA/IEA 1998; Birol 1999). 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. By the way, 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.

I have labelled 5% as a 'low' discount rate and 10% as 'appropriate', for the following reason. Many economists, eg Dimson (1989), argue that a real (ie, on top of inflation) discount rate of 4–5% is only appropriate for risk-free investments, but 10–15% is appropriate for 'average-risk' investments. For the particular case of investment in a nuclear power station within a privatised industry, Dimson (1989) chose 11%, which represents the after-tax return expected by an investor who purchases securities with the same investment risk as the power station.

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 (Jeffrey 1980, 1982; House of Commons 1981).

Making over-optimistic assumptions about operational performance, as measured by capacity factor (average power output divided by rated power) of the nuclear power station, is another method. Nuclear proponents often choose as typical the year with the highest capacity factor, 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. Ignoring the huge subsidies from government to nuclear energy also makes the technology look less expensive.

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 electricity consumers 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 (Cooper 2009a). Comprehensive quantitative data on subsidies are incomplete and difficult to obtain, so they are not included in the cost estimates in subsequent sections of this paper.

In the USA, subsidies are estimated to have accumulated over the 50-year period 1948 to 1998 to about US\$74 billion (Public Citizen website), equivalent to about US\$100 billion in 2006 currency. Another report found subsidies to US nuclear power to be

about \$9 billion per year in 2006 (Koplow 2007). In the 2000s the G.W. Bush government allocated loan guarantees worth many tens of billions of dollars (Schneider et al. 2009). 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) (Meyer et al. 2009).

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 (Mitchell 2000, table 4), 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 UK nuclear power stations to be about £70 billion. In 2006 the UK Chancellor announced that Treasury had increased this estimate to £90 billion (Morgan 2006). There is also some discussion on subsidies within the EU on the WISE/NIRS website. Next we focus on nuclear economics in the UK and USA. Subsidies are not included in the following cost estimates.

Nuclear economics in the UK

The British experience is 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 (PIU 2002). 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 (Schneider et al. 2009).

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’ (UK DECC 2003). 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.

Nuclear economics in the USA

Despite huge subsidies, the USA has not had a new nuclear power station for over 30 years. This has been attributed primarily to poor economics (Cooper 2009b), although the accident at Three Mile Island in 1979 and the anti-nuclear movement played their parts.

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 in note under Figure 1) of US\$2000/kW, a capacity factor (average power divided by rated power) 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 increasing to US 7.5 c/kWh for a capacity factor of 75% (Ansolabehere et al. 2003). 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.

Tab. 2: 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
Deutsch et al (2009) MIT 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 at end of 2009

Note: IDC is interest during construction.

In a study sponsored by nine vendors and purchasers of nuclear power stations (hardly environmentalists!), the Keystone Center (2007) 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. Shortly afterwards a study by Harding (2007) estimated capital costs at US\$4300–4550/kW in 2007 US dollars. Deutsch et al. (2009) issued an ‘update’ of MIT’s earlier report (Ansolabehere et al. 2003), however the 2009 report is notable for its brevity, its new set of authors with little strength in economics or policy, and its doubling of the MIT’s 2003 estimate of overnight cost. The cost estimates of Deutsch et al. (2009) had already been overtaken by the Moody (2008) estimate of \$7500/kW. Severance (2009) 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 would be \$7400/kW if no further escalation took place during construction and could be as high as \$10,500/kW if escalation continued through the construction period at the previous rate. This gave nuclear electricity generation costs in the range US 25–30 c/kWh, comparable to electricity from solar photovoltaic (PV) power stations. Some of these results are summarised in Table 2.

Figure 1, compiled by Cooper (2009b), summarises empirical data on overnight costs as well as the wide range of recent cost estimates for new nuclear power stations in the USA. It shows a clear trend of overnight capital cost escalation in real terms among nuclear power stations built through the 1980s and into the 90s, while the studies listed in Table 2 suggest rapid cost escalation during the 2000s. Lovins and Sheikh (2008) attribute these to ‘severe manufacturing bottlenecks and scarcities of critical engineering, construction, and management skills that have decayed during the industry’s long order lull’. As shown in Figure 1, post-2006 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 cost escalations, will be even higher. Assuming conservatively that these additional costs add 15% to overnight costs lifts this capital cost range to \$6900–12,075/kW. Assuming a mid-range discount rate of 8% and variable cost (fuel+operation+maintenance) of 2c/kWh gives a cost of energy range of 10.8–17.3 c/kWh.

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 (Schneider et al. 2009, pp.61–63). There is little published data on the actual costs of long-term nuclear waste management or decommissioning commercial-scale nuclear power stations.

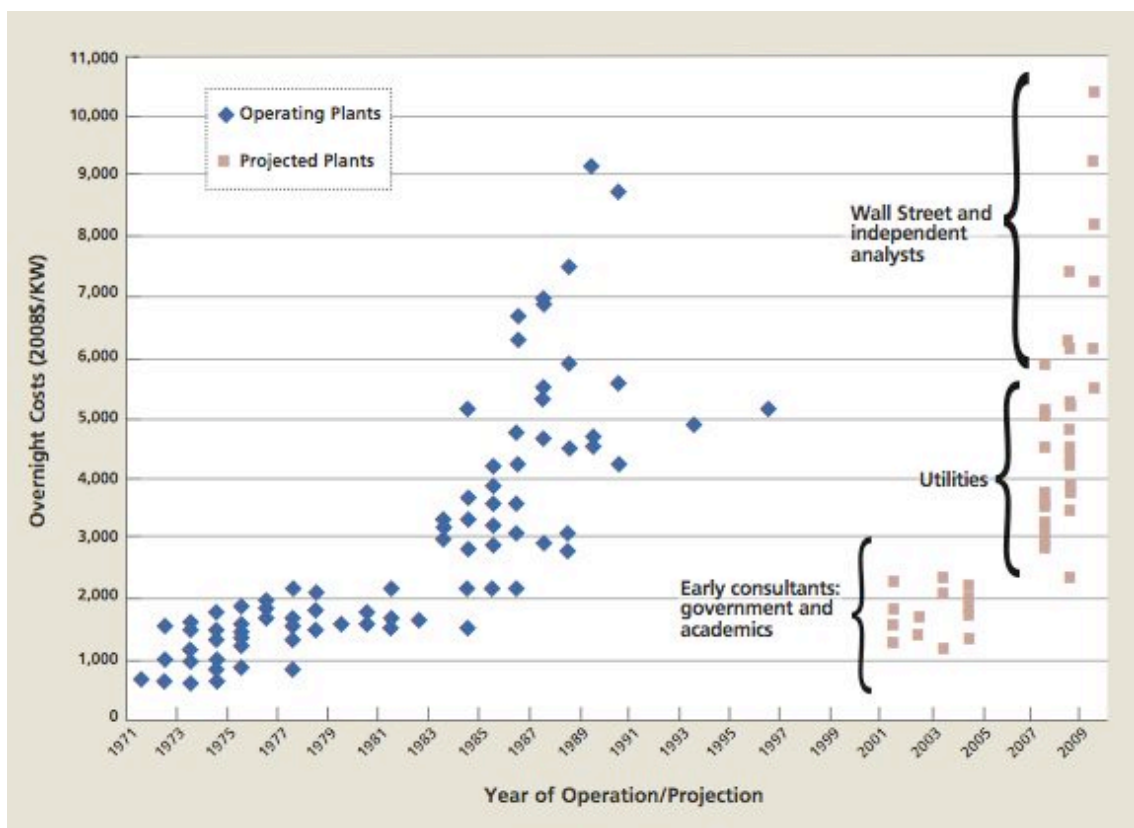


Fig. 1: ‘Overnight’ capital costs for operating and new US nuclear power stations

Source: Cooper (2009b), reviewing numerous studies.

Note: ‘Overnight’ cost is the capital cost excluding financing costs, which are dominated by IDC, and cost escalation during construction. For nuclear power, the full capital cost may be 15–50% higher than the overnight cost. Taking into account the subsidies to nuclear power would further increase its estimated costs.

ECONOMICS OF RENEWABLE ENERGY

As in the case of nuclear power, there are big variations in the costs of renewable electricity (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 3 summarises estimates made in 2008 by the US National Renewable Energy Laboratories (NREL) for the ‘overnight’ capital costs of various RElec technologies expressed in 2006 US dollars per kilowatt of rated capacity. The results for each technology are averages over several studies. I’ve added the nuclear cost as the median of Wall St studies in Figure 1. 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; 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 2009–2010, while nuclear prices are increasing. On the basis of Table 3 and known fuel, operation and maintenance costs, nuclear is already more expensive than many demand reduction technologies and measures, landfill gas, on-shore wind, conventional geothermal, and base-load biomass combustion of agricultural and forestry residues.

Tab. 3: ‘Overnight’ capital costs of new RElec and nuclear electricity in \$/rated kW and \$/average kW generated

Technology	Overnight capital cost (2006 US\$/kW rated)	Capacity factor	Overnight capital cost (2006 US\$/kW average)
MSW Landfill gas	2056	0.8	2570
Hydro, peak-load	2343	0.1	23,430
Hydro, intermediate-load	2343	0.5	4686
Wind onshore	1679	0.3	5597
Wind offshore	2879	0.45	6398
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
Solar PV, no storage	5578	0.2	27,890
Nuclear	7000	0.8	8750

Notes: With the exception of nuclear, overnight capital costs (column 2) are averages over several studies summarised by NREL (2009). Nuclear is the median of Wall St estimates from Fig. 1. Capacity factors (column 3), which depend on site on operational strategies, 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.

Clean Edge (2010), a 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).

Based on these and other data, Table 4 gives the author’s estimates for ranges of values for the prices of electrical 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.

Another factor to be considered in comparing different electricity generation technologies is the degree of reliability of the power outputs. This big topic cannot be addressed in detail here. Suffice it to say that some renewable sources (eg, hydro with a large dam, biomass, geothermal and concentrated solar thermal with a large thermal store) are just as reliable as nuclear and fossil fuels. Others (eg, wind and solar without storage) are less reliable. So long as the less reliable sources are geographically distributed and do not provide the major proportion of electricity generation, the additional costs of back-up and integration are relatively small, as shown by NREL (2010) for the case of 20% wind energy penetration into the eastern section of the US grid. For a more detailed refutation of claims that renewable energy cannot provide base-load power, see Diesendorf (2010).

Tab. 4: Cost of energy from RElec and nuclear ordered in 2010 and in 2020 (projected)

RElec technology	Cost of energy, 2010 order, (c/kWh)	Cost of energy, 2020 order, (c/kWh)	Comment
Landfill gas	2–4	2–4	Tiny resource
Wind (on-shore)	7–11	5–8	Could supply 25% of electricity in several regions
Biomass residue	8–16	8–12	From crops & plantation forests
Geothermal (existing)	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	Based on improvements to existing non-floating technology
Solar thermal + storage	20–30	10–15	Huge potential in regions with marginal land
Solar PV (power station)	20–30	12–20	
Solar PV (residential)	30–50	15–25	Competitive with some projected retail electricity prices in 2020
Nuclear (mid-range of Wall St estimates)	15	20?	As Table 3 with IDC 15% capital cost & variable cost 3 c/kWh

Sources: The author, based partly on Diesendorf (2007), Cooper (2009a), NREL (2009) and Clean Edge (2010). Notes: Fixed 2010 US currency; discount rate 8% real. External costs and subsidies are additional to these estimates.

CONCLUSION

Since there is negligible operating experience with generation III and IV nuclear power stations, there is no basis for estimating their economics. 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 inappropriate assumptions and 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 2002 the estimated capital costs of new nuclear power stations have escalated much more rapidly than the capital costs of renewable sources of electricity.

For orders made in 2010 at a midrange Wall Street ‘overnight’ capital cost of \$7000/kW, nuclear electricity cannot compete economically with landfill gas,

conventional geothermal, on-shore wind, intermediate-load hydro, or bioelectricity from agricultural and forestry residues. For orders made in 2020, it is projected that off-shore wind, solar thermal, residential solar PV and solar PV power stations could also be competitive with nuclear. Furthermore, it's possible that other promising alternatives still at the demonstration stage – hot rock geothermal power and wave power – could also become 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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BRIEF BIOGRAPHY OF PRESENTER

Dr Mark Diesendorf is Associate Professor and Deputy Director of the Institute of Environmental Studies at the University of New South Wales. Previously he was a Principal Research Scientist in CSIRO, a senior lecturer in human ecology at ANU and then Professor of Environmental Science at University of Technology Sydney. His most recent books are *Greenhouse Solutions with Sustainable Energy* (2007) and *Climate Action: A campaign manual for greenhouse solutions* (2009), both published by UNSW Press.