

Critically weighing the costs and benefits of a nuclear renaissance

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This article was submitted as a runner up and introduction to JIES 7.3, a special issue on the policy, science and dilemmas of nuclear energy in the 21st century. It provides an overview of some of the key challenges surrounding the so-called 'nuclear renaissance'. It provides a broad context for the more specific concerns with the social and political aspects of radioactive waste which will be considered in the next issue.

What are the likely consequences of a global nuclear power renaissance? This article answers that question by exploring six categories of costs and benefits associated with modern nuclear power plants: capital and production costs, safety and reliability, fuel costs, land degradation, water use, and greenhouse gas emissions. After weighing arguments on both sides, when costs and benefits are normalized across studies and different reactor types, the article finds that the typical nuclear power plant has 8.6 cents of damages attached to every kilowatt-hour of electricity it produces, and the industry as a whole has \$223.7 billion worth of net damages every year. These costs are so large (and unavoidable) that in most countries investments in nuclear power do not occur, and they raise doubts as to whether a nuclear renaissance will produce net benefits to society.

Keywords: nuclear energy; nuclear power; atomic energy; nuclear renaissance

1. Introduction

To frame the current debate over modern nuclear power plants, this article explores the costs and benefits of a global nuclear renaissance. It argues that desired sources of electricity supply ought to produce electricity at low cost, operate securely and reliably, utilize abundant sources of fuel, minimize destruction of land and pollution, use the least amount of water possible, and emit low amounts of greenhouse gases. It then tests these six theoretical attributes for nuclear power plants, investigating their (1) capital and production costs; (2) safety and reliability; (3) fuel availability; (4) land use, waste, and pollution; (5) water use; and (6) greenhouse gas emissions. When weighing the evidence, and explaining the different methodologies and assumptions behind the pros and cons, the article concludes that nuclear power plants present immense costs that raise doubts as to whether a nuclear renaissance will produce net benefits to society.

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2. Capital and production costs

The first dimension, capital and production costs, exhibits favorable and unfavorable attributes to nuclear power. On the advantageous side, nuclear power plants do have very low historic production costs and have recently improved their performance due to better capacity factors and operating procedures. Their key word here is *historic*: many of these plants have been operating for years, and their capital costs have all but been paid off. On the disadvantageous side, nuclear power plants have long construction lead times, are exposed to cost overruns, and future plants will likely be much more expensive than ones already built.

As one advantage, although particular production costs will differ by design, site requirements, and rate of capital depreciation, existing light-water reactors, which make up a majority of the world's nuclear power generation, produced electricity at costs between 2.5 cents/kWh and 7 cents/kWh, making them cheaper than almost any other source of electricity on the global market today (Schiermeier et al. 2008). (Some coal plants and hydroelectric facilities also produce power as cheaply as 2 cents/kWh, but all other sources of supply tend to cost more than 5 cents/kWh).

A second advantage concerns improvements in operational performance and maintenance, due largely to decades of research and development along with government subsidies. The World Nuclear Association tells us that existing plants in the United States, for example, have improved their capacity factor 40% from 1990 to 2008, with the average plant now operating 91.1% of the time (World Nuclear Association 2009).

Notwithstanding the advantages of operational nuclear power plants, constructing new plants often takes a very long time due to their capital intensive nature. While high on capital and low on running costs, reactors are relatively expensive when the two are combined. Nuclear plants are capital intensive at every stage of the fuel cycle, from construction, fuel reprocessing, and waste storage to decommissioning and research concerning new nuclear technology. Although most studies assume that a nuclear plant will take 60–72 months to build, the historical record of actual construction times shows a different trend. As Table 1 depicts, average construction times for all 376 new nuclear power plants built from 1976 to 2007 – that is, the time measured from the first pour of concrete to the first grid connection of the unit – were greater than 90 months. In some particular places, construction lead times were even worse: the average lead time for nuclear power plant construction in the 1980s in Europe was more than 132 months (Soderholm 1998). The last four reactors

Table 1. Average global construction time for nuclear reactors, 1976–2007.

Period	Number of reactors	Average construction time (months)
1976–1980	86	74
1981–1985	131	99
1986–1990	85	95
1991–1995	29	104
1996–2000	23	146
2001–2005	20	64
2006	2	77
2007	3	80

built in France, two units in Chooz and two in Civaux, took 186 and 150 months, respectively, to build (Greenpeace 2008).

Because of these long lead times, building a new nuclear power plant meets with a tenacious web of uncertainties during the construction process, the most severe of which is exposure to cost overruns. One 2009 assessment explored estimated and actual U.S. nuclear power plant construction costs from 1966 to 1977 – when a majority of American reactors were built – and found that in every case plants cost at least *twice as much* as expected (Ramana 2009). The results of that study are presented in Table 2. The quoted cost for these 75 plants was \$89.1 billion, but the real cost was a monumental \$283.3 billion (U.S. Congressional Budget Office 2008). These numbers tell only part of the story as they refer to only those plants that were actually built; another 130 reactors had billions of dollars funneled into them before they were abandoned in the 1970s and 1980s (Hatch 1996).

At least five factors appear to contribute to the prevalence of cost overruns in nuclear power plant construction. First is the historical genesis of nuclear power: atomic energy was not technically or economically feasible when it was embraced by the United States in 1946, meaning it did not originate as an invention from the marketplace, nor did it evolve with any particular consumers in mind. The U.S. government had to commit to 11 years of intensive research before nuclear power was even successfully demonstrated (John and Hoffman 1996). Second, earlier global planners did not consider the problem of nuclear waste until after power plants began operating. Perhaps oddly, the International Atomic Energy Agency did not hold its first meeting on decommissioning and permanent waste storage until 1973, 20 years after the first reactor was built (Raffensperger 1996). Third, most cost estimates excluded decommissioning, which can sometimes equal or exceed construction costs (Raffensperger 1996). Fourth, gaps and supply chain problems led to an inflation of key parts, delays, and a shortage of trained personnel, driving costs further up. Today, for example, only one facility in the world has the forging capability to manufacture large reactor vessels (Committee on Climate Change Science and Technology Integration 2009). Fifth, many cost estimates were made by project sponsors and vendors with a penchant for inadequately deliberating about problems, underestimating the length of delays, setting contingencies too low, and ignoring risks relating to currency exchange, inflation, and public approval, factors exacerbated by a strong interest in presenting nuclear projects in terms as favorable as possible (Flyvbjerg et al. 2003).

Table 2. Estimated and actual historic U.S. nuclear power plant construction costs (in 2006 dollars).

Construction start	Number of plants	Estimated construction cost (per installed kW)	Actual construction cost (per installed kW)	Percentage over cost
1966–1967	11	\$612	\$1279	209
1968–1969	26	\$741	\$2180	294
1970–1971	12	\$829	\$2889	348
1972–1973	7	\$1220	\$3882	318
1974–1975	14	\$1263	\$4817	381
1976–1977	5	\$1630	\$4377	269

Because of their capital intensity, long construction times, and proclivity for cost overruns, a score of studies conducted in the past 5 years of new nuclear power plants in Canada, China, Japan, South Korea, United Kingdom, and United States have confirmed that nuclear supplies could be the most expensive source of electricity on the market (Hao 2003; Steve 2005; Jim 2007; Kennedy 2007; The Keystone Center 2007). These studies have noted that a typical 1,000 megawatt (MW) plant will often cost \$3.6 to \$8 billion dollars. These studies found that most of the quoted estimates did not include interest during construction, borrowing fees, and the expense of decommissioning, meaning they sometimes underestimated the total cost of a plant by a factor of two or more. Within the first few months of 2009, the latest production estimates for a new generation of reactors have jumped to a range of 8.4 cents/kWh to 30 cents/kWh, meaning the most recent cost projections are four times higher than those made in 2000 and 2001. That study noted that the additional cost of building 100 new nuclear reactors in the United States, rather than pursuing cheaper methods such as energy efficiency, would amount to an extra \$1.9 to \$4.4 trillion over the life of the reactors (Cooper 2009a).

The financial risks of new nuclear reactors has led Wall Street firms to indicate that it will be difficult, if not impossible, to sell bonds to support these projects in capital markets (Cooper 2009b). Even in the United States, which under its Energy Policy Act of 2005 authorized \$18.5 billion in loan guarantees to cover 80% of building new reactors, the incentives were still not enough to catalyze investment (Wald 2009). As one global survey put it bluntly, “the economic cost of nuclear power has been a key barrier to the construction of new reactors around the world” (Ramana 2009). And as the physicist Amory Lovins et al. recently mused, once claimed to be “too cheap to meter”, nuclear power may now be “too costly to matter” (Lovins et al. 2008).

3. Safety and reliability

In terms of their safety and reliability, nuclear power plants have the advantage of generating large increments of base-load power, and somewhat sweeping reforms implemented after accidents at TMI and Chernobyl have contributed to a stronger safety culture within the industry. Nuclear power plants have the disadvantage, however, of being so complex that almost every reactor has experienced some sort of incident or failure over its history, and even if the risk of a true meltdown is low the impact of such an accident would be very large.

As an advantage, unlike electricity resources such as wind turbines and solar panels, which generate electricity in decentralized configurations, in small increments, and dependent on wind and sunlight, nuclear reactors generate electricity almost continuously. Once a nuclear reaction starts, each reactor will produce energy for an extended period of time (usually about a year) until it needs refuelling again. This makes them well suited to providing base-load power, electricity that is “always on” and the backbone of national electricity grids (Schiermeier et al. 2008). Put into a global context, some countries such as China and India will especially need large amounts of base-load power to drive industrialization and grow their economies, making nuclear energy an attractive option (Echavarri 2008).

Also, the safety record of existing nuclear reactors has improved over time as their margins of error have improved and safety regulations have been upgraded. The industry has incorporated research findings on human factors and safety culture through groups and organizations such as the IAEA and World Nuclear Association

of Nuclear Operators, created after the Chernobyl accident in 1986 (Ramana 2009). These efforts have produced dividends, as evidenced by one meta-survey of nuclear power plant performance that found existing plants were getting safer. The study found that industry-wide, 1.04 accidents occurred per 200,000 worker hours in 1990 but only 0.28 accidents occurred per 200,000 worker hours in 2003 (Cadwallader 2005). The study noted that better occupational safety and health regulations in Europe and North America, improved medical knowledge, and better emergency care and first aid techniques have reduced the likelihood of accidents and lessened their impact when they do occur.

Nonetheless, nuclear reactors have been prone to a perhaps surprising number of incidents and accidents. Part of the confusion stems over how one defines an accident. The NRC and the nuclear community generally separate unplanned events into two classes, incidents and accidents. Incidents are unforeseen events and equipment failures that occur during normal plant operation, resulting in no offsite releases of radiation or severe damage to equipment. Accidents refer to either offsite releases of radiation or severe damage to plant equipment (Greenberg 1996). Others define an accident as an event that must involve at least 5 fatalities, 10 injuries, or 200 evacuees; more than 25 sq.km of cleanup; and/or more than \$5 million in economic losses (Hirschberg et al. 1998; Hirschberg and Strupczewski 1999; Hirschberg et al. 2004). Under these two types of definitions, the number of nuclear accidents is low. However, if one redefines an accident to be incidents that either resulted in the loss of human life or more than \$50,000 of property damage, a very different picture emerges.

Under this different definition, no less than 76 nuclear accidents totaling \$19.1 billion in damages have occurred worldwide from 1947 to 2008 (Sovacool 2008a). These numbers translate to more than one incident and \$332 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. More than 40 accidents have occurred since the Chernobyl disaster in 1986, and almost two-thirds of all nuclear accidents have occurred in the United States, refuting the notion that severe accidents are relegated to the past or to countries without modern technologies or industry oversight. While 71 out of these 76 accidents involved no fatalities, the five that did collectively killed more people than have died in commercial U.S. airline accidents since 1982.

Such findings are backed by scores of other studies. One of the first, conducted by the U.S. Atomic Energy Commission in 1975, looked at performance of early nuclear plants in terms of occupational injury and death for 32 years of development. They documented 111 accidents involving unplanned releases of radioactivity that exposed 317 people to excess radiation as high as 80,000 rads ("safe" levels are fiercely debated but generally less than 10 rads). The study documented 321 total fatalities, of which 184 occurred in construction, 212 in operations, and 16 in inspections and government functions along with a total of 19,225 injuries not involving radiation for an unusually high frequency rate of 2.75 injuries per million man-hours (U.S. Atomic Energy Commission of Occupational Safety 1975). Such incidents and accidents not only harm humans, they also take their toll on operating performance. Using data from U.S., French, Belgian, German, Swedish, and Swiss nuclear power plants, one study found mean durations of continual operation from 35 to 88 days, meaning such plants saw lots of unplanned outages, half of which were related to equipment failure (Perin 1998). Adato et al. documented more than 200

serious accidents and partial meltdowns in commercial nuclear power plants from 1960 to 1980 in the United States alone (Adato et al. 1987).

Moving ahead to this decade, a sample of U.S. plants inspected by the NRC from May 1999 to April 2004 revealed 25 serious incidents at 23 separate facilities (Cadwallader 2005). Another study of U.S. nuclear reactors identified nearly 60 accidents or near misses, events that included radiation exposure, inhalation of toxic vapors, electrical shocks, and injuries during nuclear construction or maintenance, resulting “in serious worker injuries or facility damage.” (U.S. Government Accountability Office 2007). Yet another study performed by the agency in charge of monitoring U.S. Department of Energy oversight of nuclear facilities, including research reactors and national laboratories, found that 31 of the 205 facilities did not meet government safety requirements, and that one-third of facilities did not conform to guidelines concerning high-hazard nuclear waste (U.S. Government Accountability Office 2008). A final study identified 156 serious incidents from 2001 to 2005 at U.S. nuclear power plants that included a litany of problems ranging from unplanned changes in reactor power and failures of emergency diesel generators to inadequate maintenance and human mismanagement (U.S. Government Accountability Office 2006).

Most recently, a 2009 assessment of nuclear power performance in the U.S. warned that the technology has rushed “far ahead of its operating experience”. The study noted that every state across the northern tier from Illinois to Maine has been involved in at least one nuclear accident. These involved quality assurance breakdowns, plant equipment sinking into the mud, fuel cladding failures, emergency core cooling system shortcomings, absence of emergency plans, radioactive leaks, and water contamination (Bradford 2009). Some of these accidents would be laughable if not for their seriousness, and include:

- A maintenance worker at the North Anna nuclear plant in Virginia cleaning the floor in an auxiliary building, catching their shirt on a circuit breaker, tripping the reactor, and causing a 4-day shutdown;
- An employee changing a light bulb in a control panel at Rancho Secco in California accidentally dropping it into the reactor, short circuiting sensor arrays and leading to an increase in pressure that almost cracked the entire reactor vessel;
- A blown fuse on a sump pump at Indian Point in New York rendering the cooling system incapable of removing water leaking into a cooling unit, forcing a weeklong shutdown;
- A nest of field mice causing an electrical fire that shut the San Onofre nuclear facility in California down for 1 week (Perrow 1984).

These accidents are not limited to the United States. The 200 nuclear facilities in France, including not only power plants but also uranium enrichment and conversion plants, reprocessing plants, fuel fabrication plants, surface repositories for waste, and experimental sites for geologic disposal declare in total about 700 to 800 serious incidents or significant safety events each year (Greenpeace 2008).

Given the historical record, the risk of future accidents is highly probable. Using some of the most advanced risk assessment tools available, an interdisciplinary team at MIT 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 MIT team estimated that at least 4 serious core damage accidents will occur and concluded that “both the historical and probabilistic risk assessment data show an unacceptable accident frequency. The potential impact on the public from safety or waste management failure . . . makes it impossible today to make a credible case for the immediate expanded use of nuclear power” (Beckjord et al. 2003).

The cost of a single serious meltdown could be astronomical. The first detailed study carried out by the U.S. Atomic Energy Commission in 1957 presumed a small accident at a 100 to 200 MW research reactor near a major city and estimated 3,400 immediate deaths, 43,000 injuries, and \$7 billion in property damage. The estimate was revised upwards for being too conservative in 1964 to 45,000 immediate deaths, 70,000 injuries, and \$17 billion or more in damages. More recent studies, looking at larger reactors in the 1,100 MW range, have noted that as many as 103,000 immediate fatalities could occur along with \$300 billion in damages (Greenberg 1996).

Indeed, four factors seem to increase the risk of accidents and possibly offset improvements in safety culture. The first is that nuclear power plants used to be sited more remotely (meaning an accident would affect fewer people), but now tend to be sited closer to population centers (Greenberg 1996). Sites that had once been remote when reactors started have become more populated over time; regions in which nuclear power is most attractive tend to be urban and have a limited number of remote locations; and substantial losses and costs are associated with remote transmission of nuclear power, creating an incentive to situate plants closer to points of electricity consumption. The second is a scaling up of reactor sizes and the promotion of new designs that operators have little experience with. These larger reactors tend to use more fuel and create more heat, meaning they have bigger cores containing larger quantities of dangerous fissionable materials, increasing the magnitude of any accident that could occur. Third, the restructuring of electricity sectors around the world has motivated some operators to place profits before safety. Undue solicitude for profits of the licensee has played a large role in explaining the mishaps that have occurred at nuclear power plants. Put another way, nuclear power is least safe in environments where complacency and pressure to maximize profits are the greatest (Bradford 2009). Fourth, some of the key anthropological work on nuclear power safety culture has revealed a tendency to see incidents not as accidents, but instead as new sources of information about how a nuclear system functions. Perhaps perversely, some operators may even welcome and see value in accidents and incidents as they contribute to new knowledge about reactor and human performance (Constance 1998). This can create a norm at a particular plant that a reactor is “safest when running”, contributing to pressure to keep plants online and delay maintenance, and also to consider production of electricity first and safety second. To these operators, nuclear work is supposed to be fast and efficient, not “slowed down” by frivolous safety concerns (Perin 1998).

4. Fuel availability

One benefit to nuclear power plants is that they rely on uranium as their primary source of fuel, and that the countries controlling uranium are much friendlier and more stable than those that control most of the world’s oil, gas, and coal. A second advantage is that fuel reprocessing and advances in technology (especially breeder technology) could greatly extend the lifetime of uranium reserves. One disadvantage is

that uranium reserves are concentrated among a few countries, making self sufficiency all but impossible. A second disadvantage concerns the price volatility of uranium fuel, and a third involves the low energy payback ratio for the nuclear fuel cycle.

In 2008, the world's 370 GW of nuclear capacity needed about 65,000 tons of natural uranium to operate. It is often believed within the industry that this amount of uranium can be obtained from existing mines and sufficient secondary sources, new mines hold enough reserves to support an expansion of nuclear generation, and no fuel shortages will occur in the next decade. As one study put it, "uranium is an abundant commodity, produced in many countries with a wide range of geopolitical situations" (Echavarri 2008).

A related advantage concerns the promise of technological improvements in the nuclear fuel cycle, especially involving breeder reactors and advanced designs. Reprocessing of spent fuel and the recycling of fuel rods has the potential to increase by 30–50% the energy harnessed from a ton of natural uranium, and if the industry ever develops fast neutron and breeder systems, nuclear energy could become a "quasi-renewable source" of electricity (Echavarri 2008). Breeder reactors, which would make plutonium from uranium isotopes, could theoretically create more fuel than they use, meaning a single breeder reactor could get 60 times more energy out of a kilogram of uranium than existing systems (Schiermeier et al. 2008).

Nonetheless, while historical reserves of uranium have been plentiful, security of future supplies is uncertain. The International Atomic Energy Agency, for instance, estimates in their Red Book that primary supply of uranium will cover only 4–6% of the industry's need for fuel in 2025. They warned in 2001 that low-cost ores are being rapidly expended and countries are being forced to explore harder to reach more expensive sites (International Atomic Energy Agency 2001). Even more worrying is that the Red Book has been accused of historically overestimating uranium mining capacity and availability of reserves, with upward exaggerations of 20–30% common (Dittmar 2009). One study from the Institute of Particle Physics of ETH Zurich and CERN cautioned that extraction from known mines and secondary resources during the coming 5–10 years appears to be much more critical than generally believed, and almost no country that uses nuclear energy is self sufficient in fuel production. Table 3, for example, shows that virtually every country producing uranium is now past its peak, and that a deficit occurred in 2008 between uranium supply and demand (with demand for natural uranium exceeding supply) (Dittmar 2009). As Table 3 depicts, Germany and France have essentially stopped uranium mining, Japan, the United Kingdom, South Korea, and Sweden never had any substantial mining operations of their own, and production in the United States is not even sufficient to satisfy 10% of national demand.

For the past 15 years, only about two-thirds of global uranium requirements (between 31,000 and 44,000 tons) have been extracted from actual uranium mines, with the shortfall made up of civilian and military stocks of uranium and plutonium built up over the cold war along with mixed oxide reprocessing. These secondary sources, however, are becoming rapidly exhausted, convincing the Nuclear Energy Agency and the IAEA to declare in the press release of their Red Book 2007 that "most secondary resources [of uranium] are now in decline and the gap will increasingly need to be closed by new production. Given the long lead time typically required to bring new resources into production, uranium supply shortfalls could develop" (Dittmar 2009). Such pessimism was confirmed recently by another independent study on available uranium resources at 93 deposits and fields located in

Argentina, Australia, Brazil, Canada, Central African Republic, France, Kazakhstan, Malawi, Mongolia, Namibia, Niger, Russia, South Africa, United States, and Zambia (Mudd and Disendorf 2008).

A second disadvantage concerns the price of uranium, which has exhibited considerable escalation over the past few years. The uncertainty over sufficient reserves of uranium fuel, as well as long supply chains and almost complete dependence of importers, has contributed to large price spikes on the global market. As Figure 1 depicts, the cost of uranium has climbed from about \$10 per pound in

Table 3. Global uranium production and use for nuclear reactors, 2008.

Country	Nuclear power capacity (GWe)	Total uranium produced	Total uranium required	Peak production (tons) and year
United States	99	1,430	18,918	16,811 (1980/1981)
France	63.5	5	10,527	3,394 (1987/1988)
Japan	47.6	0	7,569	10 (1972/1973)
Russian Federation	21.7	3,521	3,365	16,000 (1987/1988)
Germany	20.3	0	3,332	7,090 (1965/1966)
South Korea	17.5	0	3,109	—
Ukraine	13.1	800	1,974	1,000 (1992/1993)
Canada	12.6	9,000	1,665	12,522 (2001/2002)
United Kingdom	11	0	2,199	—
Sweden	9	0	1,418	29 (1969)
South Africa/ Namibia	1.8	5,021	303	10,188 (1980/1981)
Australia	0	8,430	0	9,512 (2004/2005)
Kazakhstan	0	8,521	0	8,521 (2008/2009)
Niger	0	3,032	0	4,363 (1981/1982)
<i>World</i>	<i>372</i>	<i>43,853</i>	<i>65,000</i>	<i>69,692 (1980/1981)</i>

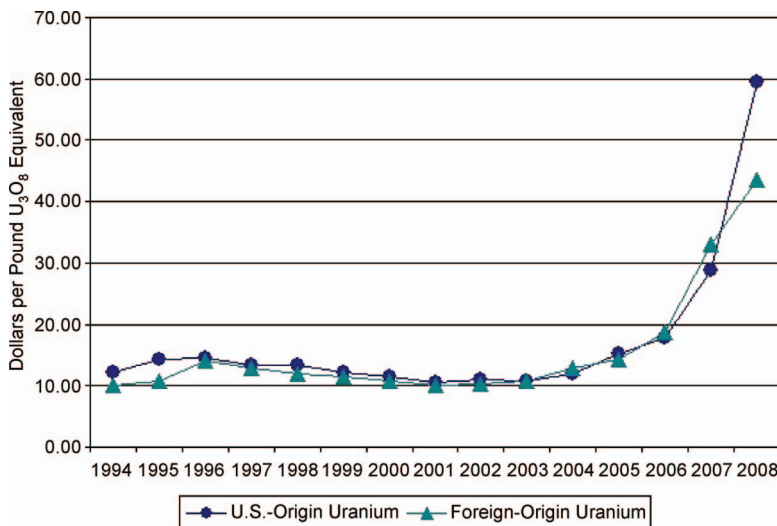


Figure 1. Average price of U.S. and foreign purchased uranium in dollars per pound, 1994 to 2008 (U.S. Energy Information Administration 2009).

1994 to \$42 in 2007 and \$60 per pound in 2008 for purchases in the United States. Since the price of uranium fuel accounts for about 15% of the lifetime costs of a nuclear plant, these increases in the price of fuel make predicting the operating costs of a nuclear plant close to impossible and also mitigate their profitability.

A third disadvantage relates to the energy payback ration of the nuclear fuel cycle, or how much energy one gets out of a nuclear power plant after they deduct the energy needed for construction, operation, fueling, decommissioning, and storage. Helen Caldicott has noted, for example, that a nuclear power plant must operate at full load for 10–18 years before it has paid off its energy debts (Caldicott 1994). A separate study looking at the energy payback ratio of different electricity systems, the ratio of total energy produced compared to the energy needed to build and operate an energy system, found that hydroelectric, wind, and biomass power plants are at least 1.5–20 times more efficient than nuclear reactors (Gagnon 2008).

5. Land use, waste, and pollution

One benefit to nuclear power plants is that they produce an incredibly small volume of waste and pollution compared to fossil-fueled power stations. The drawback is that the waste they do produce is extremely hazardous and lasts for thousands of years.

On the one hand, the impact on human health and environmental quality from fossil fuel combustion is more immediately drastic than nuclear power since nuclear waste becomes less toxic with time as radioactive materials decay, whereas the chemicals emitted from fossil fuels become quickly ingested by humans and other organisms. As Hans Blix, the former Director General of the IAEA, succinctly put it:

A 1,000 megawatt equivalent (MWe) coal plant with optimal pollution abatement equipment will annually emit into the atmosphere 900 tons of sulfur dioxide, 4,500 tons of nitrous oxide, 1,300 tons of particulates, and 6.5 million tons of carbon dioxide By contrast, a nuclear plant of 1,000 MWe capacity produces annually some 35 tons of highly radioactive spent fuel (Blix 2001).

One study estimated that the waste generated by a large nuclear plant per year was 2 million times smaller by weight and a billion times smaller by volume than wastes from a coal-burning plant (Cohen 1998). Such attributes have made nuclear power as attractive as wind and solar energy to some advocates wishing to produce electricity with minimal damage to the environment (Pacala and Socolow 2004).

On the other hand, critics respond that the depiction of nuclear power as environmentally friendly is disingenuous, since the technology generates some of the most toxic, long-lived and life-endangering wastes known to human kind (Byrne and Hoffman 1996). Because nothing is burned or oxidized during the fission process, nuclear plants convert almost all their fuel to waste with little reduction in mass. About 10,000 tons of spent nuclear fuel is discharged every year from nuclear power plants. Only 15% of this is reprocessed, and a single nuclear plant will usually produce 30 tons of high-level waste each year, waste that can be radioactive for as long as 250,000 years.

The waste problem is so technically difficult to handle and socially intractable with the public that in the past some countries got around the issue by dumping

nuclear waste into the sea. France, for example, from 1967 to 1969 dumped more than 12,000 cubic meters of high level waste from reprocessing plant at Marcoule into the ocean (Greenpeace 2008). For many years the UK organised a sea dump of radioactive waste in the North East Atlantic for its own wastes and those from Belgium, Switzerland and the Netherlands. The practice was suspended from 1983 after protests from trade unions, Greenpeace and international objections and was later outlawed. The far more benign strategy of building a permanent geologic repository for spent fuel has proven almost as problematic. The Barack Obama Administration cancelled plans for the federal government's proposed centralized waste repository at Yucca Mountain in Nevada after spending billions of dollars on the project over more than two decades. It now has nowhere to place the 70,000 tons of waste currently being stored on-site at nuclear power plants and other facilities scattered throughout the country, meaning the government is faced with having to site and build a second repository before a first one has even been licensed or constructed (von Hippel 2008).

As a final, health-related disadvantage, normally functioning nuclear reactors are still correlated with higher risks of cancer and unexplained deaths. Reactors create more than 100 dangerously radioactive chemicals, including Strontium-90, Iodine-131 and Caesium-137, the same toxins found in the fallout from nuclear weapons. Some of these contaminants, such as Strontium-90, remain radioactive for 600 years, concentrate in the food chain, are tasteless, odorless, and invisible, and have been found in the teeth of babies living near nuclear facilities. Plutonium is so dangerous that one pound evenly distributed could cause cancer in every person on earth, it remains radioactive for 500,000 years, and it mimics iron in the body (Caldicott 1994). New evidence from the United States has documented elevated rates of leukaemia and brain cancers at nuclear power plants and has been blamed for causing 18,000 infant deaths and 6,000 childhood cancers over a period of 20 years (Sovacool 2009).

Some evidence has implied that health and environmental risks are unnecessarily exacerbated by "regulatory capture" or "regulatory laxity" terms that describe when the agencies responsible for regulating nuclear power begin to promote the industry's interests over those of the public. For instance, in the 1960s uranium miners were exposed to excessively high levels of radon, hundreds died of lung cancer and thousands more had their lives shortened; and uranium mill tailings were discharged with impunity into water sources throughout the United States. The radium leached from these tailings contaminated thousands of miles of the Colorado River system, yet when Atomic Energy Commission officials were asked about this pollution in 1958, they responded that they would not penalize operators who allowed their tailings to enter streams because "we will not try to put them out of business because that in turn would put us out of business" (Cook 1982a). Another case occurred between 1966 and 1971, when thousands of homes and commercial buildings in the Colorado Plateau region were found to contain anomalously high concentrations of radon after having been built on uranium tailings taken from piles under the authority of the AEC (Cook 1982b). Lastly, and more recently, when the NRC tried to strengthen its regulation of the industry after a string of embarrassing incidents at U.S. nuclear facilities, Senator Pete Domenici, a strong advocate of nuclear power and uranium mining, threatened to cut the agency's budget by one-third if the NRC did not change its "adversarial attitude" toward the industry (Bradford 2009).

6. Water use

In terms of water use, nuclear power plants produce lots of heat and can therefore be used to desalinate seawater. However, a nuclear reactor also needs large amounts of water for its cooling system and risks a variety of environmental impacts relating to water consumption and withdrawals.

As an advantage, most desalination techniques in operation around the world rely on fossil fuels, and therefore contribute to climate change and the environmental consequences of oil, coal, and gas combustion and use. Total world desalination capacity is approaching 40 million cubic meters of water per day, desalinated by some 15,000 conventional plants in the Middle East and North Africa relying on distillation processes and reverse osmosis (World Nuclear Association 2008). Nuclear reactors have been shown to desalinate water at the same cost as these plants but without the associated greenhouse gas emissions, with integrated nuclear desalination plants operating in India, Japan, and Kazakhstan.

Perhaps an even greater disadvantage, though, is that nuclear reactors need immense amounts of water to cool reactor cores and spent nuclear fuel rods. In fact they use the most water (about 46 gallons of water for every kWh generated) compared to all other electricity generating facilities, including conventional coal and natural gas facilities. At the point of intake, nuclear plants bring water into the cooling cycle through intake structures. Seals, sea lions, endangered 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 and frequently pulverized by reactor condenser systems in a process known as *entrainment*. One study estimated that more than 90% of marine organisms surrounding a typical nuclear facility are scalded and discharged back into the rivers, streams, and oceans as lifeless sediment (Gunter et al. 2001).

The water-related impacts from nuclear plants can become quite severe and costly. In the United States, for instance, studies of nuclear power plants operating in California, Florida, Delaware, Ohio, New York have shown that they can impinge and entrain millions of fish with damages exceeding \$8.1 million per year in losses in fishery yield (Sovacool and Sovacool 2009). Nuclear plants in China, France, India, United Kingdom, and the United States have also been noted to exacerbate water shortages during droughts or risk power outages when plants are unable to operate due to lack of water.

7. Greenhouse gas emissions

Nuclear power plants have both advantages and disadvantages from a climate change standpoint: they have a much smaller carbon footprint than fossil fuels, but are still worse than energy efficiency and renewable sources of electricity.

From a strict climate-change perspective, nuclear power is an improvement over conventional coal-burning power plants. A nuclear power plant does not directly produce greenhouse gas emissions (unless it is running idle, being refuelled, or operating on backup generators) and it emits about one-tenth to one-twentieth the carbon dioxide emissions over the course of its lifecycle to a comparatively sized conventional, fossil fueled power plant (Echavarri 2008).

Still, reprocessing and enriching uranium requires a substantial amount of electricity, often generated from fossil fuel-fired power plants, and uranium milling, mining, 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 CO₂ emissions over the typical lifetime of a plant are about 66 grams for every kWh, or the equivalent of some 183 million metric tons of CO₂ in 2005 (Sovacool 2008b). If the global nuclear industries were taxed at a rate of \$24 per ton for the carbon equivalent emissions associated with its lifecycle, the cost of nuclear power would increase by about \$4.4 billion per year. These costs are apart from the actual damage associated with greenhouse gas emissions, damages that could amount to as much as \$3,500 per ton of carbon dioxide after it has been emitted (Carlin 2008). If that estimate is correct, then the cost of removing the annual emissions connected with nuclear power plants would exceed \$640 billion. A secondary impact is that by producing large amounts of heat, nuclear power plants contribute directly to global warming by increasing the temperature of water bodies and localized atmospheres around each facility (Nordell and Gervet 2008).

8. Putting it all together

What happens when one puts all of the costs and benefits from nuclear power together? Historian Peter Novick once compared compiling statistics to trying to “nail jelly to the wall”. The process of collecting and synthesizing data on the costs of nuclear power is complicated and imperfect. This is partly because there are so many things to include, from money for constructing and maintaining permanent waste storage sites, the risk of a catastrophic accident, and the price of decommissioning plants. Not all things can be quantified; not all of those that can be are consistent; and most methods suffer from methodological shortcomings. Incorporating the price of negative externalities, however, provides a more accurate picture of the real costs of nuclear energy. While definitely imperfect, it is much better at nailing the jelly to the wall.

Defined as costs and benefits resulting from an activity that do not accrue to the parties involved in the activity, “externalities” have won attention in recent decades as a way to make equitable choices concerning electricity supply. Lee explains that “externalities are part of the overall social cost of producing electric power . . . including the value of any damages to the environment, human health, or infrastructure” (Lee 1995). Another report from the U.S. Department of Energy defines externalities as “inadvertent and unaccounted for effects of one or more parties on the welfare of another” (U.S. Department of Energy and the Commission of the European Communities 1992).

Externalities can be both positive and negative. A positive externality would be a renewable power plant such as a wind turbine or solar panel that not only produces electricity, but avoids polluting the air and water (things that are not always fully valued). A negative externality would be unregulated pollution from a smokestack. A factory produces items that are priced by taking into account the demand for the products, labor, capital, and other costs, but the damages from the factory’s

pollution – health and other effects – are negative costs borne by society that are unaccounted for in the price of the factory's widgets.

The full set of positive and negative externalities associated with nuclear power generation are vast, but a partial list would at least include:

- Catastrophic risks such as nuclear meltdowns and accidents;
- An increased probability of wars due to rapid uranium extraction, the boom and bust cycles of uranium mining communities, or the inability to secure fissile materials associated with the nuclear fuel cycle;
- Public health issues and chronic exposure to radiation and its consequent advanced morbidity and mortality, as well as worker exposure to toxic substances and occupational accidents and hazards;
- Direct land use by power plants, uranium mines, enrichment stations and storage facilities;
- The destruction of land by uranium mining and leaching, including acid drainage and resettlement;
- The effects of water pollution on fisheries and freshwater ecosystems, sensitive to water chemistry, as well as the release of radionuclides into water sources;
- Consumptive water use, with consequent impacts on agriculture and ecosystems where water is scarce;
- Continual maintenance of caches of spent nuclear fuel;
- Changes to the local and regional economic structure through the loss of labor and jobs and transfer of wealth and reductions in gross domestic product;
- Incidence of noise and reduced amenity, lower property values near nuclear plants, and aesthetic objections.

While this list is still incomplete, Thomas Sundqvist and Patrik Soderholm analyzed as many externality estimates they could find (132 in all) to determine the extent that positive and negative externalities were connected to sources of electricity supply (see Table 4) (Sundqvist and Soderholm 2002; Sundqvist 2004). They found that net costs (negative externalities outweighed positive ones for every estimate) ranged from a low of less than 1 cent per kWh to a high of almost 65 cents per kWh for the nuclear fuel cycle, with a mean of 8.6 cents per kWh. This amount may not sound like much, but if correct it means that since nuclear units produced 2,601 billion kWh in 2008 they also generated \$223.7 billion in global social and environmental damages.

There are a number of reasons the estimates provided by Sundqvist and Soderholm are conservative. When surveying externalities, they did not include any

Table 4. Negative externalities associated with different sources of electricity supply, \$1998 (US Cents/kWh).

	Coal	Oil	Gas	Nuclear	Hydro	Wind	Solar	Biomass
Min	0.06	0.03	0.003	0.0003	0.02	0	0	0
Max	72.42	39.93	13.22	64.45	26.26	0.80	1.69	22.09
Mean	14.87	13.57	5.02	8.63	3.84	0.29	0.69	5.20
SD	16.89	12.51	4.73	18.62	8.40	0.20	0.57	6.11
N	29	15	24	16	11	14	7	16

value for climate change given the range of potential damages. In some cases the studies they analyzed relied on a “willingness-to-pay” metric to assess damages but many things (such as clear skies, pure water, or a dead child) are impossible to quantify in dollars. Furthermore, virtually none of the studies accounted for the risk of environmental damages – such as tipping points that are crossed as the earth’s climate changes, unknown ecological thresholds that are passed, and species extinctions that are fundamentally irreversible – that entail impacts impossible to recover from once they begin. Most of the studies surveyed modeled damages

Table 5. Summary of advantages and disadvantages to nuclear power plants.

Dimension	Advantages	Disadvantages
Capital costs and production costs	Low historic electricity generation costs Improved reactor performance and capacity factors	Long construction lead times for new plants Substantial risk of cost overruns Expected high future operating costs
Safety and reliability	The ability to provide around the clock base-load power in large increments Improves safety culture resulting from lessons learned from previous accidents	Human error and technological failure have resulted in hundreds of incidents and accidents The impact of an accident, even if the probability is low, would be potentially catastrophic
Fuel availability	Plentiful sources of primary and secondary uranium Fuel reprocessing and breeder reactors could greatly improve efficiency	Uranium reserves are consolidated among a small number of countries Dependence on foreign suppliers runs the risk of disruption and price volatility The nuclear fuel cycle has a lower energy payback ratio than other alternatives
Land use, waste, and pollution	Nuclear reactors produce a comparatively small volume of waste compared to fossil fueled power stations	The waste that they do produce is extremely hazardous and difficult to store Operating nuclear reactors have been shown to create health risks for local communities and workers
Water use	Nuclear reactors can be used to desalinate water	Existing nuclear power plants consume and withdraw vast quantities of water needed to operate and risk entrainment, impingement, and thermal discharges
Greenhouse gas emissions	The nuclear lifecycle has a much smaller carbon footprint than conventional fossil-fueled power stations	Nuclear reactors still entail considerable emissions from their lifecycle much greater than renewable energy resources and some other alternatives The heat discharges from nuclear power plants indirectly contribute to global warming

associated with a single power plant, and not the combined or cumulative damages from a fleet of nuclear power plants. Many studies assumed reference, rather than representative, technologies; that is, they assumed benchmark and state-of-the-art nuclear reactors instead of those used by utilities in the real world where the average age of a reactor is more than 20 years old.

9. Conclusion

A global nuclear renaissance would bring opportunities and costs. On the plus side are historically low production costs, improved performance of reactors, the ability to provide base-load power, a better safety culture, arguably plentiful sources of fuel, smaller amounts of waste, the potential to desalinate water, and fewer greenhouse gas emissions than conventional alternatives. However, Table 5 shows that these advantages are offset by long construction lead times and the risk of cost overruns, high future production costs for new plants, the ever present risk of severe accidents, dependence on volatile and consolidated sources of uranium, a deteriorating energy payback ratio for the nuclear fuel cycle, hazardous and extremely long-lived waste, large water requirements, and a larger carbon footprint than energy efficiency and renewable resources. Such a conclusion – that the advantages seem outweighed by disadvantages – is acknowledged in the literature on externalities, which show that nuclear power plants have a net 8.6 cents/kWh of damage for every unit of energy they produce.

The lesson appears to be that despite all of the talk about a forthcoming nuclear renaissance, new nuclear plants are prone to large risks. Nuclear units necessitate billions of dollars of investment before they produce even one unit of electricity. Their primary source of fuel, uranium, has exhibited extreme increases in price, tripling in cost over the past 15 years. Reactors produce spent fuel that will remain radioactive for hundreds of thousands of years and necessitate hundreds of millions of extra dollars in storage costs. Nuclear plants use and contaminate water and also impinge and entrain millions of fish and other riparian, aquatic, and marine organisms. The entire nuclear lifecycle (construction, operation, enrichment, reprocessing, and decommissioning) has a significant carbon footprint that contributes meaningfully to global climate change. About one to two accidents or serious incidents at a nuclear facility continue to occur every year. When roughly quantified and tallied, social costs external to the nuclear industry combine to equal more than \$220 billion in global social and environmental damages annually.

Why do otherwise educated people and investors still consider nuclear an attractive option? One study supposed that it is the superficially attractive narrative associated with nuclear energy that conflates it with national progress and pride coupled with an immensely powerful and effective lobby, a new generation that has either forgotten or never known why it failed previously, deeply rooted habits that favor giant power stations, and lazy reporting by a credulous press (Lovins et al. 2008). Whatever the reasons, however, in his assessment of energy use in the past 100 years Vaclav Smil concluded that “because of hasty commercialization, safety concerns, and unresolved long-term storage of its wastes, the first nuclear era has been a peculiarly successful failure” (Smil 2000). The conclusions reached by this article would only add that the second nuclear era, if it ever comes about from a new renaissance, may be just as unique a failure.

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Critically weighing the costs and benefits of a nuclear renaissance

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