Journal of Contemporary Asia
Vol. 40, No. 3, August 2010, pp. 369–400

A Critical Evaluation of Nuclear Power and Renewable Electricity in Asia

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ABSTRACT *This article judges modern nuclear power and renewable electricity technologies according to six criteria: cost; fuel availability; land degradation; water use; climate change; and safety/security. It concludes that when these criteria are taken into consideration, renewable electricity technologies present policy makers with a superior alternative for minimising the risk of fuel interruptions and shortages, helping improve the fragile transmission network and reducing environmental harm. These more environmentally-friendly generators cost less to construct, produce power in smaller increments and need not rely on continuous government subsidies. They generate little to no waste, have fewer greenhouse gas emissions per unit of electricity produced and do not substantially contribute to the risk of accidents. In contrast, the costs for nuclear plant construction, fuel, reprocessing, storage, decommissioning and further research are expected to rise. Modern nuclear reactors are prone to accidents, failures, shortages of high quality uranium ore may be imminent and the thermoelectric fuel cycle of nuclear plants consumes and degrades vast quantities of water. Greenhouse gas emissions associated with the nuclear lifecycle are notable and reactors and waste storage sites can degrade land and the natural environment. Thus, the article concludes that any effective response to electricity demand in an Asia facing climate change should promote the rapid expansion of renewable technologies and a more limited use of nuclear power.*

KEY WORDS: Renewable energy, energy security, climate change, energy policy, nuclear power, nuclear energy

Asian electricity planners confront a series of fundamental energy policy dilemmas. Energy use per capita for the 28 countries comprising the continent remains about three times less than the global average (APEC, 2006). Millions of people living in Southeast Asian countries still lack access to electricity, such as Cambodia (87%), Laos (56%) and Indonesia (46%), along with more than one billion people in China and India together (ASEAN Center for Energy, 2009; Asian Development Bank, 2008; World Bank, 2008). Demographers and energy analysts expect electricity demand to double throughout the region in the next 20 years and, according to

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ISSN 0047-2336 Print/1752-7554 Online/10/030369-32
DOI: 10.1080/00472331003798350

projections, this increase in demand will account for 40% of the world total (International Energy Agency, 2007; Jaffe, 2004).

Asian policy makers, however, face geographical and political challenges to developing and transporting the region's consolidated electricity fuels (such as coal, oil and gas) from their remote locations to those urban centres of production and consumption where they are needed most. There is little likelihood, given increasing demands and low reserve margins, that fossil fuel prices are likely to return to historic lows. The much-touted "hydrogen economy" faces tenacious infrastructural challenges: inability to manufacture cost-effective fuel cells, as well as problems extracting, compressing, storing and distributing hydrogen-based fuels. Fusion power is still at least 30 years away from commercialisation. The historical record also suggests that while they are incredibly cost-effective, energy efficiency practices and demand-side reduction programmes alone will be unable to offset steady increases in electricity demand. Given the severe risk of death, injury and environmental damage from coal mining and other forms of fossil fuel combustion, the true contest appears to be between nuclear power technologies and renewable power systems.

Coal's constraints, for example, have convinced many commentators that nuclear power is the solution to the region's energy problems. Environmentalist James Lovelock (2003) even goes so far as to argue that nuclear power is one of the only options that can meet electricity demand as we transition to cleaner energy sources, and that its risks are "insignificant compared with the real threat of intolerable and lethal heatwaves" associated with climate change. Backed by strong institutional supporters, such as manufacturing and trade groups, the US Department of Energy, International Energy Agency and International Atomic Energy Agency, nuclear power is set to rapidly expand in Asia. Perhaps as a result, in East and South Asia there are 109 nuclear power reactors in operation, 18 under construction, and plans for a further 110 (Jayaraman, 2008: 50). China plans to build 27 reactors over the next 15 years and has called for US$50 billion in investment; India seeks a ten-fold increase by 2010; Japan is attempting to increase its share of nuclear electricity to 40% by 2040; and South Korea has six plants under construction and 8 more planned by 2015 (Sovacool and Cooper, 2008; Xu, 2008). Even developing countries in Southeast Asia are beginning to warm to atomic energy. Thailand is planning to install 4 GW of nuclear capacity by 2020; Vietnam is aiming for their first nuclear plant by 2015; Malaysia has plans for their first nuclear power plant by 2020; and Indonesia's Mt. Muria plant is scheduled to become operational by 2018 (Symon, 2008; Tan, 2008: 21; Wilcox, 2007).

Other forms of electricity supply, such as solar panels, wind farms, geothermal facilities, hydroelectric plants and bioelectric stations, some regulators dismiss outright as "immature" and "ill-suited" (Asia Pacific Energy Research Centre, 2007: 2). Although every country in Asia has at least some type of policy incentive for renewable energy, one Southeast Asian government official impatiently explained, "cost competitiveness is a major challenge for renewable energy. Renewable energy costs more than fossil fuels in terms of specific construction and generation costs, meaning it makes little to no sense to use them" (Keong, 2008: 14). Renewable electricity technologies are generally believed to work only intermittently and to require large tracts of land even to produce this unreliable and expensive power (Li, 2007). Another analyst tells us that "alternative and non-traditional energy sources such as solar and biomass ... cannot be alternatives to large base-load power generation" (Symon, 2008: 121).

To test these claims, this paper creates a systematic method of analysis and suggests that modern electricity technologies be judged according to six criteria: (a) cost, including the expense of procuring capital equipment, fuel, operations and maintenance, decommissioning and further research and development; (b) fuel availability, including reliance on abundant, domestically available fuel sources; (c) land degradation, including the environmental footprint associated with plant operation and waste; (d) water use, including water withdrawals, consumption and contamination associated with operation; (e) climate change, including the greenhouse gas emissions associated with the lifecycle of each technology; and (f) safety and security, including the risk of occupational hazards, accidents and spills. Optimal technologies, in other words, must be affordable and available, operate safely and securely and produce electricity with minimal disruption to land, water and the Earth's climate. An exploration of the full environmental, social and political impacts of both renewable electricity and nuclear power technologies is essential if regulators are to properly assess *all* of the costs and benefits from investing in long-lived power plant infrastructure.

When these criteria are taken into consideration, renewable electricity technologies present policy makers with a superior alternative for minimising the risk of fuel interruptions and shortages, helping improve the fragile transmission network and reducing environmental harm. These smaller and more environmentally friendly generators cost less to construct, produce power in smaller increments and need not rely on continuous government subsidies. They generate little to no waste, have less greenhouse gas emissions per unit of electricity produced and do not contribute significantly to the risk of accidents. In contrast, the costs for nuclear plant construction, fuel, reprocessing, storage, decommissioning and further research are significant. Even modern nuclear reactors run the risk of accidents and failures, shortages of high quality uranium ore may be imminent and the thermoelectric fuel cycle of nuclear plants consumes and sometimes degrades vast quantities of water. Greenhouse gas emissions associated with the nuclear lifecycle are notable and reactors and waste storage sites invariably damage and degrade the natural environment.

The Case against Nuclear Power in Asia

The fissioning of atoms in a nuclear power plant and a nuclear weapons explosion differ only slightly. In a nuclear weapon detonation, all of the energy embodied in the nuclear reaction is released in one awesome moment. In a nuclear power plant, this same energy is released slowly over the lifetime of the plant, and such plants require an intricate, complicated and intensive fuel cycle in order to function. Despite all the complicated technology involved in a nuclear reactor, its primary task is quite simple: to boil water to make kilowatt-hours of electricity. When compared to other alternatives, especially renewable forms of electricity supply, this section shows that nuclear energy faces disadvantages related to cost, availability of fuel, degradation of land, water use, climate change and safety and security.

Cost

Nuclear plants are capital intensive and expensive at every stage of the fuel cycle, from construction, fuel reprocessing and waste storage to decommissioning and research and development on new nuclear technology. Nuclear power plants have long construction lead times and meet with a plethora of uncertainties during the construction process, making planning and financing difficult, especially when the balance of supply and demand for electricity can change rapidly within a short period of time.

One assessment of the real construction costs of nuclear power facilities at 16 operational reactors in Canada, China, Japan, the UK and the USA found that many quotes provided by industry representatives, promotional bodies, plant vendors and utilities were unreliable and conservative. Most estimates did not include interest during construction, borrowing fees, the expense of decommissioning or costs associated with fuel storage; indeed, some plants actually took 80 to 120 months to complete when a typical power plant should take only 12 to 48 months (Thomas, 2005). Researchers from the Keystone Center (2007) consulted with 27 nuclear power companies and contractors and concluded that the cost (with interest calculated) for building new reactors in the USA would be almost twice as much as the figure quoted by the industry, or between US$3600 and US$4000 per installed kW.

These higher capital costs translate into higher levelised costs, or the rate that generators end up charging for electricity. At a cost above US$3600 per installed kW – conservative given the new findings from the Keystone Center – the operating costs for a new nuclear plant would be about 30 ¢/kWh for the first 13 years until construction costs are paid, followed by 18 ¢/kWh over the remaining lifetime of the plant (Russell, 2008). This makes nuclear power the fourth most expensive power generator on the market, along with solar photovoltaics and combustion turbines running on the dirtiest of fossil fuels (Table 1).

A similar survey of the overnight construction costs for nine light water reactors recently built in South Korea and Japan also concluded that the cost of building new plants would likely be 30% higher than industry quoted estimates (Harding, 2007). The study cautioned that constraints in the manufacturing of nuclear components, shortage of skilled construction teams, and long lead times meant that a new nuclear plant would cost well above industry projections. Even with a stringent carbon tax of US$30 per tonne on carbon dioxide and advancements in carbon sequestration, the study calculated that new nuclear power plants would have no commercial advantage over fossil-fuelled or renewable electricity technologies. Indeed, China's Tianwan nuclear power plant, completed in June 2008 near Lianyungang, took more than two extra years to complete and cost US$3.2 billion instead of the initially quoted US$2.5 billion (Dongqing, 2003). The Madras Atomic Power Station near Chennai in India cost almost *twice* as much as expected, while construction of the Kota heavy water reactor, started in 1969 – and supposed to be completed in four years – was not commissioned until the end of 1979 due to several technical problems (Tomar, 1980). The cancelled Bataan nuclear power plant near Manila in the Philippines ended up costing ratepayers US$2.3 billion even though it was never switched on after social protests convinced the government to mothball it (Olea, 2009).

Table 1. Nominal levelised cost of electricity (LCOE) for different power generators (2007 $US)

Technology	Nominal LCOE (¢/kWh)
Energy efficiency and demand-side management	2.5
Offshore wind	2.6
Hydroelectric	2.8
Onshore wind	4.0
Biomass (landfill gas)	4.1
Geothermal	6.4
Integrated Gasification Combined Cycle (IGCC)	6.7
Biomass (Combustion)	6.9
Scrubbed coal	7.2
Advanced Gas and Oil Combined Cycle	8.2
Gas Oil Combined Cycle	8.5
IGCC with carbon capture	8.8
Parabolic troughs (solar thermal)	10.5
Advanced Gas and Oil Combined Cycle with carbon capture	12.8
Solar ponds (solar thermal)	18.8
Nuclear power	24.0
Advanced combustion turbine	32.5
Combustion turbine	35.6
Solar photovoltaics (panels)	39.0

Source: Figures for nuclear power from Russell (2008), for onshore wind from US Department of Energy (2008), for all other sources from Sovacool (2008a).

Both nuclear reactors and uranium enrichment facilities must also be carefully decommissioned – processes that are expensive, time-intensive, occupationally dangerous and hazardous to the natural environment. The decommissioning costs for specific Asian governments and reactors are largely unknown, since regulators have little experience with decommissioning nuclear programmes. Nuclear power programmes are all relatively new in Asia. South Korea's Kori-1 facility was first connected to the grid in 1978. China's first nuclear reactor Qinshan-1 was connected in 1991. While India has operated test reactors since 1969, their first commercial Pressurised Water Heavy Reactors were connected in 1987. India's Atomic Energy Regulatory Board has decommissioned isolated research reactors and one reprocessing plant, but has no experience decommissioning an operating nuclear plant housing multiple reactors and spent storage facilities (Raj et al., 2006).

The only reasonable estimate of decommissioning costs is thus the historical record, and experience in the UK and USA suggests that costs can range anywhere from US$300 million to US$5.6 billion per facility. The US National Research Council (1996) has estimated that decommissioning only the three enrichment facilities in the USA will cost US$18.7 to 62 billion,[1] with an additional US$2-6 billion to cover the disposal of a large inventory of depleted uranium hexafluoride (depleted UF_6), which must be converted to uranium oxide (U_3O_8). The US General Accounting Office (2004) surveyed how well the decommissioning process was going at these enrichment facilities, and found that the cost of decommissioning, funded by taxpayers, will have *exceeded* the plants' revenues by US$4-6.4 billion.[2] The Nuclear

Decommissioning Authority in the UK has reported similar problems with decommissioning their units, the costs of which are now estimated to be more than £73 billion.

Fuel Availability

Extreme weather events, logistical bottlenecks and accidents can stop uranium from reaching nuclear power plants in dire need of fuel. New nuclear plants also increase the region's dependence on imported uranium subject to large price spikes and price volatility.

The International Atomic Energy Agency (IAEA) classifies uranium broadly into two categories: "primary supply" including all newly mined and processed uranium; and "secondary" supply encompassing uranium from reprocessing inventories (including highly enriched uranium, enriched uranium inventories, mixed oxide fuel, reprocessed uranium and depleted uranium tails). The IAEA (2001: 11) expects primary supply to cover 42% of demand for uranium in 2008, but acknowledges that the number will drop to between 4% and 6% of supply in 2025, as low-cost ores are expended and countries are forced to explore harder to reach and more expensive sites.

But here lies a dilemma: the IAEA believes that secondary supply can contribute only 8-11% of world demand. The IAEA stated (2001: 11-12): "As we look to the future, presently known resources fall short of demand," and "it will become necessary to rely on very high cost conventional or unconventional resources to meet demand as the lower cost known resources are exhausted." The same pessimism exists even in industry assessments. Relying on highly optimistic assumptions of fuel availability from industry groups, and global reserves of uranium support only a nuclear growth rate of 2%, and even then fuel would only be available for 70 years (Li, 2007).

Such pessimism was confirmed recently by a study on available uranium resources at 93 deposits and fields located in Argentina, Australia, Brazil, Canada, the Central African Republic, France, Kazakhstan, Malawi, Mongolia, Namibia, Niger, Russia, South Africa, the USA and Zambia (Mudd and Disendorf, 2008). The study found that no "world class" discoveries of uranium have occurred since the 1980s, and that all increases in uranium mining and milling between 1988 and 2005 resulted from increased drilling and new assessments at known deposits. The study also warned that uranium miners have to go deeper and use more energy and water to extract uranium resources as the overall quality of ore declines.

Some Asian countries, such as China and India, have domestically available supplies of uranium, but these are extremely limited. The China National Nuclear Corporation expects the country's demand for uranium to rise from 1000 tonnes per year in 2007 to 7000 tonnes by 2020 (WISEUP, 2008). Then, China will be more dependent on Australia for uranium imports, and Chinese officials have already signed a deal with Australian firms to import 20,000 tonnes of uranium by 2020 (Wu et al., 2008). Supplies of uranium ore are now recognised as "probably the biggest hurdle to expansion of the mainland's nuclear sector," and Chinese analysts expect the country to be dependent on foreign sources for 88% of its uranium ore by 2020 (Chen, 2009).

Geologists have estimated that India has about 61,000 tonnes of uranium reserves, but caution that most of it is stranded – far from existing mines and reactors where fuel is needed – and of very poor quality. Uranium mining companies have argued that Indian uranium ore concentrations hover around the 0.06% mark, compared to the minimum "economically exploitable" concentration of 0.1% and far below the concentrations found in Australia and Canada, which typically exceed 20% (Gadekar, 2008). This dearth of recoverable Indian uranium has convinced many engineers to talk about shifting to thorium fuel cycles, but such advanced technology is at least a few decades away (Abram, 2006; Murty and Charit, 2008). Moreover, domestic Indian uranium supplies are already insufficient to supply existing nuclear power plants. Operators shut down five of the 17 nuclear power plants in the country at the end of 2007 and operated the remaining reactors at an average of less than 50% capacity for want of fuel. Uranium fuel shortages have also forced the Nuclear Power Corporation in India to delay commissioning of two new units at the Rajasthan Atomic Power Station and another new unit at Kaiga in Karnataka (Gadekar, 2008).

Even when supplies of fuel are abundant, investments in new nuclear plants would only make Asian countries dependent on foreign deposits of uranium in Africa, Russia, Canada and Australia (Figure 1). Admittedly, the chance that Canada and Australia will come together to become an "OPEC of uranium" is unlikely, but Kazakhstan, Namibia, Niger and Uzbekistan together were responsible for more than 30% of the world's uranium production in 2006. Over the past several years these countries have not had the most stable political regimes. It is not inconceivable to imagine a scenario in which unstable regimes controlling only 30% of the world's

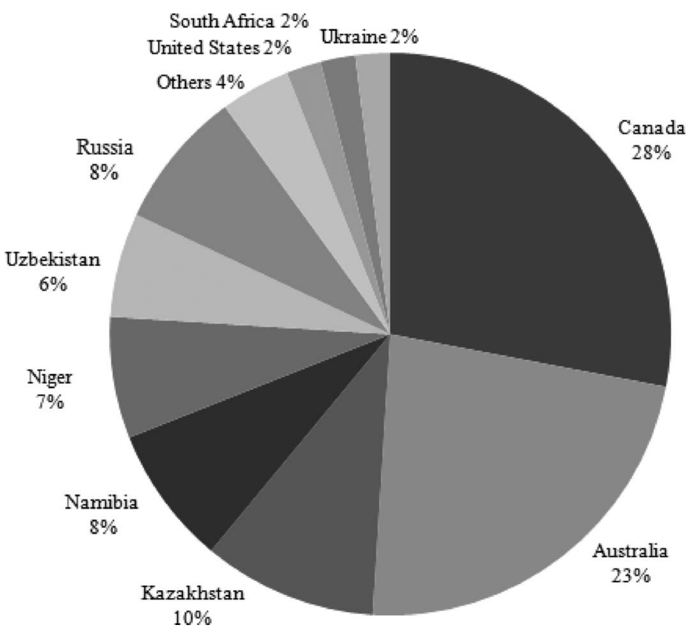

Figure 1. Shares of global uranium production, 2007. *Figure modified from*: Sovacool and Cooper (2008).

supply of uranium could none the less induce price spikes and volatility in uranium supplies that could have devastating consequences for Asian countries (Sovacool and Cooper 2008).

Finally, uranium prices are highly volatile. Historically, uranium prices have been very sporadic, with spot prices sextupling from 1973 to 1976, declining steadily through 2002, then escalating dramatically to 2007 before falling back again in 2008 (Harding, 2007; Wenske, 2008). Uranium price volatility has been influenced heavily by the unexpected introduction of secondary supplies and gluts in the market, connected in part to sudden increases in supply from cancelled and shutdown reactors and the dilution of highly enriched uranium from surplus nuclear weapons. The Nuclear Energy Agency reports 200 metric tonnes of uranium are required annually for every 1000 MW reactor and that uranium fuel accounts for 15% of the lifetime costs of a nuclear plant, so uranium price volatility can significantly affect the operating costs of a nuclear plant.

Land and Waste Storage

Because nothing is burned or oxidised during the fission process, nuclear plants convert almost all their fuel to waste with little reduction in mass. About 10,000 tonnes of spent nuclear fuel are discharged every year from nuclear power plants. Only 15% of this is reprocessed, and reprocessing is only 1% more efficient than non-reprocessed systems (Rethinaraj, 2008). Nuclear power plants thus have at least five waste streams that contaminate and degrade land (Fleming, 2007):

(1) they create spent nuclear fuel at the reactor site;
(2) they produce tailings and uranium mines and mills;
(3) they routinely release small amounts of radioactive isotopes during operation;
(4) they can catastrophically release large quantities of pollution during accidents; and
(5) they create plutonium waste.

China, which plans to build a permanent repository some time after 2040 in the Gobi Desert, stores the bulk of its nuclear waste onsite at waste storage pools (Pan and Qu, 1999). India is researching virtification (the glassification of nuclear waste) and reprocessing as well as the specifications of a permanent geological repository, but still relies on storage of waste at seven decentralised facilities, most of them next to reactors (Rethinaraj, 2008). South Korea does the same (Lee and Lee, 2007). Such onsite storage is very costly. Typically, a single nuclear plant will produce 30 tonnes of high-level waste each year, and this waste can be radioactive for as long as 250,000 years (Sovacool and Cooper, 2008). Assuming just one-tenth of that time (25,000 years), and assuming the cost of storing one tonne of nuclear waste was just US$35,000 per year (the lowest end of existing estimates), each nuclear plant around the world assumes an additional cost of US$875 million on top of its already enormous price tag. High-level nuclear waste that has already been processed into storage casks will take at least 10,000 years before it will reach levels of radiation considered safe for human exposure (Rethinaraj, 2008; Figure 2).

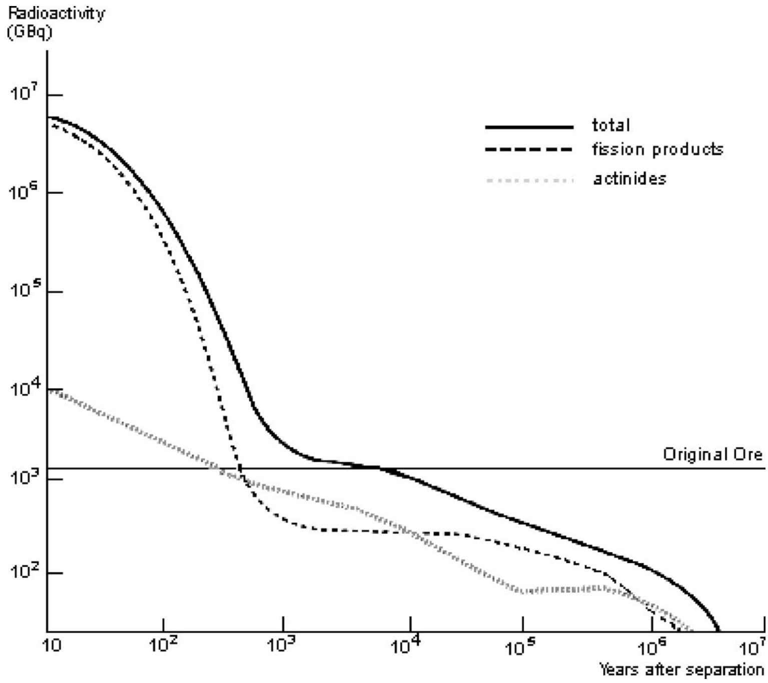

Figure 2. Decay in radioactivity of high-level processed nuclear waste (from reprocessing one tonne of spent pressurised water reactor fuel). Note that the straight line shows the radioactivity of the corresponding amount of uranium ore. *Figure modified from*: Rethinaraj (2008: 11).

Moreover, onsite storage facilities can quickly run out of space. Researchers at the Korea Advanced Institute of Science and Technology noted that a Korean underground repository for permanent disposal of spent nuclear fuel will not be ready by 2041, and expect interim onsite storage pools to reach maximum capacity until 2024 (Lee and Lee, 2007). After that point, Korean reactors will either need to export their waste or permanently shutdown.

Water

Three stages of the nuclear fuel cycle – uranium milling and mining, plant operation and nuclear waste storage – consume, withdraw and contaminate water supplies. As a result of this vast need for water, most nuclear facilities cannot operate during droughts and, in some cases, induce water shortages.

Uranium mining, the process of extracting uranium ore from the ground, is extremely water intensive. Since concentrations of uranium are mostly prevalent at very low concentrations, uranium mining is volume intensive. The problem is that such mining practices can greatly damage and degrade local water supplies. Researchers from the Bhabha Atomic Reserch Center in Mumbai, India found that underground uranium mines at Bhatin, Narwapahar and Turamdih, along with the uranium enrichment plant at Jaduguda, discharged mine water and mill tailings contaminated with radionuclides (such as radon and residual uranium, radium and other pollutants) directly into local water supplies. The researchers noted that since the quality of Indian uranium ore is relatively low, about 99% of the ore processed in the mill emerges as waste and tailings (Tripathi et al., 2008).

Nuclear reactors also require massive supplies of water to cool reactor cores and spent nuclear fuel rods, and they use the most water (about 174 litres of water for every kWh generated) compared to all other electricity generating facilities, including conventional coal and natural gas facilities. Because much of the water used by nuclear plants is turned to steam, substantial amounts are lost to the local water cycle entirely. The average nuclear plant in the USA, operating on an open-loop cooling system, withdraws 216 million litres every day from local rivers but consumes 125 million litres per day from local supply (Sovacool and Cooper, 2008). Given that many parts of Asia face water scarcity – especially China, where more than 400 major metropolitan areas have reported water shortages (Reuters, 2006) – nuclear power plants may become one of the least attractive forms of producing power.

Yet nuclear plants do not just use water, they also contaminate it at multiple points of the cooling cycle: at the point of intake, at the point of discharge and during unexpected accidents. At the point of intake, nuclear plants bring water into the cooling cycle through intake structures. To minimise the entry of debris, water is often drawn through screens. Seals, sea lions, manatees, crocodiles, sea turtles, fish, larvae, shellfish and other riparian or marine organisms are frequently killed as they are trapped against the screens in a process known as impingement. Organisms small enough to pass through the screens can be swept up in the water flow where they are subject to mechanical, thermal and toxic stress in a process known as entrainment (Baum, 2004). Billions of smaller fish, fish larvae, spawn, and a tremendous volume of other marine organisms vital to the marine ecosystem are frequently pulverised by reactor condenser systems. One study estimated that more than 90% are scalded and discharged back into the rivers, streams, and oceans as lifeless sediment that clouds the water around the discharge area, blocking light from reaching the ocean or river floor, which further kills plant and animal life by curtailing photosynthesis and the production of oxygen (Gunter et al., 2001).

At the point of discharge, nuclear plant operators often treat cooling water with chlorine, anti-fouling, anti-microbial and water conditioning agents to limit the growth of mineral and microbial deposits that reduce its efficiency transferring heat. What makes such treated water so effective in killing unwanted species also makes it a potent killer of non-target organisms as well. Chlorine, biocides and their by-products present in discharged water plumes are often toxic to aquatic life even at low concentrations. In addition, discharged cooling water is usually higher in temperature than intake waters. Significant temperature differences between intake and discharge waters (temperature deltas) can contribute to destruction of vegetation, increased algal growth, oxygen depletion and strain the temperature range tolerance of organisms. Impacts can be multiple and widespread, affecting numerous species at numerous life cycle stages (Sovacool and Cooper, 2008).

For example, a team of Indian scientists studying heated water discharges from the Madras Atomic Power Station, located at Kalpakkam in India, noted that substantial additions of sodium hypochlorite to sea water decreased viable counts of bacteria and plankton by 50% around the reactor site (Saravanan et al., 2008).

They also discovered that the plume of thermal pollution was greater at the power plant's coastal location because the tidal movements altered its direction and enhanced its magnitude. A team of Korean marine biologists and scientists utilised satellite thermal infrared images of the Younggwang nuclear power plant on the west coast of Korea and found that the plant's thermal pollution plume extended more than 100 km southward (Ahn et al., 2006). The researchers documented that the power plant directly decreased the dissolved oxygen content of the water, fragmented ecosystem habitats, reduced fish populations and induced eutrophication, a process where warmer temperatures alter the chemical composition of water, resulting in a rapid increase in nutrients (such as nitrogen and phosphorous) that then degrade the ecosystem.

Lifecycle Greenhouse Gas Emissions

From a climate-change perspective, nuclear power is an improvement over conventional coal-burning power plants, but is no panacea. Reprocessing and enriching uranium requires a substantial amount of electricity, often generated from fossil fuel-fired power plants, and uranium milling, mining, leeching, plant construction and decommissioning all generate substantial amounts of greenhouse gas. When one takes into account the carbon-equivalent emissions associated with the entire nuclear lifecycle, nuclear plants contribute significantly to climate change and will contribute even more as stockpiles of high-grade uranium are depleted. An assessment of 103 lifecycle studies of greenhouse gas-equivalent emissions for nuclear power plants found that the average CO_2 emissions over the typical lifetime of a plant are about 66 g for every kWh, or the equivalent of some 183 million tonnes of CO_2 in 2005 (Sovacool, 2008c). If the global nuclear industry were taxed at a rate of US$24 per tonne for the carbon-equivalent emissions associated with its lifecycle, the cost of nuclear power would increase by about US$4.4 billion per year.

The equivalent emissions from particular plants in Asia can be much higher than this global average. Because enrichment facilities in China are predominantly powered by coal-fired power plants, for instance, one study projected that the lifecycle emissions from Chinese nuclear plants could be as high as 80 g of CO_2 per kWh (Dones et al., 2004). In addition, the carbon-equivalent emissions of the nuclear lifecycle will only get worse, not better, since – over time – reprocessed fuel is depleted, necessitating a shift to fresh ore and reactors must utilise lower quality ores as higher quality ones are depleted. The Oxford Research Group projects that because of this inevitable eventual shift to lower quality uranium ore, if the percentage of world nuclear capacity remains what it is today, by 2050 nuclear power would generate as much CO_2 per kWh as comparable gas-fired power stations, or about half the greenhouse gas emissions of coal-fired power plants (Barnaby and Kemp, 2007).

Safety and Security

The safety record of nuclear plants is questionable at best. No less than 99 nuclear accidents (defined as incidents that either resulted in the loss of human life or more than US$50,000 of property damage, the amount the US federal government uses to define major energy accidents that must be reported), totalling US$20.5 billion in damages, have occurred world-wide from 1952 to 2009 (see Appendix A). These numbers translate to more than one incident and US$330 million in damages every year for the past three decades. When compared to fatalities from other energy sources, nuclear power ranks as the second most fatal source of energy supply (after hydroelectric dams) and higher than oil, coal and natural gas systems. Fifty-seven accidents have occurred since the Chernobyl disaster in 1986, and almost two-thirds (56 out of 99) of all nuclear accidents have occurred in the USA, refuting the notion that severe accidents are relegated to the past or to countries without US modern technology or industry oversight. While only a few accidents involved fatalities, those that did collectively killed more people than have died in commercial US airline accidents since 1982 (Sovacool, 2008b; Sovacool and Cooper, 2008).

Other studies have produced similar results. One index of nuclear power accidents that included costs beyond death and property damage – such as injuring and irradiating workers and malfunctions that did not result in shutdowns or leaks – documented 956 incidents from 1942 to 2007 (Winter, 2007). Smith (2009: 165) estimates that between the 1979 accident at Three Mile Island and 2009 there have been more than 30,000 mishaps at US nuclear power plants alone, many with the potential to have caused serious meltdowns.

Many accidents have occurred in India. The Tarapur nuclear power plant suffered a partial meltdown in 1979; a fire and explosion forced the closure of the Narora power plant in 1993; the Rajasthan Atomic Power Station at Kota leaked radioactive water into a lake for two months until it was detected in 1995; and, in December 2006, one of the pipes carrying radioactive waste from the uranium enrichment facility at Jadugoda burst and distributed highly radioactive materials as far as 100 km away. Tomar (1980: 525) estimated that before the accident at Tarapur, lack of proper maintenance exposed more than 3000 Indian personnel to "very high" and "hazardous" levels of radiation. Researchers at the American University (1996) calculated at least 124 "hazardous incidents" at nuclear units in India between 1993 and 1995.

At least six accidents have also occurred in Japan. In 1981, almost 300 workers were exposed to excessive levels of radiation after a fuel rod ruptured during repairs at the Tsuruga nuclear plant. In 1999, a fuel loading system malfunctioned at a nuclear plant in the Fukui Prefecture and set off an uncontrolled nuclear reaction and explosion. A few months later, workers at the Tokaimura uranium processing facility improperly mixed uranium oxide in buckets and set off an explosion that killed two and injured thousands of employees. In 2004, steam explosions at the Mihama nuclear power plant killed five workers and injured dozens more. In 2007, the Tokyo Electric Power Company announced that its Kariwa nuclear power plant leaked hundreds of litres of radioactive water into the Sea of Japan after an earthquake. In 2008, another earthquake cracked the reactor cooling towers at the Kurihara nuclear power plant, spilling wastewater and damaging the reactor core.

Given the historical record, the risk of future accidents is high. Using some of the most advanced probabilistic risk assessment tools available, an interdisciplinary team at the Massachusetts Institute of Technology identified possible reactor failures and predicted that the best estimate of core damage frequency was around one every 10,000 reactor years. In terms of the expected growth scenario for nuclear power from 2005 to 2055, the team estimated that at least four serious core damage accidents will occur and concluded that "both the historical and probabilistic risk assessment data show an unacceptable accident frequency" (Beckjord et al., 2003: 22).

Another assessment conducted by the Commissariat à l'Énergie Atomique (CEA) in France concluded that no amount of technical innovation can eliminate the risk of human-induced errors associated with nuclear power plant operation. Two types of mistakes were deemed the most egregious: errors committed during field operations, such as maintenance and testing, that can cause an accident; and human errors made during small accidents that cascade to complete failure (Papin and Quellien, 2006). And there may be no feasible way to "design around" these risks. For example, when they examined the safety performance of advanced French Pressurised Water Reactors, the CEA concluded that human factors would contribute to about a quarter (23%) of the likelihood of a major accident.

A team of geologists, volcanologists, geophysicists and engineers assessing the site for Indonesia's first power plant have already warned that the proposed location for the plant at Mount Muria sits atop the intersection of two tectonic plates (McBirney et al., 2003). They concluded that the plant, supposed to be completed by 2014, would be susceptible to seismic and volcanic activity. The researchers reported to the IAEA that if the power plant is completed as planned, it would be vulnerable to debris flows and avalanches from volcanic eruption and the formation of new geothermal vents that could create cracks and fissures in the reactor core.

Safety risks may be the greatest when nuclear systems are the newest (and operators have less experience with them). Nuclear engineer David Lochbaum (2004) has noted that almost all serious nuclear accidents occurred with what was at the time the most recent technology. He argues that the problem with new reactors and accidents is twofold: scenarios arise that are impossible to plan for in simulations; and humans make mistakes. As one director of a US research laboratory put it, "fabrication, construction, operation, and maintenance of new reactors will face a steep learning curve: advanced technologies will have a heightened risk of accidents and mistakes. The technology may be proven, but people are not" (Berry, 2008).

The Case for Renewable Electricity in Asia

Renewable power generators, in contrast to nuclear power plants relying on uranium mining or reprocessing, utilise sunlight, wind, falling water, biomass, waste and geothermal heat to produce electricity from fuels that are mostly free for the taking. As will be indicated, they satisfy each of the same six criteria outlined above better than nuclear power generators.

Cost

In contrast to nuclear goliaths, most renewable power technologies tend to have quicker construction lead times – taking between a few months and three years to permit and install (the exception being mammoth hydroelectric facilities). There is no need for mining, milling, or leeching uranium, enriching and reprocessing fuel assemblies, or permanently storing radioactive waste. The quicker lead times for renewables enable a more accurate response to load growth and minimise the financial risk associated with borrowing hundreds of millions of dollars to finance plants for decades before they start producing electricity (Sovacool and Cooper, 2008).

Utilities and investors can cancel modular plants more easily, so abandoning a project is not a complete loss (and the portability of most renewable systems means recoverable value exists should the technologies need to be resold as commodities in a secondary market). Smaller units with shorter lead times reduce the risk of purchasing a technology that becomes obsolete before it is installed, and quick installations can better exploit rapid learning, as many generations of product development can be compressed into the time it would take to build one giant power plant. As one study concluded,

> technologies that deploy like cell phones and personal computers are faster than those that build like cathedrals. Options that can be mass produced and adopted by millions of customers will save more carbon and money sooner than those that need specialised institutions, arcane skills, and suppression of dissent (Lovins et al., 2002: 67).

As a testament to their cost competitiveness, the United Nations (2008) calculated in a study utilising 2007 data collected from dozens of countries that renewable power sources can produce affordable power without subsidies. At the low end of the range, hydroelectric, geothermal, wind and biomass can all generate electricity for 5 ¢/kWh or less (Table 2) Without additional subsidies, most renewable power sources, with their "intermittent" or "low" capacity factors, are already cost competitive with conventional systems. Their progress is all the more impressive considering that these technologies reached such a point while receiving only a small fraction of the subsidies set aside for conventional systems.

Fuel Availability

Renewable "fuels" also happen to be in great abundance in Asia and, thus, offer a way to make the Asian electricity sector less susceptible to supply chain interruptions and shortages. Manufacturers and operators generally divide renewable power systems into five types: wind turbines (onshore and offshore, commercial and

Table 2. LCOE for renewable power technologies, without subsidies (US$2007)

Technology	Nominal LCOE (¢/kWh)
Hydroelectric	3-7
Geothermal	4-7
Wind	5-12
Bioelectric	5-12
Solar thermal	12-18
Solar PV	20-80

Source: United Nations (2008).

residential); solar photovoltaic panels and solar thermal systems (lumped together under the category "solar," and again in residential and commercial models); geothermal plants; biomass facilities (running on energy crops, agricultural residues or waste); and hydroelectric stations. When taken as a whole, at least one of these five types of fuel exists in every community in Asia, and most areas have three to four significant categories of renewable resources (National Renewable Energy Laboratory, 2009; United Nations Environment Program, 2010). Indeed, just five regions in Asia – the member countries of the Association of Southeast Asian Nations (ASEAN), China, India, Japan and South Korea – have an achievable renewable power potential of 2646.5 GW, more than 2.5 times the amount of power expected to be utilised by these areas in 2010 (Table 3). While "achievable" potential does not necessarily mean "economic" potential – it refers to what could be built today but regardless of its cost – Southeast Asia does boast significant hydroelectric and geothermal reserves; China, India, and Japan possess immense reserves of biomass and wind power; and South Korea has substantial wind and solar energy resources. More astonishingly, perhaps, is that Table 3 shows that regulators have installed only 4.7% of this achievable potential to date.

Land and Waste Storage

Renewable power sources also require less land than conventional generators, and most of the land they occupy can still be used for other purposes (unlike a repository for spent nuclear fuel, which no one wants to be near). When configured in large centralised plants and farms, wind and solar technologies use about 10-78 km^2 of land per installed GW per year, but traditional plants can use more than 100 km^2 of land per year to produce the same amount of electricity when accounting for the entire fuel cycle (such as coal mines, refineries, pipelines and so on). In open and flat terrain, newer large-scale wind plants require about 24 ha per MW of installed capacity, but the amount drops to as little as 0.8 ha per MW for hilly terrain. While this may sound like a lot, only 5% or less of this area is actually occupied by turbines, access roads and other equipment; 95% remains free for other compatible uses, such as farming or ranching. And, when integrated into building structures and facades, solar PV systems would require no new land at all (Sovacool and Cooper, 2008).

One form of renewable power, bioelectricity from energy crops, can actually improve land when managed sustainably. Although, when done poorly, planting biofuel crops can trade off with fuel supplies, cause erosion and contribute to deforestation, the cultivation of energy crops on degraded lands can help stabilise soil quality, improve fertility, reduce erosion and improve ecosystem health. Perennial energy crops usually contribute to land cover and enable plants to form an extensive root system, adding to the organic matter content of the soil. Agricultural researchers have discovered that planting grasses or poplar trees, two types of energy crops in the USA, in buffers along waterways captured runoff from corn fields, making streams cleaner (Union of Concerned Scientists, 2005). Prairie grasses, another energy crop with deep roots, build up topsoil and put nitrogen into the ground, and twigs and leaves decompose in the field after harvesting, enhancing soil nutrient composition (Lynd, 1996). Biomass crops can also create better wildlife

Table 3. Potential for commercially available renewable electricity generators in ASEAN, China, India, Japan and South Korea

Country/ Region	Projected capacity needed by 2010 (GW)	Installed renewable power capacity (GW) in 2006	Achievable renewable power capacity (GW) by 2010		Sources
ASEAN	90	14	520.8	Wind (138.7) Solar (11) Geothermal (30) Hydroelectric (254.2) Biomass (86.9)	Hydroelectric taken from Abdullah (2005); all other estimates come from Lidula et al. (2007)
China	500	75	1475	Onshore wind (253) Offshore wind (750) Solar PV (0.35) Solar thermal (60) Geothermal (5.8) Hydroelectric (400) Biomass (5.5)	Geothermal taken from Xin (2001); all other estimates come from Junfeng et al. (2007)
India	140	3.7	245.6	Wind (47) Solar (50) Geothermal (10.6) Hydroelectric (15) Biomass and bagasse (73) Ocean (50)	Geothermal taken from Chandrasekharam (2000); biomass and solar taken from Bhattacharyya and Dang (2007); all other estimates come from Meisen and Eueneudec (2006)
Japan	255	25	324.4	Wind (222) Solar (4.8) Geothermal (70) Hydroelectric (26.5) Agricultural residue (1.1)	Wind taken from Hoogwijka et al. (2004); solar taken from Kondo et al. (2006); geothermal and hydroelectric from Ushiyama (1999); biomass from Matsumura et al. (2005)
South Korea	56	3	80.5	Wind (53) Solar (4.3) Geothermal (14) Hydroelectric (6.9) Biomass (2.3)	Wind and solar taken from Ha (2005); geothermal from Song et al. (2005); hydroelectric from Han et al. (2004); biomass from Ko and Kim (2007)
Total	1041	121		2646.5	

habitats, since they frequently utilise native plants that attract a greater variety of birds and small animals, and poplar trees, sugar beets and other crops can be grown on land unsuitable for food production.

Water

Renewables, such as wind and solar PV, do not consume or withdraw water, while hydroelectric, geothermal and biomass facilities do not risk radioactive contamination of water supplies. While geothermal, biomass and small- and large-scale hydro do have other water problems, solar and wind do not. A 100 W solar panel saves approximately 7580 to 11,370 litres of water over the course of its lifetime (Brown, 2005). Small amounts of water are used to clean wind and solar systems, wind power uses less than 1/600th as much water per unit of electricity produced as does nuclear, 1/500th as much as coal and 1/250th as much as natural gas. The significant point is that *every* renewable power system uses less water than the equivalent-sized nuclear and conventional plants (Figure 3). By displacing centralised fossil fuel and nuclear generation, renewable power systems can conserve substantial amounts of water that would otherwise be withdrawn, consumed and polluted for the production of electricity.

Lifecycle Greenhouse Gas Emissions

All renewable power technologies are less greenhouse gas-intensive than any equivalent-sized nuclear power plant and, since landfill capture generators and

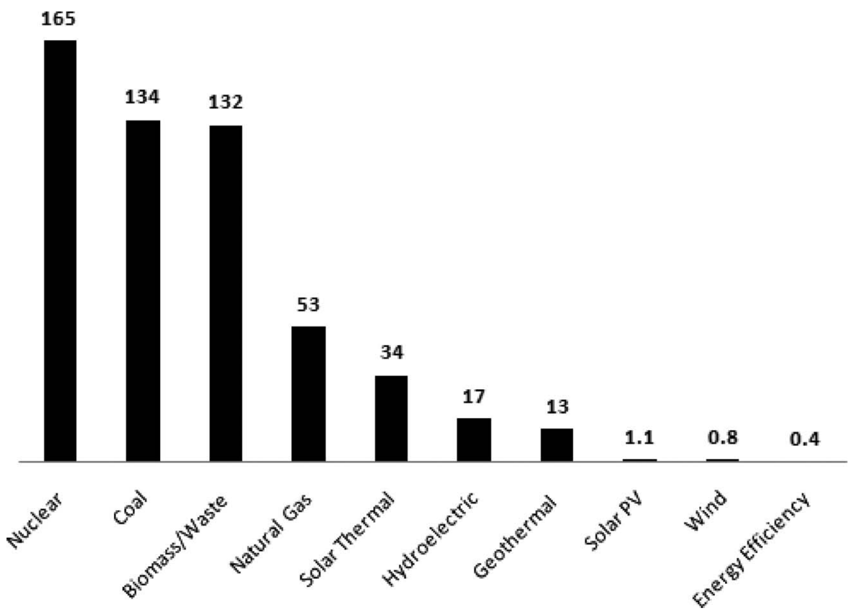

Figure 3. Total water use (consumption and withdrawals) for conventional and renewable electricity generators (litres/kWh). *Figure modified from*: Sovacool and Sovacool (2009).

anaerobic digesters harness methane and other noxious gases and transform them into electricity, they also displace greenhouse gases that would otherwise escape into the environment. Nuclear power plants produce electricity with about 66 g equivalent lifecycle carbon dioxide emissions per kWh, while renewable power generators produce electricity with only 9.5-38 g carbon dioxide per kWh (Figure 4). Renewable electricity technologies are thus two to seven times more effective than nuclear power plants on a per kWh basis at fighting climate change, and such an estimate already includes all conceivable emissions associated with the manufacturing, construction, installation and decommissioning of renewable units (Sovacool, 2008b). Therefore, even the deployment of much more intermittent renewable capacity to generate equivalent amounts of energy would still address climate change more effectively than relying on deployment of base-load nuclear generators.

Safety and Security

Contrary to the scores of nuclear accidents discussed above, not a single major energy accident in the past century has involved small-scale renewable electricity systems. One 2008 study found that accidents at nuclear power plants, on the other hand, have killed at least 4067 people and caused US$16.6 billion in damages and large-scale fossil fuelled and hydroelectric systems have killed another 178,000 and induced US$24.4 billion in property damages (Sovacool, 2008b; see Appendix A for updated data). An investigation of energy-related accidents in the European Union found that the latent effects of the Chernobyl disaster made nuclear power 41 times more dangerous than equivalent coal, oil, natural gas and hydroelectric projects (Hirschberg and Strupczewski, 1999).

Furthermore, deploying renewable power systems in targeted areas provides an effective alternative to constructing new transmission and distribution lines, transformers, local taps, feeders and switchgears, especially in congested areas or

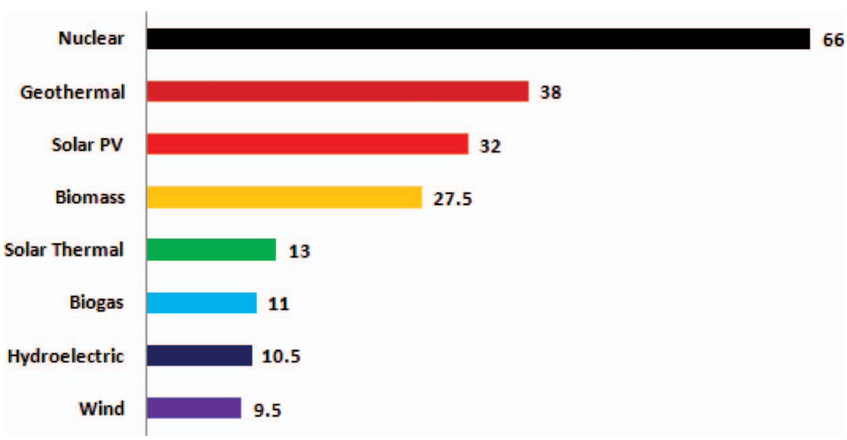

Figure 4. Greenhouse gas emissions associated with the lifecycle of nuclear and renewable power generators (in g of CO_2-equivalent/kWh). *Figure modified from*: Sovacool (2008c).

regions where the permitting of new transmission networks is difficult (Sovacool and Cooper, 2008). One study found that up to 10% of total distribution capacity in ten years in high growth scenarios could be cost-effectively deferred using distributed generation technologies, such as solar PV and solar thermal (Lovins et al., 2002). Since modern renewable technology enables utilities to remotely dispatch hundreds of scattered units, it also improves the ability of utilities to handle peak load and grid congestion problems. Another study comparing 50 1-MW distributed solar PV plants to one 50-MW central plant found that the grid advantages (in forms of load savings and congestion) more than offset the disadvantages in terms of high capital cost and interconnection of installing the new generation (Hoff and Shugar, 1995).

Lastly, reliance on renewable resources diversifies the electricity sector by substituting wind, sunlight, water, biomass and geothermal steam for oil, coal, natural gas and uranium. These former fuels are non-depletable and widely available; these latter fuels are concentrated and subject to accidental or intentional interruption. When distributed and decentralised, renewable power technologies enhance security by reducing the number of large and vulnerable targets on the grid and providing insulation for the grid in the event of an attack. While renewable technologies are constantly derided as intermittent or variable, it is far more certain to rely on the Sun shining, the wind blowing, the water falling, the Earth heating and photosynthesis occurring than to rely on a system that saboteurs could easily disrupt by blowing up a single power station or snipping a few transmission lines (Lovins et al., 2002).

Comparisons and Conclusions

Table 4 provides a comparative summary of the results of the foregoing analysis.

Nuclear power plant operators, designers, contractors, suppliers and advocates frame nuclear energy as an instrumental component of any attempt to move beyond fossil fuels in a carbon-constrained world. But this article suggests that modern nuclear power plants may satisfy none of the criteria for an affordable, available, efficient, water-conserving, climate-friendly, safe and secure energy sector. Renewable power technologies, in contrast, reduce dependence on foreign sources of fuel and, therefore, create a more secure fuel supply chain that minimises exposure to economic and political changes abroad. They decentralise electricity supply so that an accidental or intentional outage affects a smaller amount of capacity than an outage at a larger nuclear facility. They improve the reliability of power generation by producing power close to the end-user, and minimise the need to produce, transport and store hazardous fuels. Unlike generators relying on uranium and recycled plutonium, renewable generators are not subject to the volatility of global fuel markets. They can also respond more rapidly to supply and demand fluctuations, improving the efficiency of the electricity market. Most significantly, renewable power technologies have enormous environmental benefits since their use tends to avoid air pollution and the dangers and risks of extracting uranium. They generate electricity without releasing significant quantities of CO_2 and other greenhouse gases that contribute to climate change. They also create power without relying on the extraction of uranium and its associated digging, drilling, mining, leeching, transporting, storing, sequestering and polluting of land. Indeed, this study

Table 4. The costs and benefits of nuclear and renewable power systems

	Nuclear power	Renewable electricity
Cost	High capital costs, volatile fuel costs, significant decommissioning costs, dependency on government subsidies	Comparatively lower capital costs, negligible fuel costs, independence from government subsidies
Fuel availability	Reliant on depletable and scarce supplies of uranium concentrated in a few countries	Reliant on non-depletable and plentiful supplies of fuel found in every country
Land degradation	Produces hazardous and highly radioactive waste degrading to land and harmful to human health	Produces fewer waste materials and integrates well into existing buildings and landscapes
Water use	Uses trillions of litres of water and contaminates water supplies	Uses and contaminates little or no water supplies
Climate change	Has significant greenhouse gas emissions associated with lifecycle of each power plant	Has at least half the equivalent greenhouse gas emissions of nuclear plants
Safety and security	Severe risk of occupational hazards, accidents and spills	Virtually no risk of hazards, accidents and spills, and decentralises power generation, decreases dependence on foreign fuel supplies and enhances energy security

has found they could supply more than twice the expected power needs of five Asian regions by 2010.

In a carbon-constrained world, continued Asian investment in nuclear technologies deepens reliance and dependence on diminishing stocks of usable uranium that will require more and more energy input to enrich to fuel-grade status. Renewable electricity technologies, by contrast, require little or no energy input to harness free and clean fuels widely available in Asia. The most effective response to electricity demand in an Asia facing climate change should consequently include an expansion in the use of renewable electricity and a more limited use of nuclear power.

Notes

1 In 2007 US dollars.
2 *Ibid.*

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Appendix A1. Major Nuclear Power Accidents 1952–2010

Date	Location	Description	Fatalities	Cost (US$ million 2006)
12 December 1952	Chalk River, Ontario, Canada	Hydrogen explosion damages reactor interior, releasing 30 kg uranium oxide particles	0	45
8 October 1957	Windscale, UK	Fire ignites plutonium piles, destroys surrounding dairy farms	33	78
24 May 1958	Chalk River, Ontario, Canada	Fuel rod catches fire and contaminates half of facility	0	67
26 July 1959	Simi Valley, California, USA	Partial core meltdown takes place at Santa Susana Field Laboratory's Sodium Reactor Experiment	0	32
3 January 1961	Idaho Falls, Idaho, USA	Explosion at National Reactor Testing Station	3	22
5 October 1966	Monroe, Michigan, USA	Sodium cooling system malfunctions at Enrico Fermi demonstration breeder reactor causing partial core meltdown	0	19
2 May 1967	Dumfries and Galloway, Scotland	Fuel rod catches fire and causes partial meltdown at the Chaplecross Magnox nuclear power station	0	76
21 January 1969	Lucens, Canton of Vaud, Switzerland	Coolant system malfunctions at underground experimental reactor	0	22
1 May 1969	Stockholm, Sweden	Malfunctioning valve causes flooding in Agesta pressurized heavy water nuclear reactor, short-circuiting control functions	0	14
16 July 1971	Cordova, Illinois, USA	An electrician is electrocuted by a live cable at the Quad Cities Unit 1 reactor on the Mississippi River	1	1
11 August 1973	Palisades, Michigan, USA	Steam generator leak causes manual shutdown of pressurised water reactor operated by the Consumers Power Company	0	10
22 March 1975	Browns Ferry, Alabama, USA	Fire burns for seven hours and damages more than 1600 control cables for three nuclear reactors, disabling core cooling systems	0	240
5 November 1975	Brownsville, Nebraska, USA	Hydrogen gas explosion damages the Cooper Nuclear Facility's Boiling Water Reactor and an auxiliary building	0	13
22 February 1977	Jaslovske Bohunice, Czechoslovakia	Mechanical failure during fuel loading causes severe corrosion of reactor and release of radioactivity into the plant area, necessitating total decommission	0	1700

(continued)

Appendix A1. (*Continued*)

Date	Location	Description	Fatalities	Cost (US$ million 2006)
10 June 1977	Waterford, Connecticut, USA	Hydrogen gas explosion damages three buildings and forces shutdown of Millstone-1 Pressurized Water Reactor	0	15
4 February 1979	Surry, Virginia, USA	Virginia Electric Power Company manually shuts down Surry Unit 2 in response to failing tube bundles in steam generators	0	12
28 March 1979	Middletown, Pennsylvania, USA	Equipment failures and operator error contribute to loss of coolant and partial core meltdown at Three Mile Island nuclear reactor	0	2400
25 July 1979	Saclay, France	Radioactive fluids escape into drains designed for ordinary wastes, seeping into the local watershed at the Saclay BL3 Reactor	0	5
12 September 1979	Mihama, Japan	Fuel rods at the Mihama Nuclear Power Plant unexpectedly bow and damage the fuel supply system	0	11
13 March 1980	Loir-et-Cher, France	A malfunctioning cooling system fuses fuel elements together at the Saint Laurent A2 reactor, ruining the fuel assembly and forcing an extended shutdown	0	22
22 November 1980	San Onofre, California, USA	Worker cleaning breaker cubicles at San Onofre Pressurized Water Reactor contacts an energised line and is electrocuted	1	1
11 February 1981	Florida City, Florida, USA	Florida Light & Power manually shuts down Turkey Point Unit 3 after steam generator tubes degrade and fail	0	2
8 March 1981	Tsuruga, Japan	278 workers exposed to excessive levels of radiation during repairs of Tsuruga nuclear plant	0	3
26 February 1982	San Clemente, California, USA	Southern California Company shuts down San Onofre Unit 1 out of concerns for earthquake	0	1
20 March 1982	Lycoming, New York, USA	Recirculation system piping fails at Nine Mile Point Unit 1, forcing two-year shutdown	0	45
25 March 1982	Buchanan, New York, USA	Multiple water and coolant leaks cause damage to steam generator tubes and main generator, forcing the New York Power Authority to shut down Indian Point Unit 3 for more than a year	0	56
18 June 1982	Senaca, South Carolina, USA	Feedwater heat extraction line fails at Oconee 2 Pressurised Water Reactor, damaging thermal cooling system	0	10
12 February 1983	Fork River, New Jersey, USA	Oyster Creek nuclear plant fails safety inspection, forced to shut down for repairs	0	32

(*continued*)

Appendix A1. (*Continued*)

Date	Location	Description	Fatalities	Cost (US$ million 2006)
26 February 1983	Pierce, Florida, USA	Workers discover damaged thermal shield and core barrel support at St Lucie Unit 1, necessitating 13-month shutdown	0	54
7 September 1983	Athens, Alabama, USA	Tennessee Valley Authority discovers extensive damage to recirculation system pipeline, requiring extended shutdown	0	34
23 September 1983	Buenos Aires, Argentina	Operator error during fuel plate reconfiguration causes meltdown in an experimental test reactor	1	65
10 December 1983	Plymouth, Massachusetts, USA	Recirculation system piping cracks and forces Pilgrim nuclear reactor to shut down	0	4
14 April 1984	Bugey, France	Electrical cables fail at the command centre of the Bugey nuclear power plant and force a complete shutdown of one reactor	0	2
18 April 1984	Delta, Pennsylvania, USA	Philadelphia Electric Company shuts down Peach Bottom Unit 2 due to extensive recirculation system and equipment damage	0	18
13 June 1984	Platteville, Colorado, USA	Moisture intrusion causes 6 fuel rods to fail at Fort St Vrain nuclear plant, requiring emergency shutdown from Public Service Company of Colorado	0	22
15 September 1984	Athens, Alabama, USA	Safety violations, operator error and design problems force 6-year outage at Browns Ferry Unit 2	0	110
9 March 1985	Athens, Alabama, USA	Instrumentation systems malfunction during start up, convincing the Tennessee Valley Authority to suspend operations at all three Browns Ferry Units	0	1830
9 June 1985	Oak Harbor, Ohio, USA	Loss of feed water provokes Toledo Edison Company to inspect Davis-Besse facility, where inspectors discover corroded reactor coolant pumps and shafts	0	23
22 August 1985	Soddy-Daisy, Tennessee, USA	Tennessee Valley Authority Sequoyah Units 1 and 2 fail NRC inspection due to failed silicon rubber insulation, forcing 3-year shutdown, followed by water circulation problems that expose workers to excessive levels of radiation	0	35
26 December 1985	Clay Station, California, USA	Safety and control systems unexpectedly fail at Rancho Seco nuclear reactor, ultimately leading to the premature closure of the plant	0	672

(*continued*)

Appendix A1. (*Continued*)

Date	Location	Description	Fatalities	Cost (US$ million 2006)
11 April 1986	Plymouth, Massachusetts, USA	Recurring equipment problems with instrumentation, vacuum breakers, instrument air system and main transformer force emergency shutdown of Boston Edison's Pilgrim nuclear facility	0	1001
26 April 1986	Kiev, Ukraine	Mishandled reactor safety test at Chernobyl nuclear reactor causes steam explosion and meltdown, necessitating the evacuation of 300,000 people from Kiev and dispersing radioactive material across Europe	4056	6700
4 May 1986	Hamm-Uentrop, Germany	Operator actions to dislodge damaged fuel rod at Experimental High Temperature Gas Reactor release excessive radiation to 4 km^2 surrounding the facility	0	267
22 May 1986	Normandy, France	A reprocessing plant at Le Hague malfunctions and exposes workers to unsafe levels of radiation and forces five to be hospitalised	0	5
31 March 1987	Delta, Pennsylvania, USA	Philadelphia Electric Company shuts down Peach Bottom units 2 and 3 due to cooling malfunctions and unexplained equipment problems	0	400
12 April 1987	Tricastin, France	Areva's Tricastin fast breeder reactor leaks coolant, sodium and uranium hexachloride, injuring seven workers and contaminating water supplies	0	50
4 May 1987	Kalpakkam, India	Fast Breeder Test Reactor at Kalpakkam has to shut down due to the simultaneous occurrence of pump failures, faulty instrument signals and turbine malfunctions that culminate in a refuelling accident that ruptures the reactor core with 23 fuel assembles, resulting in a two-year shutdown	0	300
15 July 1987	Burlington, Kansas, USA	Safety inspector dies from electrocution after contacting a mislabelled wire	1	1
17 December 1987	Hesse, Germany	Stop valve fails at Biblis Nuclear Power plant and contaminates local area	0	13
19 December 1987	Lycoming, New York, USA	Fuel rod, waste storage and water pumping malfunctions force Niagara Mohawk Power Corporation to shut down Nine Mile Point Unit 1	0	150
29 March 1988	Burlington, Kansas, USA	A worker falls through an unmarked manhole and electrocutes himself when trying to escape	1	1
10 September 1988	Surry, Virginia, USA	Refuelling cavity seal fails and destroys internal pipe system at Virginia Electric Power Company's Surry Unit 2, forcing 12-month outage	0	9

(*continued*)

Appendix A1. (*Continued*)

Date	Location	Description	Fatalities	Cost (US$ million 2006)
5 March 1989	Tonopah, Arizona, USA	Atmospheric dump valves fail at Arizona Public Service Company's Palo Verde Unit 1, leading to main transformer fire and emergency shutdown	0	14
17 March 1989	Lusby, Maryland, USA	Inspections at Baltimore Gas & Electric's Calvert Cliff Units 1 and 2 reveal cracks at pressurised heater sleeves, forcing extended shutdowns	0	120
10 September 1989	Tarapur, Maharashtra, India	Operators at the Tarapur nuclear power plant find that the reactor had been leaking radioactive iodine through its cooling structures and discover radiation levels of iodine-129 more than 700 times normal levels. Repairs to the reactor take more than a year	0	78
24 November 1989	Greifswald, East Germany	Electrical error causes fire in the main trough that destroys control lines and 5 main coolant pumps and almost induces meltdown	0	443
17 November 1991	Scriba, New York, USA	Safety and fire problems force New York Power Authority to shut down the FitzPatrick nuclear reactor for 13 months	0	5
21 April 1992	Southport, North Carolina, USA	NRC forces Carolina Power & Light Company to shut down Brunswick Units 1 and 2 after emergency diesel generators fail	0	2
13 May 1992	Tarapur, Maharashtra, India	A malfunctioning tube causes the Tarapur nuclear reactor to release 12 curies of radioactivity	0	2
3 February 1993	Bay City, Texas, USA	Auxiliary feed-water pumps fail at South Texas Project Units 1 and 2, prompting rapid shutdown of both reactors	0	3
27 February 1993	Buchanan, New York, USA	New York Power Authority shuts down Indian Point Unit 3 after AMSAC system fails	0	2
2 March 1993	Soddy-Daisy, Tennessee, USA	Equipment failures and broken pipes cause Tennessee Valley Authority to shut down Sequoyah Unit 1	0	3
31 March 1993	Bulandshahr, Uttar Pradesh, India	The Narora Atomic Power Station suffers a fire at two of its steam turbine blades, damaging the heavy water reactor and almost leading to a meltdown	0	220
25 December 1993	Newport, Michigan, USA	Detroit Edison Company prompted to shut down Fermi Unit 2 after main turbine experienced catastrophic failure due to improper maintenance	0	67

(*continued*)

Appendix A1. (*Continued*)

Date	Location	Description	Fatalities	Cost (US$ million 2006)
6 April 1994	Tomsk, Russia	Pressure build-up causes mechanical failure at Tomsk-7 Siberian Chemical Enterprise plutonium reprocessing facility, exploding a concrete bunker and exposing 160 onsite workers to excessive radiation	0	44
14 January 1995	Wiscasset, Maine, USA	Steam generator tubes unexpectedly crack at Maine Yankee nuclear reactor, forcing Maine Yankee Atomic Power Company to shut down the facility for a year	0	62
2 February 1995	Kota, Rajasthan, India	The Rajasthan Atomic Power Station leaks radioactive helium and heavy water into the Rana Pratap Sagar River, necessitating a two-year shutdown for repairs		280
16 May 1995	Salem, New Jersey, USA	Ventilation systems fail at Public Service Electric & Gas Company's Salem Units 1 and 2	0	34
20 February 1996	Waterford, Connecticut, USA	Leaking valve forces Northeast Utilities Company to shut down Millstone Units 1 and 2; further inspection reveals multiple equipment failures	0	254
2 September 1996	Crystal River, Florida, USA	Balance-of-plant equipment malfunction forces Florida Power Corporation to shut down Crystal River Unit 3 and make extensive repairs	0	384
5 September 1996	Clinton, Illinois, USA	Reactor recirculation pump fails, prompting Illinois Power Company to shut down Clinton boiling water reactor	0	38
20 September 1996	Senaca, Illinois, USA	Service water system fails and prompts Commonwealth Edison to close LaSalle Units 1 and 2 for more than 2 years	0	71
9 September 1997	Bridgman, Michigan, USA	Ice condenser containment systems fail at Indiana Michigan Power Company's D.C. Cook Units 1 and 2	0	11
25 May 1999	Waterford, Connecticut, USA	Steam leak in feed-water heater causes manual shutdown and damage to control board annunicator at the Millstone Nuclear Power Plant	0	7
18 June 1999	Shika, Ishikawa, Japan	Control rod malfunction sets off uncontrolled nuclear reaction at Shika Nuclear Power Station's Unit-1	0	34
29 September 1999	Lower Alloways Creek, New Jersey, USA	Major Freon leak at Hope Creek Nuclear Facility causes ventilation train chiller to trip, releasing toxic gas and damaging the cooling system	0	2

(*continued*)

Appendix A1. (*Continued*)

Date	Location	Description	Fatalities	Cost (US$ million 2006)
30 September 1999	Ibaraki Prefecture, Japan	Workers at the Tokaimura uranium processing facility try to save time by mixing uranium in buckets, killing two and injuring 1200	2	54
27 December 1999	Blayais, France	An unexpectedly strong storm floods the Blayais-2 nuclear reactor, forcing an emergency shutdown after injection pumps and containment safety systems fail from water damage	0	55
21 January 2002	Manche, France	Control systems and safety valves fail after improper installation of condensers, forcing a two-month shutdown	0	102
16 February 2002	Oak Harbor, Ohio, USA	Severe corrosion of control rod forces 24-month outage of Davis-Besse reactor	0	143
22 October 2002	Kalpakkam, India	Almost 100 kg radioactive sodium at a fast breeder reactor leaks into a purification cabin, ruining a number of valves and operating systems	0	30
15 January 2003	Bridgman, Michigan, USA	A fault in the main transformer at the Donald C. Cook nuclear power plant causes a fire that damages the main generator and back-up turbines	0	10
10 April 2003	Paks, Hungary	Damaged fuel rods haemorrhage spent fuel pellets, corroding heaver water reactor	0	37
9 August 2004	Fukui Prefecture, Japan	Steam explosion at Mihama Nuclear Power Plant kills 5 workers and injures dozens more	5	9
19 April 2005	Sellafield, UK	20 tonnes uranium and 160 kg plutonium leak from a cracked pipe at the Thorp nuclear fuel reprocessing plant	0	65
16 May 2005	Lorraine, France	Sub-standard electrical cables at the Cattenon-2 nuclear reactor cause a fire in an electricity funnel, damaging safety systems	0	12
16 June 2005	Braidwood, Illinois, USA	Exelon's Braidwood nuclear station leaks tritium and contaminates local water supplies	0	41
4 August 2005	Indian Point, New York, USA	Entergy's Indian Point Nuclear Plant, located on the Hudson River, leaks tritium and strontium into underground lakes from 1974 to 2005		30
6 March 2006	Erwin, Tennessee, USA	Nuclear fuel services plant spills 35 litres of highly enriched uranium, necessitating 7-month shutdown	0	98
24 December 2006	Jadugoda, India	One of the pipes carrying radioactive waste from the Jadugoda uranium mill ruptures and distributes radioactive materials over more than 100 km^2	0	25

(*continued*)

Appendix A1. (*Continued*)

Date	Location	Description	Fatalities	Cost (US$ million 2006)
18 July 2007	Kashiwazaki, Japan	The Tokyo Electric Power Company announces that their Kariwa nuclear plant leaks 1192 litres of radioactive water into the Sea of Japan after being damaged by a 6.8 magnitude earthquake	0	2
4 June 2008	Ljubljana, Slovenia	Slovenian regulators shut down the Krsko nuclear power plant after the primary cooling system malfunctions and coolant spills into the reactor core	0	1
14 June 2008	Fukushima Province, Japan	A 7.2 magnitude earthquake cracks reactor cooling towers and spent fuel storage facilities, spilling 19 litres of radioactive wastewater and damaging the Tokyo Electric Power Company's No. 2 Kurihara Power Plant	0	45
4 July 2008	Ayrshire and Suffolk, UK	Two British Energy nuclear reactors (the Largs and the Sizewell B facilities) shut down unexpectedly after their cooling units simultaneously malfunction, damaging emergency systems and triggering blackouts	0	10
13 July 2008	Tricastin, France	The nuclear power operator Areva reports that dozens of litres of wastewater contaminated with uranium are accidentally poured on the ground and runoff into a nearby river	0	7
15 March 2009	Oskarshamn, Sweden	A maintenance worker repairing a shutdown reactor at the Oskarshamn dies after falling from the top of the turbine hall	1	0
12 August 2009	Gravelines, France	Assembly system fails to properly eject spent fuel rods from the Gravelines Nuclear Power Plant, causing the fuel rods to jam and the reactor to shut down	0	2
27 August 2009	St Petersburg, Russia	A cracked discharge accumulator and malfunctioning feed pump force the Leningrad Nuclear Power Plant reactor number 3 to close for extended repairs	0	110
1 February 2010	Montpelier, Vermont, USA	Deteriorating underground pipes from the Vermont Yankee nuclear power plant leak radioactive tritium into groundwater supplies in Vermont, resulting in the eventual shutdown of the plant	0	700

Source: American University (1996), Cadwallader (2005), Sovacool (2008b), Greenpeace (2008), Tripathi et al. (2008), Sovacool and Cooper (2008), Bellona (2009), Associated Press (2010).