Introduction

This study aims to establish a stance on the adoption of nuclear power, through answering the question – "Are you a proponent or opponent of nuclear power?". The question has two-fold motives – to find an energy source to address the future demand for electricity amidst a burgeoning world population, and to tackle climate change by making electricity production carbon-neutral.

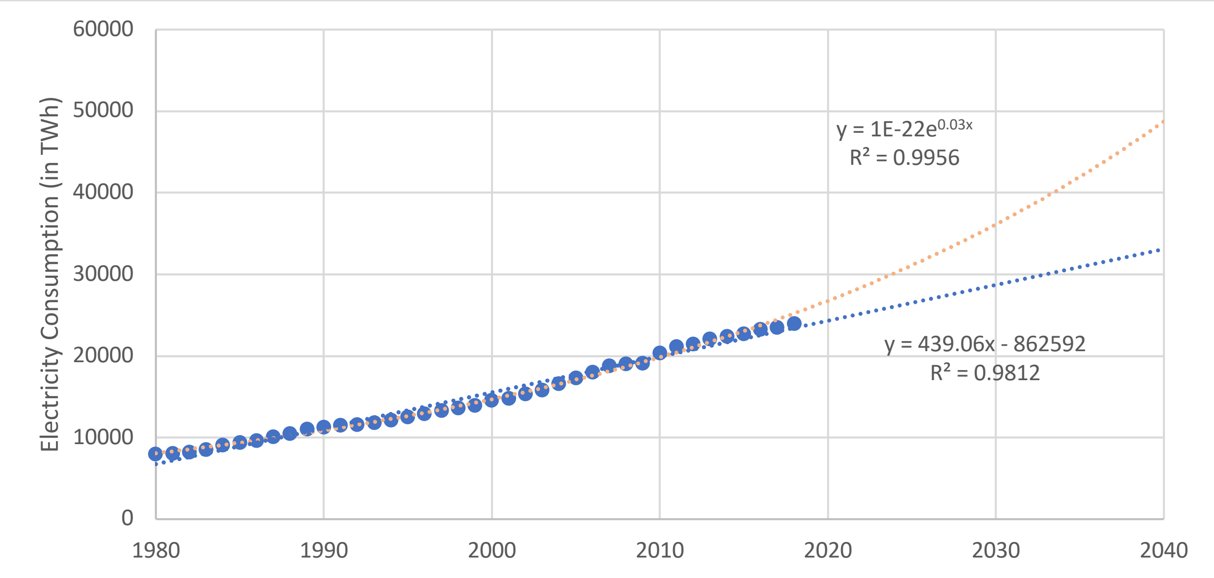


Figure 1: World electricity consumption (TWh), 1989-2018 [UNSD][1]

The figure above shows data for world electricity consumption in TWh from 1980-2018, forecasted to 2040 using linear [section 2] and exponential models [in red and blue colors]. Both project a substantial increase in demand for electricity production. Further, the Special Report of the IPCC[2] states that to have a 67% chance of limiting global average temperature above pre-industrial levels to 1.5°C, the remaining carbon budget for the planet is 570GT of CO_2 – and we are on track to exceed this in 12 years. This precipitates a need for changing policy on fossil fuels– and the need to answer our question.

Methodology

This study defines as nuclear power as electricity generated from fission reactions in a nuclear reactor, where water is heated, and the produced steam is used to drive a turbine. The sources of energy considered in the study are nuclear, coal, natural gas, solar photovoltaic (PV) and wind. A notable exclusion is hydropower, which is justified since capacity additions and investments for hydropower have been declining since 2013, with capacity factors decreasing by 20% due to droughts in Latin America[3]. The study considered data from only 1996-2019 in the lifecycle assessment of energy sources (sections 1 and 4), to ensure that the results obtained are applicable as far as possible to the present and exclude older generation technologies, and since 1996 marks the commencement of the first Gen-III nuclear reactor [Kashiwazaki ABWR]. A global spatial scope was used to enable generalization of the findings. A statistical significance level of α=0.05 was adopted, in line with other energy LCA studies. A cost-benefit analysis was conducted to assess the following quantities:

1. Cost-effectiveness using Levelized Cost of Energy in USD/kWh
2. Sustainability (reserves-to-production ratio) in years
3. Association between electricity prices (in USD PPP/kWh) and electricity mix of a country
4. Environmental impact in terms of grams of CO2 equivalent per kWh;
5. Safety in terms of Years of Life Lost (YOLL) per TWh

The specific lens the study adopts is that of a supplement to a government policy paper, and it aims to inform a policy maker of the optimal choice for an energy investment. This is significant as nuclear energy policy remains uncertain in many countries as governments try to reconcile political pledges, public opinion, climate objectives and energy supply security.

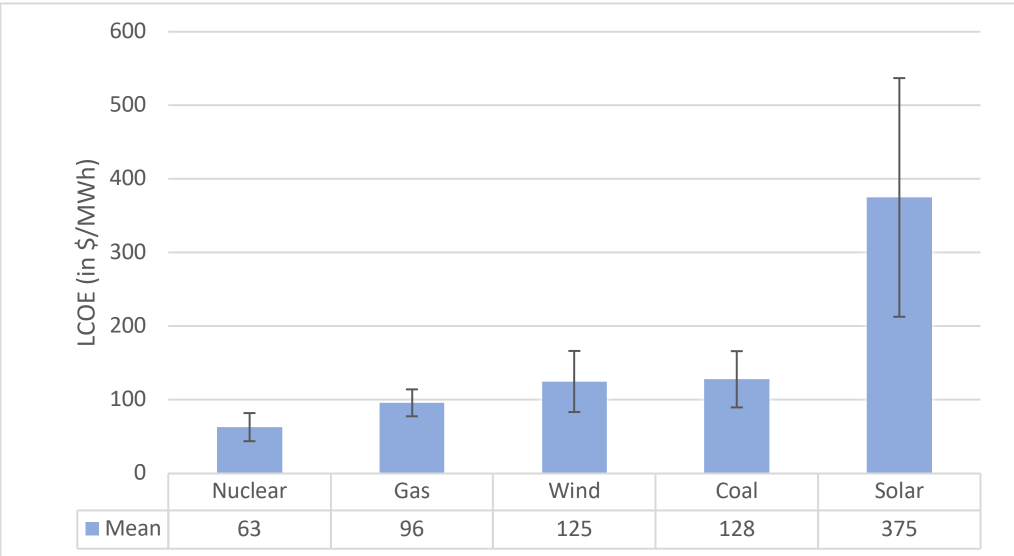
---

[1] United Nations Statistics Division (2018). Energy Statistics Database.
[2] Inter-Governmental Panel on Climate Change : Summary for Policy Makers (Annex : Paris Agreement)
[3] International Energy Agency, 2018 Report on Renewables

I. Economic Cost-Effectiveness Analysis (CEA)

It is essential to quantify cost-effectiveness since governments and private corporations have limited fiscal resources, and must optimize capital to maximize electricity production. It has been operationalised through the Levelized Cost of Energy (LCOE), which is defined as the average revenue required per unit of energy output (in US dollars per MWh) over a project's lifetime such that the plant (and its investor) breaks even[4]. This is a comprehensive tool for comparing the unit costs of different technologies over their economic life, as it includes costs incurred from construction, maintenance, operation, fuel cycle, and decommissioning.

The calculation of LCOE[5] includes a parameter known as the discount rate (or the weighted average cost of capital if the entity is for-profit). It is the rate that an entity pays to finance the power plant, and is also called the cost of capital. To simplify calculations, this study assumes all capital costs (construction and contingency) to be invested in Year 0, and that electricity output is constant per year. Data was gathered from individual plants from the IEA[4], and discount rates of 3, 5, 7 and 10% were considered. 3% and 5% were considered as social capital cost, 7% was considered to be the public sector cost of capital and 10% was labelled as high-risk investment for private corporations[6]. For final computation of LCOE, the 7% discount rate was used as a pragmatic scenario, keeping in line with this study's lens.



Source	*n*	*SD*
Nuclear	20	19.1
Coal	48	38.2
Gas	27	18.3
Solar	17	162.1
Wind	26	41.5

Figure 2 : Mean LCOE for energy resources [IEA and NEA 2015][4]

While $\mu_{nuclear}$ is the lowest amongst the energy sources, given that the estimated means of other energy sources coincide within one standard deviation, hypothesis testing using a one tailed t-test was carried to evaluate whether the result is statistically significant. The null hypothesis (H_0) was $\mu_N = \mu_S$ for any source (S), and the alternative hypothesis (H_A) was $\mu_{source} > \mu_{nuclear}$, since the study aimed to establish whether nuclear power is the optimal choice, and because a one-tailed test provides more information.

Source	**Natural Gas**	**Wind**	**Coal**	**Solar PV**
P-value	0.00045	< 0.0001	< 0.0001	< 0.0001
Conclusion	*H_0 rejected*	*H_0 rejected*	*H_0 rejected*	*H_0 rejected*

Table 1 : One tailed t-test for LCOE means (reference : $\mu_{nuclear}$)

H_0 was rejected for all other energy sources, since p-values were less than α. Thus, the CEA indicates that nuclear energy is the most cost-effective source of energy.

<u>Assumptions, Limitations and Strengths</u> : The two main assumptions inherent in the calculation of LCOE are[4]: 1) Discount rate for costs/benefits is stable and does not vary during the lifetime. 2) Electricity prices do not change during the lifetime of the project. Further, this study made the following assumptions : **1)** All capital is invested in Year 0 i.e the first year **2)** Electricity Output (in kWh) is

[4] IEA & NEA, "Projected Costs of Generating Electricity, 2015"

[5] The IEA defines LCOE mathematically as $LCOE = \frac{\sum_{t=0}^{T}\frac{C_t+M}{(1+r)^t}}{\sum_{t=0}^{T}\frac{Q_t}{(1+r)^t}}$, where $C = capital\ costs, M = maintenance\ and\ fuel\ costs, Q_t = electricity\ generated\ in\ year\ t.$

[6] *World Bank. 2015. "Guidelines for Economic Analysis of Power Sector Projects : Renewable Energy Projects World Bank"*

constant for each year of a plant's lifespan **3)** A standard capacity factor of 85% is assumed for nuclear, natural gas and coal plants, with country-specific factors used for wind and solar.
4) Assumes levelized carbon costs ($30/tonne) and constant fuel costs. **5)** Generic lifespan of a power plant is assumed to be 60 years for nuclear, 40 years for coal, 30 for natural gas, and 25 years for both solar and wind power plants. **6)** Decommissioning costs were considered to be 15% of TIC

One of the limitations of the approach is that the study only considers data from OECD countries (and BRICS nations), and as such may not be representative of world energy economics. It does not consider costs and benefits related to carbon capture and storage. It does not take account of costs of transmission, distribution and impacts on the electricity system as a whole. Further, since all currencies are converted to USD at market rates, the study does not adjust for purchasing power parity or fluctuating exchange rates, which might influence final calculations. A considerable degree of uncertainty also persists in carbon costs in the future since fuel prices are subject to volatility and radical improvements in mining technology.

Another limitation of LCOE is that it is not a viable indicator of the feasibility of undertaking a project. This is because initial capital costs are amortized over a long period of time. This hides high installation costs which can prove to be a major drawback in investing in a power plant. Further, change in carbon costs due to cap-and-trade mechanisms (such as EU ETS or Kyoto Protocol) was not considered.

A primary strength is that the LCOE allows for a cross technology comparison. Conventional plants can be compared to variable renewable sources like wind and solar power even though they have different cost structures (e.g. the ratio of capital cost to fuel costs is different for different sources). The data was collected from individual plants that utilized latest generation technologies, thus preventing both ecological fallacies and selection bias. While only 7% discount rate was used in the comparison, all four interest brackets were calculated (3, 5, 7 and 10%), and it was observed that solar PV had the greatest sensitivity to discount rates ($92/MWh increase between 7 and 10%), majorly because of its high installation costs. Policy considerations could be adjusted based on this result to fit the economic climate of the corresponding country. Considerations of costs at all stages (construction, contingency, operation, decommissioning, etc) supports the comprehensive LCA characteristic of the result. Finally, the LCOE results serve as a useful indicator for public policy as it provides officials with a basic reference to build an efficient energy economy, where electricity is produced at the lowest cost possible.

II. Sustainability

Central to a government decision in investing in both production and research & development of an energy source is the sustainability that it offers. It is not advisable to invest in an energy source that will not proffer long-term benefits. This study operationalises "sustainability" as "number of years that an energy source can be exploited" at varying rates of its share in the electricity mix, which is a modified definition of the reserves-to-production ratio. Only nuclear, coal and natural gas were considered for this analysis, as solar and wind are renewable, perennial sources of energy, and the metals used can be potentially recycled with 96% recovery [IRENA][7].
First, the study attempted to project electricity consumption using IEA data on world electricity consumption (in TWh) from 1980-2018. A linear model of electricity consumption versus time was determined to be the best choice. The equation of the line was : $y_{consumption} = \beta_1 \cdot t_{years} + \beta_0$, with an R^2 of 0.98. Next, hypothesis testing was conducted to determine whether the linear relationship is statistically significant. The null hypothesis (H_0) was $\beta_1 = 0$, and the alternative (H_A) was $\beta_1 \neq 0$. A linear regression t-test was then conducted. The assumptions for linear regression were also tested - normality using Shapiro-Wilk p-value, homoscedasticity using the White test, and multicollinearity by observing the VIF (variance inflation factor < 2.5). This resulted in the verification of the assumptions, and rejection of H_0 for both the slope and intercept of the model.

Predictor	Coefficient	Standard Error	t-Stat (=β/SE)	p-value
Slope (β_1)	6752.45	220.88	30.56	3.87×10^{-32}
Intercept(β_0)	439.06	10.00	43.89	5.67×10^{-33}

Table 2: Linear Regression t-test for Slope and Intercept of Linear Model

Consequently, country-wis DEPO[8] which also tracks utilisation status (like operating, exploration, dormant, et al). Energy density of uranium was

7 IRENA and IEA-PVPS (2016), "End-of-Life Management: Solar Photovoltaic Panels,"
8 IEA, World Distribution of Uranium Deposits (UDEPO), Vienna (2018).

calculated by using WNA 2018 data[9]. Country-wise data on proven coal and natural gas reserves were then obtained[10]. Classification of coal grade (anthracite, semi-bituminous, peat, etc) as a percentage of world coal reserves was obtained from the US EIA[11], along with the corresponding calorific value in a typical thermal power plant. Their weighted average was taken so as to maintain a representative estimate of the quality of coal worldwide. Finally, the following equation was solved for time (T).

$$Resource\ reserve \times \text{energy density} = \frac{\%\ share\ of\ production}{100} \cdot \int_{38}^{T} (439t + 6752.45)\, dt$$

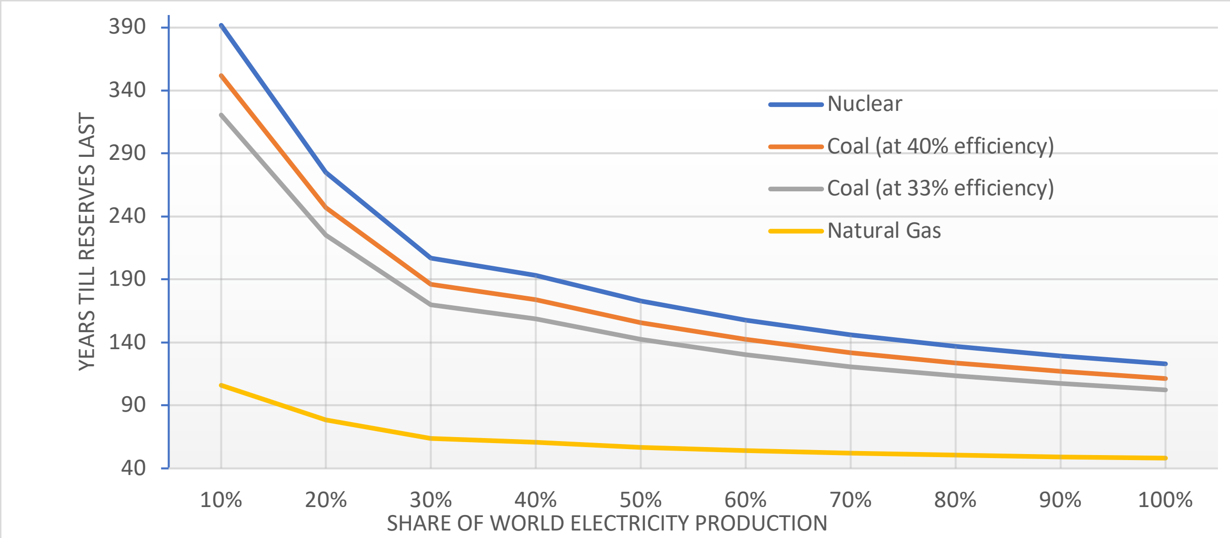


Figure 3: Years till reserves last for energy sources [BP, EIA 2018]

Thus, nuclear energy can be utilized over a relatively greater time-frame at any given share of world electricity production [122 years at 100% share]. It must be noted that data for coal was bifurcated into two efficiencies based on IEA CIAB recommendations[12] (since 33% efficiency represents the typical value for a modern coal plant, and 40% efficiency is the physical limit imposed by the Rankine cycle).

Assumptions, Limitations and Strengths **:** Uranium reserves were calculated by including the following categories in the stage of utilization: operating, exploration, dormant, feasibility study and development. Categories of "partially explored" and "unconventional" were assumed to have no bearing on the quantity of the uranium reserves that can be commercially extracted with present-day technology. The capacity factor for coal power plants was assumed to be 33% in the worst case, and 40% in the best case (most efficient). Most importantly, a linear model of regression analysis was assumed (despite exponential models having a greater R^2 value) since the underlying mechanism for growth in electricity consumption was considered to be population size, which itself was found to have a linear growth from 1962-2018[1].

A limitation is that the classification of "proved reserves"[10] was accepted without scrutiny, and this is liable to fluctuations with exploration of new reserves and improved efficiency in mining. Moreover, due to the study's current policy focus, it did not take into account scenarios where additional reserves of a resource ("probable reserves") are discovered. Finally, the scarcity of materials used in solar and wind power such as silicon, cobalt or aluminium were not considered on account of high recycling rates [see section header].

Strengths lay in the fact that this study did not merely use the current share of an energy source in world production to calculate the time till reserves last, since a more energy-efficient source might be under-represented in the mix due to geopolitical or energy security reasons. Further, the study factored into account the sector-wise percentage of coal and natural gas to produce electricity (eg - since only 35% of natural gas is used for electricity production, the study used this ratio for calculating energy reserves. The rest 65% is assumed to continue to be used in other sectors such as chemicals or transport in the future).

---

[9] World Nuclear Association (2018), "World Nuclear Power Reactors and Uranium Requirements"
[10] British Petroleum, "Statistical Review of World Energy 2018", (2018), 68th edition.
[11] US Energy Information Administration, "Annual Coal Report 2018" (2019).
[12] IEA Coal Industrial Advisory Board, "Power Generation from Coal : Measuring Efficiencies", (2010), page 83

Additionally, while not considered for the final comparison, the impact of use of “unconventional” sources of uranium (such as sea water) could be calculated, yielding a time of 64,278 years till reserves last if nuclear energy accounts for 100% of world production. This information might have a bearing on policy relating to R&D in the energy sector as well. Sustainability, as operationalised by the study, offers a key macro-metric for analysing the value of long-term investments in an energy source.

III. Electricity Prices and Electricity Production Mix

One of the limitations of the LCOE analysis was that it did not take into account the costs of electricity distribution, reliability of an energy source and its “down-time”. These are some of the reasons why pro-nuclear activists such as Michael Shellenberger claim that an increase in renewable energy share leads to higher electricity prices (f.e Germany). This study aimed to investigate the claims of electricity prices being influenced by the share of nuclear or renewables in the electricity mix, by considering the 2018 pre-tax, pre-levies and subsidies bulk cost of electricity (in US$/kWh) purchased by industries in 24 countries, and its relationship with the share of any energy resource in the country’s electricity mix.

Data was collected from EuroStat[13] for 24 OECD countries, and from respective government information agencies for India, China and Russia. In case data on electricity prices was available for both halves of a year, the period from July-December was considered. Prices were collected in the respective national currencies of the countries, and converted to USD using the Big Mac Index 2018. Data on the respective countries’ energy mix was collected from [BP 2018]. The correlation coefficient was computed to depict the relationship between electricity prices and the energy mix.

Source	**Nuclear**	**Coal**	**Natural Gas**	**Solar PV**	**Wind**
Pearson’s r	*-0.158*	*0.189*	*0.264*	*-0.195*	*-0.12*

Table 3: Pearson’s r for adjusted electricity prices and % share of electricity mix

The sample size for all energy sources was n = 26, yielding $df = n - 2 = 24$. The corresponding 95% critical values for the sample correlation coefficient table was ±0.388. Since all values of r lie in this range, the null hypothesis ($\rho = 0$, where ρ = population coefficient) was not rejected. However, this is not sufficient to disprove correlation. Further, Bayes hypothesis testing was done (using a Bayes factor (BF) for linear correlation) to then prove that there is no significant correlation between electricity prices and electricity mix, where $BF = \frac{likelihood\ of\ data\ given\ H_0}{likelihood\ of\ data\ given\ H_A}$. The generated Bayes factor was 10.953 (H_0 is 11 times as likely as H_A), which is in favour of the null hypothesis meaning that renewables or nuclear do not have a bearing on pre-tax electricity prices.

Assumptions, Limitations and Strengths **:** It was assumed that a country’s electricity production mix is similar to the corresponding electricity consumption mix (i.e. that a disproportionate amount of electricity from a particular energy source is not diverted towards exports). Further, the assumption of using electricity prices from the second half of the year was used to avoid seasonal effects.

A limitation of the approach is that it considers non-household industry prices to be a proxy for the true price of electricity, and doing so it might hide price increases due to additional costs of transmitting electricity to household consumers in urban centres. Data from only 26 countries could be taken, and while they represent 60% of world electricity consumption [IEA 2018], the sample size might not be representative of the true reality. Another potential limitation is that the Big Mac Index uses only a single commodity as its CPI (consumer price index) rather than a basket of essentials (electricity, food grains, clothing), but research by Ong et al[14] indicates a strong linkage between the Big Mac Index and traditional consumer baskets. Moreover, the Bayes factor might be misleading in cases where likelihood of both the null and alternative hypothesis is low, or in scenarios with large-samples and small effects.

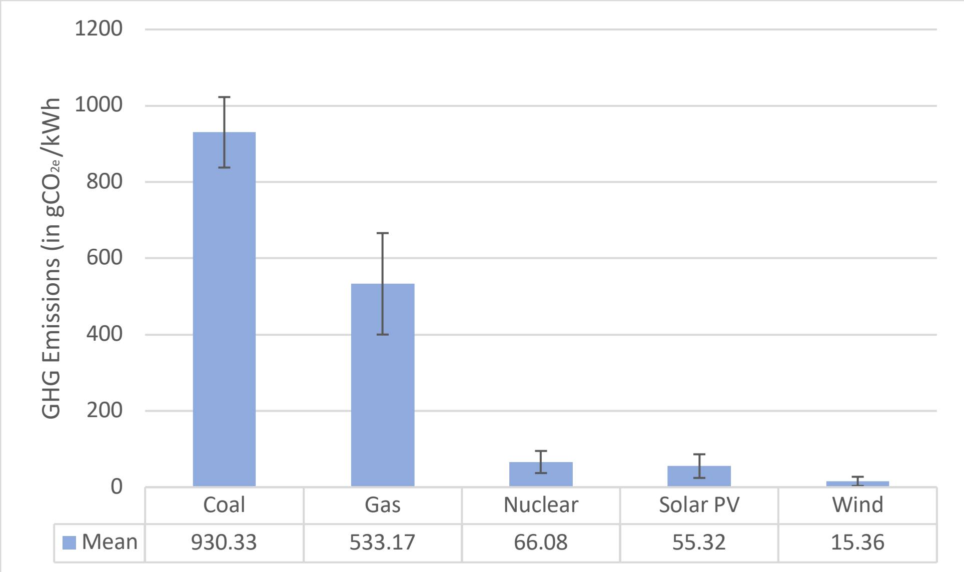
One of the strengths of the approach is the exclusion of tax, subsidies and levies from the electricity prices, since these are a function of political and economic ideology and economic health rather than the source of energy production (for example, a more welfare state such as Germany might have the “lowest wholesale electricity prices in the region”[13] but might choose to tax it at a high rate to amortize healthcare costs for an ageing population). Further, the study considered PPP-adjusted electricity prices to prevent

[13] EuroStat Database and Price Information Report, last retrieved October 30, 2019.
[14] Ong L.L. (2013) “The Economics of the Big Mac Standard. In The Big Mac Index”

market exchange rates from distorting the true value of the currency. The Big Mac Index was used since its conversion rates are publicly available, updated every year and an accurate measure of purchasing power parity[15]. Finally, a comparative approach of Bayes factor was used over frequentist p-values, which are limiting since their utility is restricted by the researcher's choice of null hypothesis.

IV. Environmental Impact

Having considered the economic implications of energy source, it is prudent for public policy to consider environmental impact of an energy source, especially in keeping with the second salient topic set out in the context – climate change. Results from ICCP 2018[2] indicate that greenhouse gas emissions play a pivotal role in irreversible climate change, which can affect habitable conditions drastically. This study considered the grams of CO2 equivalent per KWh of electricity produced to quantify greenhouse gas emissions. Data for coal (hard coal, direct combustion), natural gas (single cycle) and nuclear power plants was taken from the LCA metanalysis studies[15/16], while for solar PV and wind energy, data was gathered from OpenEI's harmonized LCA results since data from individual plant installations was available.



Source	n	SD
Nuclear	19	29.5
Coal	30	92.0
Gas	20	133.2
Solar	92	31.43
Wind	252	12.3

Figure 4 : Mean GHG for energy sources (Sovacool 2008, OpenEI 2018).

Since the mean GHG values obtained for solar and wind fall below or within one standard deviation of $\mu_{N,}$ a one-tailed t-test was performed twice to test the relative ranking of nuclear energy in the cost-benefit analysis. First, the null hypothesis (H_0) as $\mu_{nuclear} = \mu_{source}$, with H_A : $\mu_{nuclear} < \mu_{source}$.

Source	**Coal**	**Gas**	**Solar PV**	**Wind**
P-value	< 0.0001	< 0.0001	0.9983	0.9999
Conclusion	*H_0 rejected*	*H_0 rejected*	*H_0 NOT rejected*	*H_0 NOT rejected*

Table 4 : One tailed t-test for GHG means (reference : $\mu_{nuclear}$)

High p-values for solar and wind indicated the need to perform a one-tailed t-test with another energy source as reference. Wind (μ_{Wind}) was chosen since m_{wind} was the lowest amongst the energy sources.

Source	**Coal**	**Gas**	**Nuclear**	**Solar PV**
P-value	< 0.0001	< 0.0001	<0.0001	<0.0001
Conclusion	*H_0 rejected*	*H_0 rejected*	*H_0 rejected*	*H_0 rejected*

Table 5 : One tailed t-test for GHG means (reference : μ_{wind}).

H_0 was rejected for all energy sources in this test, since p-values were less than α. The results of the hypothesis testing led to the conclusion that nuclear energy had a lower GHG value than coal and gas, but compared to solar and wind power. Further, wind power was the best option out of all sources considered. The monetary value of each gram of CO_2 emitted was taken to be $0.00042, which is the social cost of carbon dioxide emitted as calculated by the EPA[17]. This was carried forward in the final calculation for cost incurred per unit energy.

[15] Sovacool, B. (2008). Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy*, *36*, 2950-2963
[16] Turconi, Boldrin, Astrup (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews*, *28*, 555-565
[17] https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

Assumptions, Limitations and Strengths : A primary assumption is that estimation based on a meta-analysis of LCA studies will be representative of the actual value of GHG the energy source (especially for coal and natural gas). Further, several studies[18] quantify GHG emissions from nuclear, wind and solar power by calculating the energy intensity of lifetime processes and then converting the energy required to gCO_2e by assuming that the economy is purely run on black-coal, yielding a conversion factor of 0.3214 kg-CO2e/$kWh_{thermal}$. This might not hold for a radically changing energy landscape, and hence the estimates might be exaggerated in a renewable-dominant electricity mix.

A salient limitation is that the study does not consider other potential environmental hazards such as the impact on biodiversity, deforestation, PM2.5 or PM10 emissions. This is mitigated since the former two are difficult to operationalise while the latter is assumed to have a lower precedence to GHG emissions in the context of the study. Secondly, only GHG emissions from hard-coal direct combustion method were considered for coal, with the same for single-cycle combustion for natural gas, since both are respectively the most efficient and clean methods of combustion for the fuels. Thirdly, variation in GHG emission values for different types of wind and solar plants (like onshore/offshore and p-Si/m-Si) were not taken into account in the analysis. Finally, the use of LCA to calculate GHG emissions means that policy makers get information only about the impact of the energy source – no “safe” threshold can be determined.

The use of gCO_2e/kWh provides a holistic analysis of the not only the quantity, but also the impact of greenhouse gas emissions. This is because greenhouse gases such as methane, carbon dioxide, water vapour and NOx have different impacts on the environment per unit mass emitted, and gCO_2e consolidates these into one number that is representative of the impact to the environment. Similarly, use of the LCA also aids in a comprehensive outlook of all processes involved in energy production. Finally, data from solar PV and wind power is likely to be more representative and less liable to aggregate error since individual plants are considered.

V. Public Safety

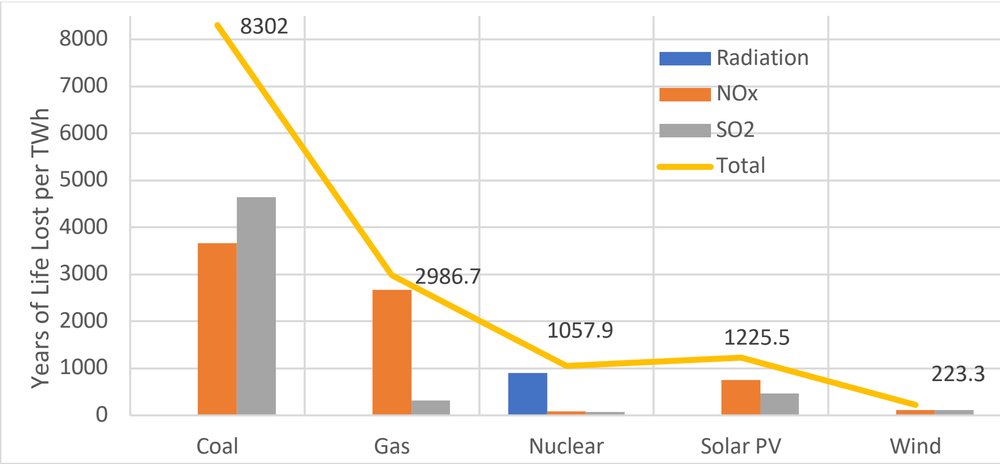
The key motivation behind any public policy is the welfare of constituent citizens, and in this respect impact on public safety should be a vital consideration. The quantity considered to operationalise safety is Years of Life Lost (YOLL) per TWh of electricity produced. YOLL is the difference between life expectancy at a given age for a healthy individual and the actual age at death due to burden of disease. It is a measure of premature mortality that assigns more weightage to the death of a young individual as compared to an older person. The main drivers considered were radiation, NO_x and SO_2 emissions.

Data on population distribution around nuclear, coal and natural gas power plants and radiation release was collected from UNSCEAR[19], with all operating sites considered, and population numbers divided into varying bands of 0-10km, 10-100km, 100-500km, 500-1000km, and 1000-1500km. The dose due to electricity from solar PV and wind power was calculated by summing public doses from mining and manufacture of various metals in their respective equipment[20]. Cancer rates per man Sv of dose were collected from ICRP 1991 (0.05 per man Sv for fatal cancers, 0.12 per man Sv for non fatal cancers), along with the conversion factor for YOLL (15.6 YOLL per cancer incidence)[21]. Data on nitrogen and sulphur oxide emissions[18] and the respective conversion factors[20] was gathered, yielding 1.65 and 2.98 YOLL per $\mu g/m^3$ increase in concentration of NO_x and SO_2 respectively. This was then multiplied by the world population in 2017 (7.2 billion) and divided by the amount of electricity produced in 2017.

Figure 5 imputes that wind power causes the lowest burden of disease in terms of the years of life lost per unit energy, with nuclear energy being the next best alternative. The monetary value of productivity loss from each year of life lost was taken as $2,600 based on a cost of illness approach by Najafi et al[21]. This was then used in the final calculation for cost incurred per unit energy.

---

[18] Lenzen, Manfred. (2008). “*Life cycle energy and greenhouse gas emissions of nuclear energy: A review*” Energy Conversion and Management. 49. 2178-2199. 10.1016/j.enconman.2008.01.033.
[19] UNSCEAR (2018), *Sources, Effects and Risks of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2017 Report: Report to the General Assembly, with Scientific Annexes*, UN, New York,
[20] Classen, M., and S. Blaser. Life cycle inventories of metals. Ecoinvent Report No. 10, Swiss Centre for Life Cycle Inventories
[21] ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60
[20] He, T. *et al*. Ambient air pollution and years of life lost in Ningbo, China. *Sci. Rep*. **6**, 22485; doi: 10.1038/srep22485 (2016)
[21] Najafi F, Karami-Matin B, Rezaei S, Khosravi A, Soofi M. “Productivity costs and years of potential life lost”, 2016



Source	*YOLL/TWh*
Coal	8302
Gas	2986
Nuclear	1057
Solar	1225
Wind	222

Figure 5: Years of life lost per TWh for energy sources [UNSCEAR]

Assumptions, Strengths and Limitations**:** It is assumed that the conversion factor for cancer derived from ICRP 1991 holds for non-Japanese populations as well. All doses are assumed to be received uniformly across the body, with no localization or shielding effects by external sources. Further, cancer is a stochastic effect. The level of dose influences the probability of occurrence of the disease, and it is not known whether there exists a threshold below which the dose has no effect. Hence a conservative assumption is taken that there is no threshold and the dose-response function is considered to be linear and beginning at the origin. The study itself used a linear, no threshold model. In the calculation of radiation due to mining of metals used in equipment for solar PV and wind, it is assumed that only underground mining is carried out.

A salient limitation of this approach is that other harmful substances such as PM2.5, hydrocarbons and PM10 particulate matter released during the lifecycle of a power plant were not considered due to a lack of data on their emissions. This leads to an understatement of the years of life lost for a given energy source. Health impact due to GHG emissions is however considered through the social costs of each gram CO_2 emitted. The lack of empirical data for public exposure to very low doses implied the study was limited to LNT – which might to an overestimation of the number of cancer incidences in the population. Further, uncertainty in terms of confidence intervals could not be propagated in the calculation since CI ranges cannot be multiplied, and hypothesis testing could not be conducted since only one data point was computed. Finally, to convert YOLL to monetary terms, only productivity losses were taken due to subjectivity in approaches quantifying the intrinsic health value of a human-year.

Strengths of the approach lie in the usage of the years of life lost (YOLL) as a quantity that consolidates the social cost of mortality across different causes of death (since the death of a young individual results in a greater loss to society). The quantity was standardized via dividing by the amount of electricity, and hence was independent of the current energy mix. Further, public safety was considered over occupational safety, since the former cannot be regulated using standard safety protocols. Finally, population data around power plants was collected for all energy sources, providing a better estimate of the true cost to human health.

Conclusion

This study addressed the policy-oriented motivations behind the central question – rising demand for electricity and the need to decarbonize the power grid. Globally, nuclear power emerged as the one of the best options for each of the metrics, ranked consistently better than fossil fuels, was relatively the most sustainable of non-renewables, and did not associate with unwanted externalities such as increase in electricity prices. However, all metrics considered different quantities, were global in scope and cannot be specialized to a country-level. Summing up the per kWh cost approximations for sections 1, 4 and 5 yields \$0.7 for wind, \$2.84 for nuclear, \$3.58 for solar, \$8.08 for natural gas and \$22.10 for coal, which assigns a tangible approximation to the results in favour of nuclear power. Thus, if the "you" in the central question is a policy maker, the study concludes in favour of adopting and investing in nuclear power, specifically to phase out fossil fuels from the electricity production mix.