UQF2101G Essay

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Introduction

Nuclear power, defined as the production of electricity by use of nuclear reactions, has come a long way - from the first nuclear power plants in the 1950s, to becoming one of the world's major energy sources. However, there are many issues surrounding the use of nuclear power, and there is much debate about its pros and cons. In order for an individual or a country to decide whether to support or oppose nuclear power, it is necessary to critically examine and compare nuclear power to other sources of electricity, before reaching a balanced conclusion.

Scope of essay This essay will examine the economic costs, risk factors, and environmental impact of nuclear reactors, and compare these to other energy generation technologies, in particular fossil fuel, wind, solar, and hydroelectric sources. Issues not directly related to electricity production, such as the use of nuclear technology in medical applications, will not be discussed.

Some technologies (in particular, solar cells) can be dispatched and used on a small scale, for domestic or industrial purposes. However, for this essay we will be restricting our discussion to utility-scale implementations of each technology, ie. plants which generate electricity directly into the grid.

Nuclear security, terrorism and proliferation are legitimate concerns related to nuclear power. Even in countries with advanced use of nuclear energy, such as France, poor waste management has created a 50-ton stockpile of plutonium, with inadequate security measures for protection (Gronlund, Lochbaum, & Lyman, 2007). However, these issues overlap and intertwine with geopolitical and other concerns, and we will not attempt any further analysis.

Economic costs

Cost of electricity We first look at the cost of different energy sources per MWh of electricity produced. This is the most direct measure of cost-effectiveness, and hence the economic feasibility, of different techologies. Furthermore, this also determines scalability of a technology, ie. whether it is able to meet a significant proportion of the energy demands of a city.

Implementing a power generation technology necessarily incurs many different expenses, such as construction/installation, operations, maintenance and fuel. These factors are taken into account when calculating the levelised cost of electricity (LCOE), an estimate of the cost of electricity per MWh over the life cycle of a power plant.

However, for variable energy sources such as wind and solar power, there are additional costs associated with storage and backup generation, as the plant itself is unable to match the output to the level of demand. Hence, instead of a direct comparison between LCOE values, which might not be meaningful. it would be better to compare the LCOE values of each technology with the levelised avoided cost of energy (LACE) as generated by current sources. Hence a positive difference (LACE − LCOE > 0) signifies that it would be cheaper to generate one additional MWh of electricity with this technology than with sources which are currently in operation.

The LCOE and LACE values of various energy sources have been estimated by the US Energy Information Administration (EIA), and are summarised in Table 1.

	Nuclear	Coal	Gas	Wind	Solar	Hydro
Capital Cost	70.1	76.9	15.9	57.7	109.8	70.7
Variable O&M	12.2	30.7	53.6	0.0	0.0	7.0
Total LCOE	95.2	115.7	72.6	73.6	125.3	83.5
LACE − LCOE	−23.2	−44.7	−1.2	−9.0	−33.9	−14.0
in 2040	−10.3	−26.6	−0.1	−3.4	−16.1	−12.2

Table 1: US average levelised costs for different plant types (in 2013 US$/MWh), projections for 2020 (except last row). Variable O&M (operations and maintenance) include fuel costs. Adapted from US EIA, 2015.

All the LACE − LCOE differences in the table are negative, indicating that there is no need for new power plants on average in the US. However, it suggests that nuclear power (and technologies such as gas and wind power) might have positive LACE − LCOE values in selected regions, and thus remain competitive. When considering long-term plans up to 2040, these technologies are seen to gain an even more marked economic advantage.

Fuel For non-renewable energy sources, another factor to consider is the volatility of fuel prices, and how this translates into price of electricity. Since modern power plants operate on the time scale of several decades, rising fuel costs over this time period might render a technology useless in the future due to economic infeasibility, even if it is cost competitive today.

Tarjanne and Rissanen (2000) conducted a sensitivity analysis on the effect of fuel prices on the cost of electricity of various sources of energy, and their results are summarised in Table 2.

To put this into perspective, a hypothetical doubling of the cost of fuel, from 75% to 150% of prices in 2000, will result in a increase in cost of 10% for nuclear electricity, 35% for coal plants, 70% for natural gas planes, and 42% for peat plants.

Most of the cost of nuclear electricity comes from capital costs associated with construction of the power plant (see Table 1). Thus, compared with coal and natural gas plants, fuel accounts for a smaller fraction of the cost of nuclear energy, and hence it can be reasonably expected that the cost of nuclear electricity is less sensitive to fuel price changes. By this measure, nuclear energy is the most economically stable of the non-renewable energy sources, within its operational life span.

Change in fuel cost	Electricity cost (€/MWh)			
	Nuclear	Coal	Gas	Peat
−25%	21.60	21.87	21.36	27.40
0%	22.31	24.43	26.33	31.27
+25%	23.03	27.00	31.30	35.15
+50%	23.74	29.56	36.26	39.02

Table 2: Impact of fuel costs on electricity generation costs in Finland (Tarjanne & Rissanen 2000). Fuel costs are given relative to prices in 2000.

Risk Factors and Safety

Nuclear accidents Of course, other than economics, we also have to consider the risks associated to nuclear power. Much of the public stigma against nuclear power, and nuclear technology in general, has arisen from the fear of catastrophic incidents, such as the reactor meltdowns at Chernobyl and Fukushima, and long-term radiation-related health effects. To justify (or debunk) these claims, we need a realistic, objective comparison between the risks of nuclear energy and other forms of energy production.

Hirschberg, Spiekerman and Dones (1998) studied severe accidents around the world from 1969 to 1996 associated with different energy production systems, and calculated key risk indicators per unit electricity generated. Their results are summarised in Table 3.

	Damage Indicator (per GWe per annum)			
	Immediate fatalities	Injured	Evacuees	Cost
Nuclear	0.01	0.10	75.7	93.5
Coal	0.34	0.07	0	0.02
Oil	0.42	0.44	7.22	0.64
Gas	0.08	0.21	5.90	0.09
LPG	3.28	13.9	522	1.74
Hydro	0.88	0.20	34.2	0.62

Table 3: Damage indicators of severe energy-related accidents, 1969–1996. Monetary costs are given in millions of 1996 US dollars per GWe per annum. Adapted from Hirschberg et al. (1998).

It is important to note a number of limitations of these figures. First, Hirschberg et al. noted that their definition of a severe accident (at least 5 fatalities, 10 injuries, or 200 evacuees, among other criteria) was designed to be inclusive, and they acknowledge that accidents with minor consequences were most likely underreported. This could lead to an underestimate of the above values, especially for fossil energy production chains (p. 283).

Second, the Chernobyl disaster single-handedly dominates most of the values for nuclear energy in Table 3, except for the number of evacuees (second only to the Three Mile Island incident), see Table 4. However, Hirschberg et al. also noted that most Western nuclear plants meet stringent requirements on engineering, regulation

Incident (Year)	Damage Indicator			
	Immediate fatalities	Injured	Evacuees	Costs
Tomsk-7 (1993)	–	–	0	–
Chernobyl (1986)	31	370	135000	339000
Three Mile Island (1979)	0	0	140000	5000

Table 4: Severe nuclear accidents, 1969–1996. Monetary costs are given in millions of 1996 US dollars. Adapted from Hirschberg et al. (1998).

and safety culture, in contrast to the Chernobyl plant, so "the Chernobyl accident is essentially irrelevant for the evaluation of the safety level" of most modern nuclear plants (p. 142).

The data presented in Table 3 can now be intepreted as follows. There are less immediate fatalities and injuries in nuclear plant accidents than for other power plants, and this conclusion is likely to be strengthened after accounting for under-reporting in the fossil fuel plants. Also, after excluding the Chernobyl accident, the number of evacuees and cost drops to 39.1/(GWe·a) and US$1.46m/(GWe·a), respectively. These values are likely to be more representative of modern nuclear plants, and they are comparable to the values for other technologies.

We note here that the Hirschberg et al. study only quantifies *immediate* effects of energy accidents, but long-term effects, such as the number of *delayed* fatalities of accidents, is also of interest in risk assessment. This is particularly relevant in the case of estimating long-term health risks (such as cancer incidence) for nuclear accidents. To put this into context, Hirschberg et al. cited the delayed fatalities for the Chernobyl accident at 2.5–8.9 per GWe per annum, though they do not give estimates for other power sources.

Chronic health risks to workers It might be expected that workers in nuclear energy-related domains receive high radiation doses, but this is not the case. The UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2008) examined the occupational radiation exposure to workers involved in the nuclear fuel cycle, along with those who worked in environments with elevated levels of radiation, see Table 5.

	Monitored Workers ($\times 10^3$)	Average annual effective dose (mSv)
Nuclear fuel cycle	660	1.0
Coal mining	6900	2.4
Other mining	4600	3.0
Aircrew	300	3.0

Table 5: Global occupational exposures due to the nuclear fuel cycle and other natural sources of radiation. Adapted from UNSCEAR (2008).

The UNSCEAR found that the occupational exposure associated with the nuclear fuel cycle is 1.0 mSv per year, which is about one-third of background levels.

Interestingly, this is less than the dose received by miners, where workers are exposed to radon gas and small amounts of radioactive minerals, and even the crew of commercial airline flights, who are exposed to more cosmic radiation at high altitudes.

Chronic health risks to public Even residents living near a nuclear power plant are not exposed to higher radiation levels than normal. Nuclear power plants do release small amounts of radioactive gas and liquid effluents into the environment, as part of waste management during normal operation. However, the dose to a person living near a nuclear plant due to these emissions is on the order of 0.001 mSv per year (Harris & Miller, 2008). This is negligible when compared to the annual background radiation dose of ~ 3 mSv.

In fact, fossil fuel power plants are responsible for hazardous pollution on a much larger scale. Atmospheric emissions, such as $PM_{2.5}$, sulphur dioxide, nitrogen oxides, ozone and carbon monoxide, are known to reduce life expectancy, cause cancer, and increase the risk of respiratory, cardiac and cerebrovascular conditions (Markandya & Wilkinson, 2007).

To quantify this effect, Markandya and Wilkinson (2007) have reviewed the health effects of electricity generation in Europe, see Table 6.

	Deaths	Serious illness	Minor illness
Nuclear	0.052	0.22	–
Coal	24.5 (6.1–98.0)	225 (56.2–899)	13288 (3322–53150)
Gas	2.8 (0.70–11.2)	30 (7.48–120)	703 (176–2813)
Oil	18.4 (4.6–73.6)	161 (40.4–645.6)	9551 (2388–38204)

Table 6: Air pollution-related effects of electricity generation in Europe. Values are given in deaths/cases per TWh, with 95% CIs. Adapted from Markandya and Wilkinson (2007).

Even with the large uncertainty in these estimates, it is clear that the number of deaths and serious illnesses per unit electricity caused by nuclear power is substantially less than those of other fossil fuel plants.

On the basis of this and other historical data, Kharecha and Hansen (2013) calculated that the use of nuclear energy instead of coal and oil had prevented 1.86 million deaths from 1971 to 2009, as compared to 4900 deaths caused by nuclear energy. They also predict that between 0.42 and 7.04 million deaths will be averted by the use of nuclear energy between 2010 and 2050. These figures were arrived at without taking into account the effects of anthropogenic global warming, the full effects of which will not be discussed here. This makes a strong case for nuclear energy over fossil fuels, as measured by human cost.

Environmental impact

Greenhouse gas emissions As global warming increases in prominence in relation to energy production in the next few decades, the amount of greenhouse gases that an energy source produces, commonly known as the 'carbon footprint', has become an important metric of environmental impact. Therefore, estimating and reducing the carbon footprint of electricity is a central concern to evaluating the impact of nuclear energy on the environment.

However, it is not straightforward to calculate a standardised value of the carbon footprint which can be compared across different sources, whose gaseous emissions might be of different compositions. In order to do so, for each greenhouse gas one must first determine its *global warming potential* (GWP), ie. ability to trap heat in the atmosphere, as a multiplicative factor relative to CO_2. Then, by measuring the quantity of each type of gas emitted at a source, each weighed by their GWP factor, the total greenhouse effect of the emissions can be expressed by the CO_2 mass equivalent.

	Nuclear	Coal	Gas	Solar	Hydro	Wind
Emissions	12	820	490	48	24	11

Table 7: Median life cycle emissions of electricity sources, in grams CO_2 equivalent per kWh. Adapted from Schlömer et al. (2014).

Table 7 summarises the analysis of the emissions of various energy sources carried out by Schlömer et al. (2014). Fossil fuel plants, with combustion as the main step in electricity production, have emissions an order of magnitude higher than the other sources.

Also, even for 'low-carbon' technologies, there are significant variations in the carbon footprint, due to the different energy-intensive phases in the respective life cycles of the energy sources: silicon extraction and purification for solar cells, dam construction for hydroelectricity, uranium mining for nuclear power, and steel/concrete manufacturing and construction for wind turbines (UK Parliamentary Office of Science and Technology [POST], 2006).

Although a reduction in carbon footprint is expected in some of these phases, most notably in development of new materials for solar cells (POST, 2006), such reduction is limited in most cases by the inherent nature and design of the power system. Nuclear energy, which currently has close to the lowest greenhouse emission levels among all energy sources, can thus be expected to remain as such in the near future.

Other environmental impact All power plants generate waste and have other adverse effects to the environment during their life cycle. Some of these major impacts are summarised in Table 8. The comparison of diverse and complex issues surrounding the waste disposal and environmental impact of other energy production technologies are beyond the scope of this essay.

Nuclear waste management Around 11500 metric tons of heavy metal are generated every year, of which 8000 tons need to be stored in specialised facilities (International Atomic Energy Agency [IAEA], 2006). High-level waste, such as spent nuclear fuel, accounts for most of the radiation generated by nuclear waste, and thus the treatment and disposal of high-level waste is of central concern to the nuclear industry.

Spent nuclear fuel is composed of 95-96% uranium, 1% plutonium, and 3-4% fission products (IAEA, 2006). Some countries may choose to reprocess this waste to

Nuclear	Release of radioactive material from major accidents, eg. Chernobyl, Fukushima
Coal	Mercury emissions; radiation from fly ash (McBride, Moore, Witherspoon, & Blanco, 1978)
Oil	SO_2 and NO_x emissions; toxicity of petroleum
Wind	Pollution associated with extraction of rare earth metals for use in magnets, particularly neodymium and dysprosium (Alonso et al., 2012)
Hydro	Impact on river ecosystem; erosion of sedimentary deposits downstream
Solar	Energy used in silicon extraction; toxic heavy metals used in cells, such as cadmium and lead

Table 8: Environmental impacts of various energy sources throughout their life cycle.

recover the uranium and plutonium for reuse in nuclear plants, while others dispose of them without further reprocessing. In either case, the fission products present in the high-level waste have half lives on the scale of tens to hundreds of thousands of years, and must be stored in geological repositories designed for this time scale (IAEA, 2006). However, many countries have been unable to propose such storage sites for their nuclear waste, including the US after the Yucca Mountain Project was cancelled in 2011.

In short, despite continued interest in this issue, a satisfactory long-term solution to nuclear waste has not yet been found in many cases. However, there has been decades of experience with short-term storage of high-level wastes. For example, storage pools at reactors, used for initial cool down of used fuel rods, can be adapted to store high-level wastes for decades, by expanding their capacity by up to five times (Gronlund et al., 2007). Another solution is to place the waste in steel cylinders, additionally protected by concrete or more steel, and store them as dry casks. These interim solutions are safe and economically viable for at least 50 years (Gronlund et al., 2007).

Conclusion

Having analysed the economic, risk, and environmental aspects of nuclear power in relation to other power sources, many of the arguments against it have been inaccurate, or even untenable. Nuclear power is cost-effective in selected regions, to a greater extent than many other energy sources, renewable or otherwise, and will remain so for the next few decades. Once constructed, nuclear electricity prices have more stability against fuel price changes as compared to fossil fuel. Energy from modern nuclear plants come at a much smaller human cost than other sources, both in terms of accidents and chronic health effects. In addition, nuclear energy has one of the smallest carbon footprints, and current waste management technologies are feasible for at least 50 more years.

These results in support of nuclear power is compelling justification for the support of nuclear power in general. However, one of the themes running through this essay is that the effectiveness of nuclear power, like any other energy generation techology, is highly dependent on local variation and conditions. The data presented in this essay are national or global averages, and thus are not representative of every locality or circumstance. For example, it is clearly ill-advised to build a nuclear power plant in Singapore for many reasons: lack of land space, no practical waste management plans, etc. As such, separate analyses must be carried out in each case of a proposed implementation of nuclear power.

The recent 2011 nuclear accident at the Fukushima Daiichi plant did not expose a new flaw inherent in the design of nuclear reactors; rather, they were a result of lax implementation of existing safety guidelines and best practices. Undelying all the conclusions of this essay, safety protocols need to be a top priority of any country which is considering nuclear power in the future, or even those which have operational nuclear plants.

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