ARE YOU A PROPONENT OR AN OPPONENT OF NUCLEAR POWER?

UQF2101G: Quantifying Nuclear Risks – Final Essay

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Introduction

With increasing population, the share of fossil fuels in total energy consumption is decreasing. Almost 25% of global electricity was generated from oil in the 1970s, and by 2002, that figure dropped to 7.2%. To cope with the higher energy demands even when fossil fuels decline[1], the world is becoming increasingly dependent on alternative sources of energy, including nuclear energy, whose share increased from 3% to 16.6% during the same period[2]. Nuclear energy is the energy present inside the nucleus of an atom, which can be harnessed to produce electricity by splitting the atom, a process known as fission.

Like most technology, nuclear power has its own pros and cons. Radioactive meltdowns like the one in Chernobyl have been disastrous in terms of financial costs[3], and radioactive waste disposal is still searching for solutions. A quantitative analysis of nuclear power is important to weigh its benefits against its potential harms. The essay aims to answer whether one should be a proponent or an opponent of nuclear power. The essay considers data from NPPs (nuclear power plants) around the world to make its claims and arguments, and the data which is worked on usually concerns with time periods from 1970 to 2018.

The essay approaches the question from different perspectives: sustainability, environmental safety, economic costs and impact on human health. Using quantities and quantitative tools deemed suitable, it determines nuclear energy's desirability against other sources of energy, from fossil fuels like oil, natural gas and coal to renewable energies like solar, wind and hydroelectricity.

Sustainability

The decline in available fossil fuels, and concerns over how long they can support energy generation, is what has prompted many countries and governments to turn towards alternative sources of energy. Understanding sustainability in the context of different energy sources is important, since it helps us establish which energy source can fulfill our demands for the longest, based on available resources.

To estimate how long different energy sources will last, data for the proven reserves of coal, oil, natural gas and uranium at the end of a year, and the production based on that resource for the corresponding year is obtained. A reserves-to-production (RP) ratio is computed, which quantifies for how many years an energy source can last until the resources required to produce that kind of energy are no longer available. If nuclear energy has a higher R/P ratio, it incentivizes the use of nuclear energy over other alternatives.

$$RP\ ratio = \frac{Proven\ global\ reserves}{Global\ production\ per\ year}$$

Simply comparing the global reserves is not a good approach, since the rate at which those reserves get utilized determines how long the reserves will last, which is why RP ratio is used. Production is a better quantity than consumption because it accounts for stock changes and losses during conversion of available

[1] Data extracted from World Bank Open Data (data.worldbank.org)

[2] Yemane Wolde-Rufael, Kojo Menyah, Nuclear energy consumption and economic growth in nine developed countries, Energy Economics, Volume 32, Issue 3, 2010, Pages 550-556, ISSN 0140-9883, https://doi.org/10.1016/j.eneco.2010.01.004.

[3] Samet, J. M., & Seo, J. (2016). The Financial Costs of the Chernobyl Nuclear Power Plant Disaster: A Review of the Literature. 23-30. Retrieved November 13, 2018, from https://uscglobalhealth.files.wordpress.com/2016/01/2016_chernobyl_costs_report.pdf.

supplies, thus accounting for the usage of the resource more completely. Proven reserves are considered because their extraction is ensured with a reasonable amount of certainty from well-established and known reservoirs, unlike probable and undiscovered reserves. Proven reserves are not directly measured, but a direct measurement is not feasible, which makes them the most reliable estimates available. The proven reserves and production for oil, coal and natural gas is measured in thousand barrels, million tonnes and billion cubic meters respectively. Data for these has been drawn from the *BP Statistical Review of World Energy, 2016*. Reserves and production for uranium are measured in tonnes, with data derived from the "Red Book" on Uranium by IAEA and Nuclear Energy Agency (NEA), released in 2016.

Type of energy source	Countries considered	World proven reserves	World Production	RP Ratio (in years)
Oil	55	1696.6×10^6	3381.6×10^4	50
Coal	40	1035012	7727.3	133
Natural Gas	50	193500	3680.4	52
Uranium	17	7641600	55675	137

The results from the table show nuclear as the most sustainable source of energy, slightly above coal and significantly higher than oil and natural gas. While this serves as an indication that nuclear may last longer than fossil fuels, the limitations of the analysis must be clearly acknowledged. It is assumed that uranium, regardless of isotope, is the only measure for nuclear energy reserves. Also assumed is that both the proven reserves and the production per year will stay constant. These are important limitations, since the proven reserves might change depending on how much money is being spent on extraction, and production amounts will change depending on energy needs and fuel prices. The analysis also fails to account for technological advancements, and renewable energies are not considered here, since consideration of the resources needed to produce them is very complex to quantify. A solution to the following limitations would be considering historical data on reserves and production and setting up trends in these quantities to estimate the RP ratio in a future year, since a trend based on past data would account for technological developments and changes in reserves/production.

These limitations, however, apply to each source of energy, and technological advancements will lead to more efficient production of nuclear power too. Reported undiscovered reserves can significantly increase the available uranium[4], and fuels like plutonium can account for increased fuel reserves[5]. Based on the above results and arguments, it can be concluded that natural gas and oil can be used for the next 50 years or so, after which energy production will largely have to rely on coal and nuclear power.

Environmental Impact

The International Atomic Energy Agency (IAEA) describes nuclear power as one of the lowest emitters of greenhouse gases available to generate electricity[6]. It is important to consider emissions not just during operation but using a *lifecycle assessment* (LCA). LCAs consider emissions from all stages in the life cycle of an electricity generation technology, from component manufacturing, to operation of the generation

[4] *Uranium: Resources, production and demand*. (2016). IAEA and NEA.

[5] Plutonium – World Nuclear Association, Retrieved from http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx

[6] "Nuclear Power and Climate Change.", IAEA, 13 Apr. 2016, www.iaea.org/topics/nuclear-power-and-climate-change

facility to its decommissioning, and including acquisition, processing and transport of any required fuels[7]. Comparing the LCA emissions from a nuclear power plant to other sources of energy helps in ascertaining whether nuclear power is more carbon-efficient than different available sources of energy. To compare the environmental impact of different power sources, the greenhouse gas (GHG) emission for different sources per unit energy is computed. This is because considering only GHG emissions is an unfair comparison, since greater emissions can be related to higher energy production. GHG emissions are measured in *grams of carbon dioxide equivalent*[8] *(gCO_2e)*, ensuring a standardized consideration of various GHGs. The source with the lowest ratio is deemed to be the most preferable in terms of environmental impact. Data is retrieved from the Open Energy Information Database, and it must be noted that the values are derived from secondary sources and estimates, which may not be perfectly accurate.

The t-test for independent samples is used to determine if differences in GHG emissions are statistically significant, with the null hypothesis that the mean values of GHG emissions from nuclear power and another source of energy are equal. P-values <0.05 are regarded as significant. The test assumes that sample means are normally distributed, sampling is random, and observations are independent. The t-test is preferred over ANOVA because it is designed to test differences between two samples, unlike ANOVA which is designed to test differences between more than two samples.

Type of Energy source	**Sample size**	**Mean emissions per unit energy (gCO_2e/kWh)**	**Standard deviation in emissions per unit energy (gCO_2e/kWh)**	**t-test p-value for difference of means**
Bioenergy	267	52.04	44.14	<0.0001
Solar Photovoltaic	46	60.88	33.46	<0.0001
Concentrated solar	42	50.77	62.53	0.001329
Hydropower	27	19.68	33.5	0.276758
Geothermal	8	39.38	24.47	0.254811
Wind	126	15.80	14.19	0.000185
Natural Gas	62	504.36	120.62	<0.0001
Coal	164	1026.17	198.75	<0.0001
Nuclear	132	27.24	30.85	Reference

From the above table, nuclear power has one of the lowest mean ratios, with only hydropower and wind energy having lower mean GHG emissions per unit energy. Fossil fuels like coal and natural gas are significantly higher in their GHG emissions per unit energy, and although oil was not a part of the dataset, studies have shown that oil has a greenhouse gas impact comparable to that of coal and natural gas[9]. Due to limitations from the dataset, it is assumed that different energy generation technologies of a source have similar emissions, and these values will not change significantly over time. Overcoming this would require gathering more data on emissions from different technologies within an energy source and segregating a single energy source to get emissions for each different technology. Energy sources like hydropower and geothermal have extremely small sample sizes, thus their values may not be as precise, which is reiterated by the p-values being insignificant. More data needs to be collected for these energies.

To go beyond this analysis and further support the claim above, we consider the correlation between use of nuclear power for electricity generation and CO_2 emissions per unit energy in different countries. A negative

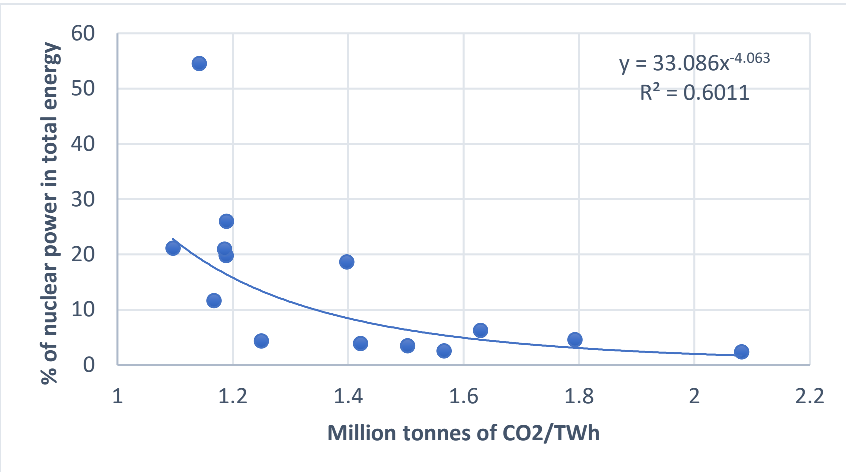
[7] LCA Harmonization. (n.d.). Retrieved from https://openei.org/apps/LCA/

[8]The emissions from a gas is multiplied by the factor of its warming potential relative to that of carbon dioxide. (OECD, glossary of statistical terms)

[9] *Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources*. (2011). Retrieved November 2018, from www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf

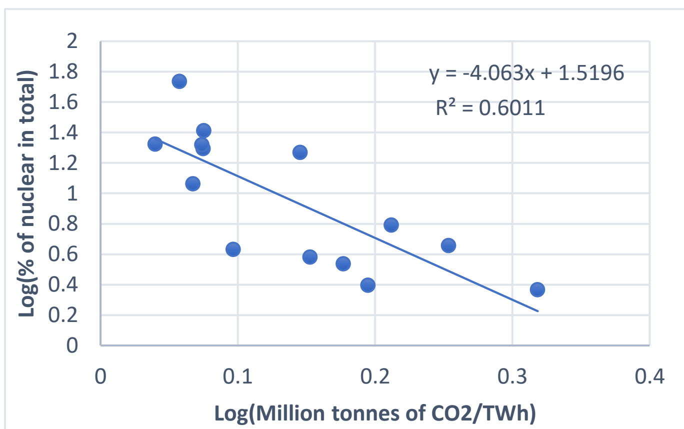
association between amount of nuclear power used and CO_2 emissions per unit energy would further hint at nuclear power as a low-emission source of power generation.

14 countries' data on nuclear power generation and CO_2 emissions for the year 2017 is drawn from *BP Statistical Review of World Energy*. The two variables are percentage of nuclear power in total energy generation and million tonnes of CO_2 per TWh (terawatt-hour). The Pearson correlation coefficient is a standardized measure of the strength of *linear* association between two variables, and is denoted by **r**. The first graph shows the data points and sets up a power trendline, with the x-axis as million tonnes of CO_2/TWh, and the y-axis as the percentage of nuclear power in total energy generation.



A power-model is chosen because it gives the highest value of **the coefficient of determination (R^2)**, which quantifies how well a model fits observed data. Here, a choice of choosing a power model is made to represent the relation between the two variables. Based on this assumption, logarithm on both variables can be used to transform power into a linear model.

$$y = 33.086x^{-4.063} \rightarrow \log(y) = 1.5196 - 4.063\log(x);\ \beta = -4.063$$

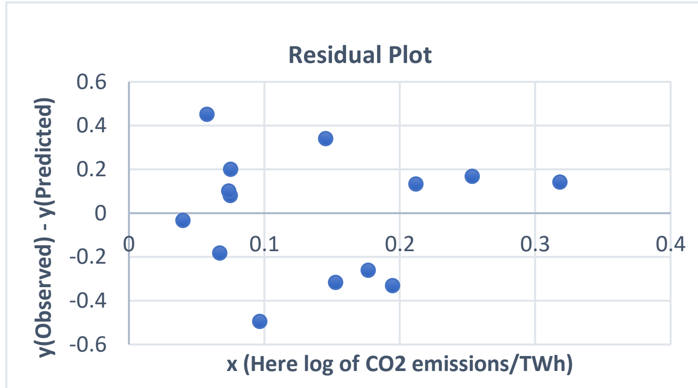


It is assumed that CO_2 emissions are representative of all GHG emissions, and that the trend seen from the 14 countries is applicable to the entire world's nuclear power. This is justified since CO_2 is the majority of GHG emissions and can serve as a representation of all GHG emissions[10]. Most importantly, the model only sets up an association between nuclear power use and GHG emissions and does not establish any causation between the two. Changes in emissions might be due to different power-generation technologies, but it is assumed that there are no technological differences among the considered countries. It must be noted that the choice of a linear model is also based on certain assumptions. These include that a linear model (and a power model for the first graph) is a good fit for the observed data, and that the rate of change of one variable with respect to the other is constant. Correlation coefficient also assumes that discrepancies along the line of best fit remain similar as we move along the line[9]. The linear model is non-deterministic, meaning the linear trend is a stochastic model providing only estimates and expected values for the dependent variable. This assumes that the errors are distributed normally. While the

[10] Sources of Greenhouse Gas Emissions. (2018, October 09). Retrieved from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

primary goal here was to highlight a correlation and not a trend, the linear model can be used for prediction, since the coefficient of determination is 0.6011, accompanied by a residual plot which shows no observable pattern. Accounting for other environmental externalities would include comparing pollution levels (air, water or soil) around different kinds of power plants. We could also use correlation models like above to correlate other externalities like air pollution levels to the use of different kinds of energy.

On converting the power model to a linear model, **a correlation coefficient of -0.77 is seen,** indicating that there is a strong *negative association* between carbon dioxide emissions and nuclear power use[11]. Moreover, data considered is from a single year and a single dataset, so discrepancies in emission-monitoring techniques are kept to a minimum. This result further strengthens the argument that nuclear power may be a low-emission energy source as compared to other sources.



Economic Costs

As resources become scarce and cost of extracting these resources increase, relying on energy sources which provide the same amounts of energy at cheaper costs becomes more and more significant. Like GHG emissions, to learn whether nuclear energy is cost-effective when placed against other sources of energy, it is important to consider the lifecycle costs of different kinds of power plants.

$$\begin{aligned}\textbf{\textit{Cost of Energy}} &= \frac{Capital\ Cost\ per\ kW}{Lifetime * 8760 * Capacity\ factor} + \frac{Fixed\ O\&M\ Costs\ per\ kW\ (annual)}{8760 * Capacity\ Factor} \\ &+ Variable\ O\&M\ costs\ per\ kWh + (Fuel\ Costs\ per\ Btu * Heat\ Rate)\end{aligned}$$

To calculate the costs of electricity generation for different energy sources, the overnight capital costs (the cost of building a power plant overnight), the fixed operating costs (operation and maintenance costs that do not change with amount of power generation), variable operating costs (operation and maintenance costs that paid per unit of energy produced), and fuel costs per unit heat produced are divided by the total energy produced. Capacity factor is the unitless percentage of annual capacity converted into power, and the heat rate refers to the electrical energy generated from 1 British Thermal Unit (Btu) of heat by a fuel. Since capital cost is an investment lasting the entire lifetime (once a plant is built, construction costs can be covered in its entire lifetime), lifetime is divided by capital cost. The term (8760 * Capacity factor) denotes the annual energy generated in kilowatt-hour. Overall, every term of the formula has the unit US$/kWh, and lifetime of all the considered power plants is assumed as 30 years. Data is retrieved from the Open Energy Information Database, and values are derived from secondary sources and estimates published at different times, which may not be perfectly accurate. 95% confidence intervals are used to provide region estimates for capital, fixed O&M and variable O&M costs, leading us to assume that the mean of costs is normally distributed.

[11] Pearson Product-Moment Correlation. (n.d.). Retrieved from https://statistics.laerd.com/statistical-guides/pearson-correlation-coefficient-statistical-guide.php

Energy source	Sample size	Capital costs per kW	Annual fixed O&M costs per kW	Variable O&M costs per kWh, x10^3	Mean Heat Rate	Mean Fuel price per Btu, x10^6	Mean Capacity Factor	**Cost of Energy**
Onshore wind	53	2116.37 ± 170.44	31.91 ± 5.76	8.81 ± 2.35	..	..	38%	**0.039**
Solar PV	124	4534.77 ± 246.52	34.72 ± 4.59	..	..	..	19%	**0.111**
Solar Thermal	42	6433.64 ± 614.87	68.44 ± 3.93	8.16 ± 3.63	..	..	42%	**0.085**
Hydroelectricity	20	3064.6 ± 1399.88	29.23 ± 14.42	3.16 ± 1.25	..	..	48%	**0.037**
Biopower	68	3390.28 ± 408.90	135.29 ± 29.30	6.08 ± 1.27	11557.54	2.27	51%	**0.087**
Natural Gas	49	1062.15 ± 84.71	15.28 ± 2.94	4.23 ± 1.34	8213.81	4.4	50%	**0.051**
Coal	20	4734.16 ± 1283.9	42.79 ± 8.68	5.55 ± 1.17	9702.94	2.34	85%	**0.055**
Nuclear	18	5465.08 ± 850.43	84.5 ± 23.46	1.39 ± 1.62	10325.67	0.76	89%	**0.043**

.. – Data not available or not applicable

As is clear from the results, nuclear power seems cheaper than most forms of energy except wind and hydropower. We also assume that the results from the table above can be generalized to power plants all over the world. As with previous sections, the costs are assumed to not change with technological differences within one source, which poses a limitation which can be addressed after gathering more specific data. While we assume that construction costs and fuel prices are constant around the world, these quantities are region-dependent, determined by availability of cheap labor and different kinds of resources.

Other assumptions include zero discount rates, no inflation or financing costs, no changes in fuel cost during lifetime, and no tax during the lifetime of the power plant. Quantifying capital costs with varying discount rates would make the formula sufficiently complicated, and assuming zero discount rates and tax is justified because these would be applied to all energy sources, resulting in different absolute values of costs but similar comparisons. A more accurate cost estimate can be obtained if environmental externalities due to waste dumping, GHG emissions and radiation releases are accounted for in the cost formula[12]. Nuclear power is hence economically viable and offers energy at lower costs than many fossil fuels and even some renewable sources of energy like solar power.

With technological advances, the capacity factors of power plants are expected to change[13]. For further analysis of the above formula, we can conduct sensitivity analyses of cost of energy on capacity factors. Sensitivity analyses determine the variation of a quantity (in our case, the cost of energy) when only one of the parameters deciding it are changed, to check how sensitive the quantity is to the parameters. The capacity factors for all energies are varied from 20% to 100% and corresponding costs are calculated. If nuclear power shows lower costs even when capacity factors are high, it can be concluded that when other kinds of power plants reach an efficiency as high as nuclear, nuclear power is still cost-effective.

A key assumption of the analysis includes constancy in other components of the cost as capacity factors increase. This makes it relatively easier to implement sensitivity analyses but is still a major limitation. Another important limitation is that since other factors are kept constant, the analysis fails to capture modifications and interactions between different components as capacity factors vary. Considering other factors like lifetime and fuel prices for separate sensitivity analyses will offer deeper insights into how cost of energy varies, and these can be examined as a part of moving beyond the scope of this essay. As a strength, sensitivity analyses offer good insights on which parameters are more important in determining a quantity, and focus can be given to improving these parameters.

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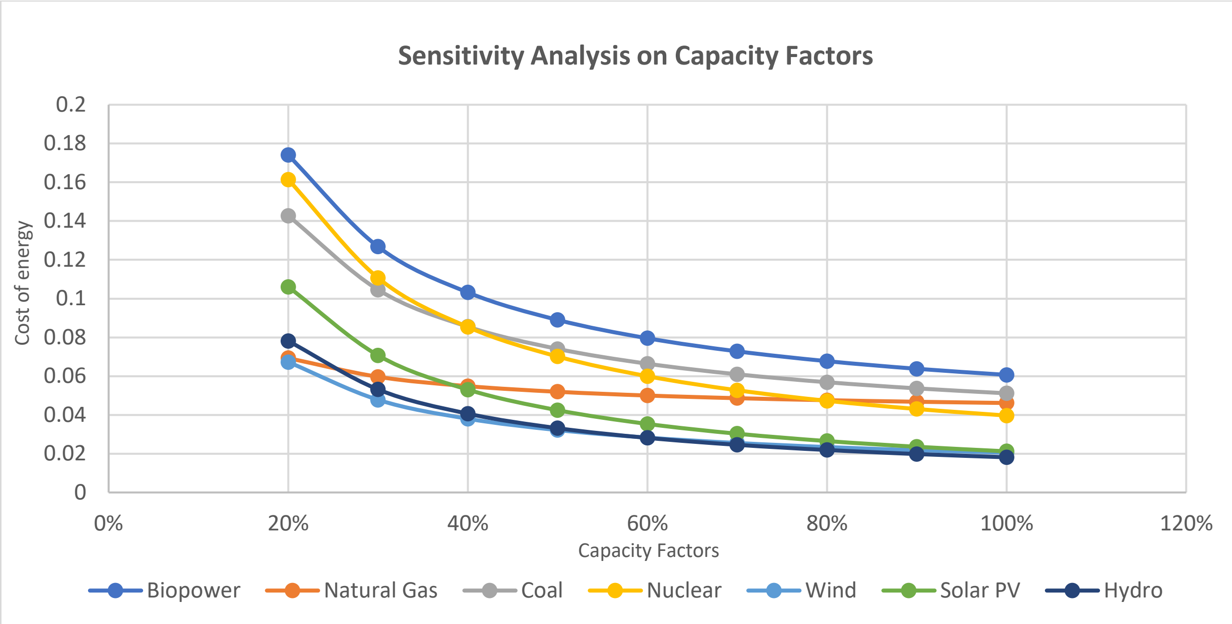
[12] Rhodes et al (2017). A geographically resolved method to estimate levelized power plant costs with environmental externalities. *Energy Policy, Volume 102.* Pages 491-499.
[13] What are the Capacity Factor Impacts on New Installed Renewable Power Generation Capacities? (n.d.). Retrieved November 10, 2018, from https://www.energycentral.com/c/ec/what-are-capacity-factor-impacts-new-installed-renewable-power-generation



To overcome the limitation of constancy in other components, we can consider the historical capital and O&M costs as well as capacity factors and come up with models relating the two. With each different value of capacity factor, a corresponding value of different cost components can be estimated, leading to a more accurate sensitivity analysis. Irrespective of the capacity factor, renewable energies like wind, solar PV and hydroelectricity are always cheaper than nuclear energy. We see that at capacity factors greater than 80%, nuclear energy becomes cheaper than biopower, coal and natural gas. This indicates that even with technologically-advanced power plants having high efficiency, nuclear power remains cheaper than most fossil fuels.

Impact on Human Health

Radiation exposure from NPPs is one of the biggest concerns against the use of nuclear power. Having argued for nuclear power through the perspectives environment, sustainability and economics, the issue of human health impact must not be left untouched. The question considered here is whether operation of an NPP affects the health of people living around it. A retrospective cohort study conducted in 2012 by the Illinois Department of Public Health considered the incidence of cancer around an NPP, and how that incidence varies with proximity[14]. However, the study fails to conduct hypothesis testing and does not show p-values for its results. Using a Chi-Squared distribution on the observed and expected counts, p-values are calculated to validate the results of the study. Standardized Incidence Ratio (SIR) is the ratio of observed number of cases to expected number of cases. A Chi-Squared SIR test is widely used on observed and expected counts, and the sample size and expected number of cases are the right size for the test to provide accurate statistical significances[15]. The exposure is operationalized by distance from the power plant, as directly measuring radiation exposure for individual participants will be resource-intensive and difficult. We assume that the diseases occur independently, and the count of cases follow a Chi-squared distribution. The one-tailed p-values and confidence intervals are obtained using the *OpenEPI SMR Analysis Calculator*, and p-values < 0.05 are regarded as significant.

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[14] Ma, F., Lehnherr, M., Fornoff, J., & Shen, T. (2011). Childhood cancer incidence in proximity to nuclear power plants in Illinois. *Archives of environmental & occupational health*, *66 2*, 87-94.
[15] (2013). The chi-square test of independence. *Biochemia medica*, *23*(2), 143-9.

Only leukemia is considered here because of lack of space, and because leukemia is one of the most common childhood cancers[16]. The null hypothesis is that there is no association between proximity to an NPP and incidence of leukemia, and a statistically significant discrepancy between observed and expected cases would indicate that radiation exposure from living around an NPP can lead to serious health problems.

Proximity (Mile)	**Observed**	**Expected**	**SIR (95% CI)**	**X^2 value**	**p-value**
≤ 10	47	38	1.24 (0.92-1.63)	2.13	0.14
>10 and ≤20	116	119	0.97 (0.81-1.16)	0.075	0.78
>20 and ≤30	287	258	1.11 (0.99-1.25)	3.26	0.07
>30	815	851	0.96 (0.89-1.02)	1.52	0.22

The strengths of the study include a population-based cancer incidence data (resulting in a large dataset of 2,710,843 people), and controlling for potential confounders of sex, age and race. However, the distance from an NPP may not be a good measure of exposure, since radioactive substances can travel great distances through dust, wind and water[17]. Confounders like socioeconomic status and previous history of individuals is not known to determine predispositions to cancer. Moreover, the study only pertained to NPPs and children in Illinois, so the results are not generalizable to different age-groups and NPPs around the world.

Another limitation is that the health risks are not studied for other sources of energy, solving which would require similar studies and hypothesis testing for other kinds of power plants. This study also fails to capture the severity of a nuclear accident, solving which would require case-control or cohort studies which measure increased risks of cancer due to radiation exposure from nuclear meltdowns. Based on the table, none of the p-values are significant, and hence we fail to reject the null hypothesis. Thus, radiation exposure from NPPs, during normal operation, involves very low doses posing no significant threat to human health.

Conclusion

We have seen that NPPs stand out in areas of sustainability, greenhouse gas emissions, costs and health impacts. Throughout the essay, we also noticed that renewable energies like wind power and hydroelectricity are better than nuclear energy in terms of economic costs and GHG emissions. Being renewable, they are competitive when it comes to sustainability as well. However, such renewable energies are very dependent on the geography of a region, hence construction of power plants based on renewable sources is not feasible everywhere[18]. Nuclear energy itself is location-dependent, small countries like Singapore should be cautious because a nuclear accident could affect large populations within the country[19]. With technological advances and advent of safer and cheaper technologies, nuclear power will become feasible in many more regions than it is now. Active research on molten salt reactors, small modular reactors and fusion reactors shows that nuclear power can overcome many of its limitations. Nuclear power is not a panacea to the world's energy needs, but it certainly provides solutions to some problems.

Having its own limitations, the essay does not provide a final verdict on the desirability of nuclear power, and instead aims to provide one of the many possible quantitative takes at it. Based on the above analyses, it concludes that nuclear power is competitive, and it offers advantages across different areas when compared to fossil fuels like coal, oil and natural gas and other alternative energies like biopower.

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[16] Pearce et al (2012). Radiation exposure from CT scans in childhood and subsequent risk of leukemia and brain tumors: a retrospective cohort study. *Lancet (London, England)*, *380*(9840), 499-505.

[17] White, Virginia. Radiation Basics. Retrieved Nov 13, 2018, from https://edenotes.extension.org/2011/03/radiation-basics/

[18] Pimentel et al. Renewable Energy: Current and Potential Issues: Renewable energy technologies could, if developed and implemented, provide nearly 50% of US energy needs; this would require about 17% of US land resources, *BioScience*, (2002).

[19] Siong, O. (2012, October 15). Current nuclear energy technology "not suitable for use in S'pore". Channel NewsAsia.