Liu Zechu (A0188295L) Quantifying Nuclear Risk – Final Essay

Title: Should governments pursue nuclear power?

Introduction

Nuclear power can be defined as the civil usage of nuclear fission reactions to generate heat, which vaporises water into steam that turns turbines, generating electricity. Despite various catastrophes involving nuclear reactors, such as the Chernobyl and Fukushima incidents, many countries are still adopting nuclear energy, with about 50 reactors[1] under construction in 2019. At the same time, there is a profound dilemma facing governments around the world today. On one hand, global demand for electricity rose by 2.3% in 2018, its fastest pace in the last decade (International Energy Agency [IEA]). On the other hand, atmospheric carbon dioxide concentration has been growing at 2.3 ppm per year in the past decade, 100 times faster than previous natural increases before the Industrial Revolution (National Oceanic and Atmospheric Administration, 2019). This points to an anthropogenic cause to global warming. In particular, coal-fired electricity generation accounted for 30% of global CO_2 emissions (IEA, 2019). Some have suggested nuclear power technology as a low-carbon alternative for power generation, but contention abounds over whether the risks of utilising nuclear power outweigh the potential benefits it promises.

In this essay, I shall quantitatively evaluate whether governments worldwide should pursue nuclear power as the primary means to tackle the energy-environment dilemma, considering its possible effects in various aspects. I will limit the discussion to governments in advanced economies in the industrialised world with the capacity to construct nuclear power plants. I will focus on data in the past decade as compared to older ones, as recent developments would allow for more valuable and readily applicable insights on which energy source is more beneficial. This essay will compare nuclear power in relation to two other main classes of energy sources: fossil fuels (including coal, oil, natural gas) and renewables (including hydroelectricity, biomass, solar energy, wind, geothermal). These energy sources will be compared in terms of various criteria on an equal footing. This essay will comprise five sections, examining the economic, safety, environmental, reliability and sustainability aspects of various energy sources.

Section 1: Economic

This section will attempt to ascertain which type of power plants generates electricity at the lowest cost in the long run, considering their construction and operation costs in the entire life cycle. The quantity of interest is the average cost per unit of electricity generated in the life cycle of a power facility. To provide a consistent basis of comparison, all costs are calculated in US dollars inflation-adjusted to the same base year 2010. Thus, the unit of this quantity is the US dollar per kilowatt-hour ($/kWh). The average cost of electricity generation of a given power plant is obtained by summing the total construction and operation costs of a power-generating asset over its life time, divided by the total amount of electricity produced in that life time. The levelized cost of electricity (LCOE) is used represent this quantity. Its formula is given by $LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electrical\ energy\ produced\ over\ lifetime}$. The numerator consists of the summation of investment expenditures, operations and maintenance expenditures, and fuel expenditures for all the years within the expected lifetime of the system, adjusted by the discount rate (7%) to account for the cost of capital. The denominator is the summation of the electrical energy generated in all the years within the expected life time, adjusted by the discount rate.

For each type of power generation, a sample is taken from the population of all power-generating installations of this type. The LCOE associated with each power plant is calculated. These values are obtained from an OpenEI database[2]. Then, the sample mean of the LCOEs of all plants in a sample is calculated. The confidence interval is computed at 95% level of confidence. For each energy source, I conducted a two-sample t-test assuming unequal variances at $\alpha = 0.05$ level of significance to test the null hypothesis that the mean LCOE of nuclear is equal to that of a given source. The calculated results are summarised in Table 1 and presented in Fig. 1. Since the p-value of hydropower is more than 0.05, the null hypothesis that both hydropower and nuclear power have the same mean LCOE is not rejected. We can conclude that the cheapest ways to produce electricity are hydropower and nuclear.

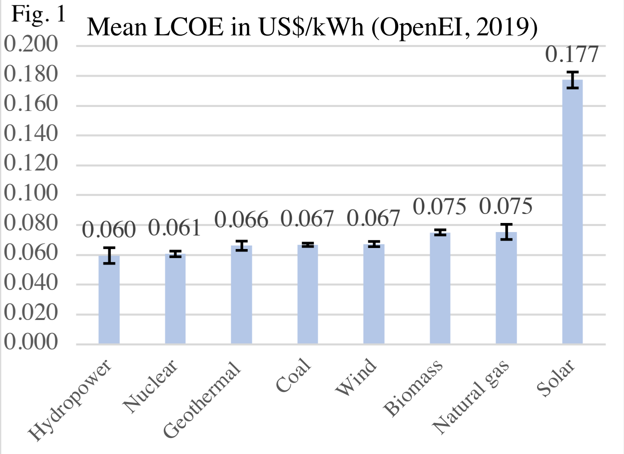
[1] *Nuclear Power in the World Today*, World Nuclear Association, from https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

[2] These data are gathered from the U.S. Environmental Protection Agency, *Annual Energy Outlook* by U.S. Energy Information Administration, U.S. National Renewable Energy Laboratory, International Energy Agency, Lazard, the European Solar Thermal Electricity Association.

Table 1: Calculations for the mean LCOE for each energy source

Energy source	Hydropower	Nuclear	Geothermal	Coal	Wind	Biomass	Natural gas	Solar
Mean LCOE / US$ kWh^{-1}	0.060	0.061	0.066	0.067	0.067	0.075	0.075	0.177
CI at 95%	0.054-0.065	0.059-0.063	0.063-0.069	0.066-0.068	0.066-0.069	0.073-0.077	0.070-0.080	0.172-0.183
Sample size	166	240	390	986	1473	666	777	1269
p-value	0.697	1 (reference)	0.003	<0.001	<0.001	<0.001	<0.001	<0.001

Fig. 1



The LCOE is highly dependent on several assumptions. Firstly, the cost of capital to invest in and finance electricity generation projects is assumed to be fully accounted for by the discount rate used in the computation. We also assume that the power plants will operate for the duration specified by their expected lifetimes. The fuel prices are assumed to not fluctuate substantially in the future. The dependency on these assumptions limits the effectiveness of using the LCOE. In addition, it is challenging to calculate the energy output of a system over its lifetime. Even after assuming the expected lifetime is accurate, the energy production is heavily dependent on the efficiency of energy conversion and the proportion of time during which the power plant is actively producing electricity. These two quantities are hard to measure. Another limitation is that the data values are predominantly from the US, so the samples may not be representative of the costs in other countries. To address the limitations of LCOE, a possible solution is to gather more data from non-US power plants. Also, sensitivity analyses can be performed to assess whether variations in parameters impact the computed results significantly. For instance, a sensitivity analysis can be conducted on the discount rate of 7%, as it was an arbitrarily fixed parameter used in the calculations.

Nevertheless, the strength for using the average cost per unit output is that it better reflects the actual cost of electricity considering the entire power generation process. The costs of building power facilities vary greatly, and they also produce vastly different amounts of energy for different durations of time. The cost-benefit analysis approach provides a consistent basis of comparison between different methods of power generation. Also, given the sheer practical difficulty in collecting data for all the possible expenditures associated with a power plant over the course of its lifetime, which usually spans 20 to 40 years, very few other measurements are available in online databases that represent the average cost of electricity and are applicable across all energy sources. Using a widely used and standardised formula provided by the LCOE allows data collectors from all around the world to use similar methodology in computing this quantity, so that we have a large pool of data to analyse from power facilities of different types.

Section 2: Safety

This section will assess the impact on worker safety involved in the entire production process of various energy sources. Worker safety is quantified as the number of deaths per unit electricity produced in the entire production process, including the extraction and transportation of raw materials, construction of infrastructure, daily operation of power facilities, maintenance and repair works, and waste disposal. The unit is deaths per gigawatt-year of electric power (GWey^{-1}).

The data is obtained from an OECD[3] report in 2010. The report utilised the database assembled by the Paul Scherrer Institute (PSI) based in Switzerland. This database contains severe accident data from full energy

[3] Organization for Economic Co-operation and Development (OECD) members: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, UK, Australia, Canada, Chile, Israel, Japan, Mexico, New Zealand, South Korea, US.

chains on 1870 energy-related accidents that resulted in five or more prompt fatalities that have actually occurred from 1969 onwards. For each energy source, the total number of fatalities resulting from severe accidents (≥ 5 fatalities) is calculated by summing all the fatalities within a given time period recorded in PSI's database. This value is then divided by the total amount of electricity generated in that same time period for that energy source. This process is repeated from all energy sources, and respectively for OECD and non-OECD countries. The results are summarised in Table 2 below.

Table 2: Summary of severe accidents in various energy chains in the period 1969-2000 (OECD, 2010)

Energy chain	[OECD countries] Fatalities/GWey	[Non-OECD countries] Fatalities/GWey
Coal	0.157	0.597
Oil	0.132	0.897
Natural Gas	0.085	0.111
Hydropower	0.003	10.285
Nuclear	–	0.048

A data point on the number of fatalities from severe nuclear accidents is missing as there was only one such accident in the nuclear energy sector worldwide from 1969 to 2000, which happened in Ukraine, a non-OECD country. Results were stratified into OECD and non-OECD countries as there were significant differences in levels of technological development and safety regulatory frameworks. Nevertheless, comparison across all energy sources within OECD and non-OECD countries shows that nuclear energy has the lowest number of fatalities in severe energy accidents per unit of electricity produced.

The assumptions in the computation of these results are: firstly, PSI's database fully covers every severe accident that occurred during the specified time period, and there was no non-reporting of severe accidents. Secondly, all these accidents occurred during the life cycle of energy production. Thirdly, the amount of electricity generated from each energy source is accurately calculated. Fourthly, the number of fatalities due to smaller accidents (< 5 fatalities) and that due to latent deaths (deaths as a result of an energy accident but that did not occur immediately) were not sufficiently significant to change the overall results.

There are several limitations in this data set. Data on accidents related to wind, solar, biomass and geothermal energies were unavailable in the database. Consequently, based on the current data, we are unable to draw conclusion on their associated worker safety, since there was no comparison with these energy sources. Moreover, due to the technical difficulty in data collection, not all accidents could be reported and documented. The exclusion of deaths due to smaller accidents and latent deaths may skew the results. The total sum of the many small accidents with minor consequences may be more substantial. Also, the data collection period ended in 2000, and thus the data is outdated and unable to represent the current values. To address these limitations, with the improvement in energy accident protocols and data coverage, a more comprehensive database can be set up to record all energy-related accidents across all energy sources. Metrics other than the number of immediate deaths can also be used in the comparison between energy sources to provide a more holistic picture on the impact on workers' health. For example, the numbers of various levels of injuries, and changes in life spans of workers can be considered.

Notwithstanding these limitations, the dataset has numerous strengths. When assessing energy-related accidents and risks, it is essential to consider full energy chains because, in general, an energy chain comprises stages running from exploration and extraction to distribution and waste treatment, and not all these stages are applicable to every energy chain. Considering all stages treats different energy sources equally. Moreover, PSI has defined severe accidents as those that result in five or more prompt fatalities. This clear definition also enables the collection of a more reliable data set since smaller accidents attract less attention and may go largely unreported. Even if some of them do get reported, small accidents from different energy sources may attract different attention and as a result, different levels of coverage.

Section 3: Environmental

This section aims to address the environmental impact of various energy sources. Specifically, it aims to answer the question: which energy source contributes the least to global warming per unit electricity produced. Global warming refers to the long-term continued rise of Earth's atmospheric surface temperature. This increase in global average temperatures has been supported by direct temperature measurements. Substantial evidence suggests that the current level of warming is attributed to anthropogenic emissions of greenhouse gases (GHGs). An Intergovernmental Panel on Climate Change

(IPCC) report published in 2018 states that the observed global mean surface temperature for 2006–2015 was 0.87°C higher than the average over the 1850–1900 period. Estimated anthropogenic global warming is currently increasing at 0.2°C per decade due to past and ongoing GHG emissions.

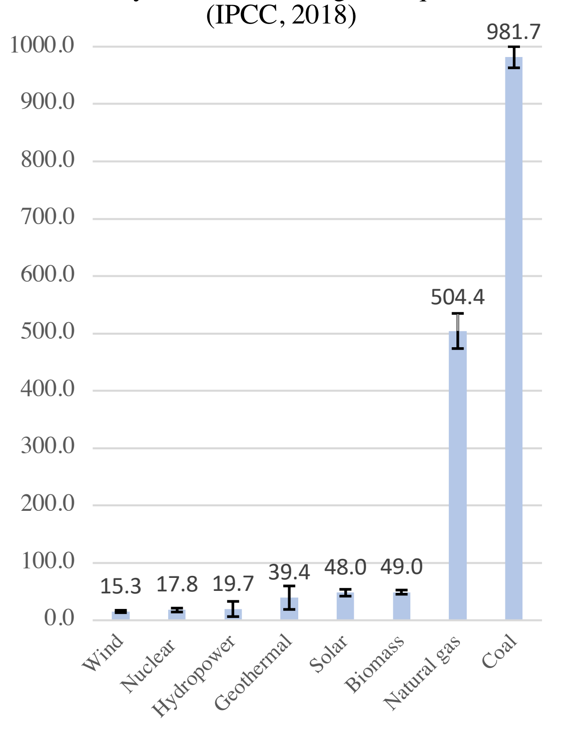
As a result, to assess the impact of an energy source on global warming, we should consider how much GHGs are emitted per unit of electricity in its entire lifecycle. However, there are many types of GHGs, such as carbon dioxide, methane and chlorofluorocarbons. Different types of GHGs have different global warming potential[4] (GWP). In addition, different energy sources may produce different proportions and amounts of GHGs with varying global warming potentials. To provide a consistent basis of comparison between various energy sources, the following computation considers the amount of GHGs measured in equivalent carbon dioxide (CO_2eq). A carbon dioxide equivalent is a metric measure used to compare the emissions from various greenhouse gases on the basis of their GWP, by converting the amount of a gas to the equivalent amount of carbon dioxide with the same GWP (Eurostat, 2017). The carbon dioxide equivalent of a gas is calculated by $mass\ of\ the\ gas \times GWP\ of\ the\ gas$.

In addition, the life cycle assessment is used in measuring the GHG emissions of different energy sources. This means that the GHG emissions in every stage of the lifecycle of electricity production are accounted. A cost-benefit analysis approach is used to compute the amount of equivalent carbon dioxide generated per unit electricity for each energy source. Thus, the unit of this quantity is grams of carbon dioxide equivalent per kilowatt-hour of electricity generated (gCO_2eq/kWh).

Table 3: Calculations for the mean lifecycle emissions for each energy source

Energy source	Wind	Nuclear	Hydropower	Geothermal	Solar	Biomass	Natural gas	Coal
Mean lifecycle emissions / gCO_2eq kWh^{-1}	15.3	17.8	19.7	39.4	48.0	49.0	504.4	981.7
CI at 95%	13.3-17.4	14.4-21.2	6.4-32.9	18.9-59.8	42.1-53.9	45.4-52.7	473.7-535.0	963.2-1000.1
Sample size	107	99	27	8	176	534	62	164
p-value	0.220	1 (reference)	0.781	0.040	<0.001	<0.001	<0.001	<0.001

Fig. 2 Lifecycle emissions in gCO2eq/kWh (IPCC, 2018)



The calculated results are summarised in Table 3 and presented in Fig. 2. These values are obtained from a 2014 IPCC report, which gathered data on lifecycle GHG emissions from a wide range of scientific studies. A confidence interval of 95% is used and for every energy source, a two-sample t-test assuming unequal variances at $\alpha = 0.05$ level of significance is conducted to test the null hypothesis that the mean lifecycle emission of nuclear is equal to that of a given source. Since the p-values of wind and hydropower are greater than 0.05, it can be concluded that wind, hydropower and nuclear have the lowest GHG emissions per unit of electricity generated, and therefore, contribute the least to global warming per unit of electricity.

There are some underlying assumptions. Firstly, the conversion of the various GHGs into carbon dioxide equivalent accurately reflects their impact on global warming. Secondly, the total amount of electricity generated for each energy source is measured accurately. Thirdly, these data are representative of power generation around the world.

[4] The Global Warming Potential (GWP) is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of CO_2. The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. (Environmental Protection Agency, 2017)

One limitation of this approach to quantifying the environmental impact of each energy source is that it does not paint a sufficiently holistic picture of their multifaceted effects on the environment. The amount of carbon dioxide equivalent only deals with the heat trapping abilities of various gases, but ignores other effects like acid rain, ozone layer depletion and particulate air pollution. In addition, in practical aspects, each energy source may harm the environment in a particular unique way. For example, hydroelectric dams directly result in the flooding of large swathes of land, disrupting the ecosystem both on land and in the water body. This effect is generally not present in other energy sources and thus hard to compare. A possible solution to address the limitations is that more metrics can be used to consider the environmental impact of each energy source. For example, the amount of particulate matter released into the atmosphere and the amount of water consumed/contaminated during the production process can also be analysed in a lifecycle analysis and per unit cost-benefit analysis approach.

The approach discussed in this section has several strengths. Firstly, GHG emissions are common to all energy sources, providing a consistent basis for comparison. Secondly, global warming is regarded as the one of the most pressing issues on the global scale. Assessing the impact of various energy sources on global warming can provide governments with valuable insights into planning the future energy mix of the country while balancing the need for climate change mitigation. Thirdly, the lifecycle and cost-benefit analyses rule out the effects of variations in production procedures and amounts of electricity generated between different energy sources, but instead focus on the per unit environmental cost of electricity.

Section 4: Reliability

This section aims to ascertain which energy source provides the most reliable output of electricity. The reliability of an energy source can be assessed by its efficiency and stability. Specifically, I will answer the following question: which energy source consistently provides the highest percentage output in proportion to the maximum capacity of its power plant.

Answering this question tells us how fully a power-generating system is utilised. Since the operation of a power facility is subject to many constraints that affect the actual power output in contrast to expected output, a power system that is efficient most of the time is preferred. An unstable output will cause the power plant to not be efficiently utilised at all times. Also, this quantity also shows whether an energy source can be relied upon to produce the bulk of the electricity demand. Industrial and economic activities require a large and stable output of electricity. An unreliable output can cause serious economic damage if the whole grid is heavily dependent an inconsistent energy source.

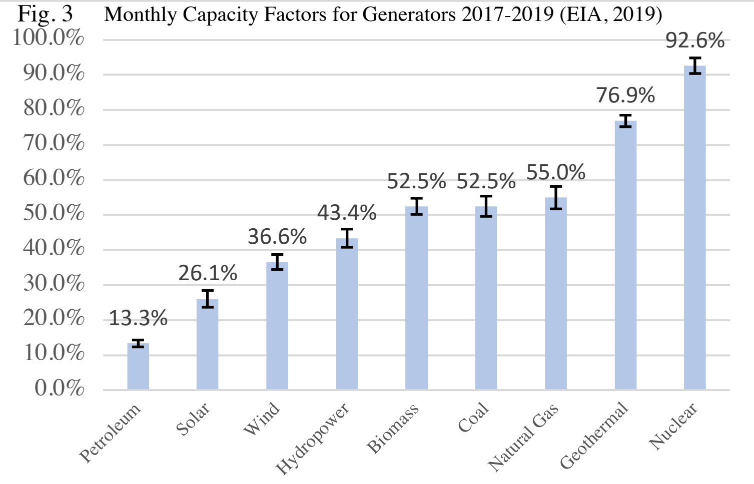
To answer the question, I have gathered data on the monthly capacity factors for utility scale generators of various energy sources, from January 2013 to July 2019, in the US. The dataset is from *Electric Power Monthly* by the U.S. Energy Information Administration (EIA), published in September 2019. The capacity factor is the unitless ratio (expressed as a percent) of the actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period. The capacity factor for a particular fuel/technology type over a given month is calculated using the following formula: $Capacity\ Factor = \frac{\sum generation}{\sum capacity \times available\ time}$. In particular, the numerator $\sum generation$ represents the summation of the amount of electricity generated by each generator in the sample over a given month. In the denominator, $\sum capacity$ represents the summation of the maximum capacity, expressed as the amount of electricity per unit time, of each generator in the sample. Finally, $available\ time$ is the time period over which the capacity factor is computed, i.e. the duration of a given month. Generation and capacity are specific to each generator. Available time is also specific to the generator in order to account for differing online and retirement dates. These values are collected from a monthly sample of approximately 1900 plants in the US. Also, units that began operation or retired during the month are excluded.

Table 4: Calculations for the mean monthly capacity factor for each energy source

Energy source	Petroleum	Solar	Wind	Hydropower	Biomass	Coal	Natural gas	Geothermal	Nuclear
Mean monthly capacity factor / %	13.3	26.1	36.6	43.4	52.5	52.5	55.0	76.9	92.6
CI at 95%	12.3-14.3	23.7-28.5	34.4-38.7	40.8-46.0	50.2-54.8	49.6-55.4	51.7-58.2	75.2-78.5	90.4-94.9

Sample size (number of months)	31	31	31	31	31	31	31	31	31
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	1 (reference)

Fig. 3 Monthly Capacity Factors for Generators 2017-2019 (EIA, 2019)



To process the data for a particular energy source, I took the mean of and calculated the 95% confidence interval for the capacity factors for all the months. Then, a 2-sample t-test is performed with reference to nuclear to test the null hypothesis that the mean monthly capacity factor of nuclear is equal to that of a given source. This process is repeated for every energy type and the results are summarised in Table 4 and presented in Fig. 3.

From the results, we can see that nuclear energy has significantly the highest mean monthly capacity factor out of all energy sources. All other sources have p-values less than 0.05. This means that nuclear power plants generally operate efficiently, close to the full capacity. Thus, nuclear energy is the most reliable. Energy sources like wind and solar may have intermittent output due to physical constraints, such the lack of strong winds or sunshine.

In the derivation of the above results, there are several assumptions. Firstly, all the energy generated from a given generator is assumed to be attributed to a single type of technology. The amounts of electricity generated by power plants of mixed technologies (e.g. coal plus natural gas) are negligible with respect to the overall results. Secondly, the maximum capacity of a generator is accurately measured.

These assumptions are closely linked to the limitations. Some power plants indeed run on more than one technology type. This report attributes all the electricity output to the primary technology type, so the amount produced by the non-primary energy source is not accounted for. Nevertheless, since the vast majority of power plants operate on only one type of energy source, the accuracy of the results is not affected to a significant extent. Also, the theoretical maximum capacity of a generator can be hard to calculate. In fact, the monthly capacity factor for nuclear energy in January 2018 was 100.70%, suggesting that more electricity was generated than the theoretical maximum, contradicting the very definition of "maximum". Moreover, taking the mean of all the monthly capacity factors may not produce the true average capacity factor over the entire time period, because the amount of electricity produced differs from month to month. Furthermore, supply-side constraints may not always be the cause of low capacity factors. A low demand for electricity may also result in power plants not operating at full capacity. In addition, all the generators are from the US. Thus, the results are not generalisable to other countries and to the whole world, but may only serve as a proxy to the industrialised world.

To address the limitation that the data is not generalisable to non-US countries, more data can be collected from generators of various energy sources in other countries. The calculated capacity factors can be compared and contrasted with those from the US. It can be checked whether these values are consistent.

Notwithstanding these limitations, there are numerous strengths. Firstly, the monthly data covers approximately 1900 plants out of a total of 9,719[5] in the United States. The sample size is relatively large, so that capacity factors obtained are likely to be close to the true value of the population. Secondly, the use of monthly capacity factors instead of annual ones give us insight into potential seasonal fluctuations of certain energy sources. Seasonal fluctuations adversely affect the reliability of an energy source, since the reduced output in a down season has to be compensated for by other energy sources, reducing the ability of that energy source to be relied upon by the electricity grid.

[5] As of December 31, 2018. Data obtained from EIA, 2019, https://www.eia.gov/tools/faqs/faq.php?id=65&t=2

Section 5: Sustainability

The last section of this essay will assess the sustainability of the various energy types. The question to be discussed is: how many years from now will fuels for various energy sources last, assuming the current rates of consumption and current reserves remain unchanged? Since the conventional concept of "fuel" is only applicable to non-renewable energy sources, namely, coal, oil, natural gas and nuclear energy, I will focus on the quantitative analysis of these energy sources.

For each non-renewable energy source, I have collected data from BP Statistical Review of World Energy published in 2019, on the total primary energy[6] consumption and total proved reserves on the Earth in 2018. To facilitate comparison between different fuels, their amounts are converted to million tonnes of oil equivalent (toe), which is a unit of energy defined as the amount of energy released by burning one tonne of crude oil. Lastly, the number of years left for each fuel is calculated by: $\text{number of years left} = \frac{\text{Total proved global reserves in 2018 (in million toe)}}{\text{Primary energy consumption in 2018 (in million toe } year^{-1})}$. The results are summarised in the following Table 5. As seen from this table, if the world were to continue consuming the same amounts of energy fuels at 2018's levels, and if no new reserves were to be discovered, uranium will fulfil our energy demands for the longest duration, at 209 years, closely followed by coal which stands at 196 years. Both oil and natural gas have only approximately 50 years remaining. Thus, nuclear energy is able to satisfy our energy needs for the longest duration compared to other sources, with assumptions which will be discussed below.

Table 5: Calculations for the number of years left for each non-renewable fuel

Fuel type		Coal	Oil	Natural gas	Nuclear (uranium)
Primary energy consumption in 2018 / million tonnes oil equivalent per year		3772.1	4662.1	3309.4	611.3
Total proved global reserves at end of 2018	In respective units from raw data	1054782 million tonnes	244.1 thousand million tonnes	196.9 trillion cubic metres	7 988 600 tonnes of elemental uranium
	Converted to million tonnes oil equivalent	738347[7]	244100	169334[8]	127817[9]
Number of years remaining from 2018 / year (rounded to nearest year)		196	52	51	209

Some of the quantities used in the above calculations may need further clarification. Total proved reserves of coal/oil/natural gas are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions (BP, 2019). Also, since the BP report does not provide a value for total proved reserves for uranium, the value was obtained from *Uranium 2018: Resources, Production and Demand* by OECD. The uranium reserves in this case are defined as identified resources consisting of reasonably assured resources[10] and inferred resources[11] recoverable at a cost of less than US$260/kgU[12].

First, it should be noted that the above results assume that the current levels of consumption for all the fuels stay unchanged in the future. A consequent limitation is that this is an unrealistic assumption, because global energy production will continue to grow given the continual increase of world population and industrialisation. And the global energy mix is bound to change as more countries switch to renewables (BP, 2019). Second, all the data were summed from individual countries' reports, which were assumed to be accurate. However, different countries may have different methodologies of measuring the same quantity. Third, to calculate the numbers of years remaining, current reserves were assumed to be accurately determined. In addition, no new reserves would be discovered and no current reserves would

6 Primary energy comprises commercially-traded fuels.

7 Conversion factor: 1 toe = 1.42857143 tonnes of coal equivalent (tce). (IEA, 2019)

8 Conversion factor: 1 billion cubic metres NG x 0.860 = 1 million tonnes oil equivalent (BP, 2019, Appendices: Approximate conversion factors)

9 Conversion factor: 1 tonne of uranium (light-water reactors, open cycle) = 16 000 toe (Annex A.5 World Energy Resources, World Energy Council 2013)

10 Reasonably assured resources (RAR) refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities, which could be recovered within the given production cost ranges with currently proven mining and processing technology, can be specified. (OECD, 2018)

11 Inferred resources (IR) refers to uranium, in addition to RAR, that is inferred to occur based on direct geological evidence. (OECD, 2018)

12 Kilograms of elemental uranium

be wasted/unusable in the future. Again, this assumption is unrealistic. In fact, new reserves of various fuels are being discovered every year. Fourth, the conversion factors are assumed to accurately convert different fuel types into oil equivalent. This is practically difficult as different fuels even within the same category have different qualities and thus energy densities. Also, the electricity generated eventually also depends on the efficiency of power plants, which differs among different technologies. Fifth, the above calculation does not consider potential advancement of technology in the future that may improve efficiency of utilising existing reserves or even change the type of fuels required. For example, thorium can be used as an alternative to uranium in nuclear fission. Nuclear fusion reactors, if commercialised in the future, will require hydrogen isotopes instead of uranium. Sixth, in this discussion, renewables are assumed to be able to last forever, since their "fuels" can be regenerated naturally. However, the construction of certain renewable power installations, such as solar panels and associated power storage units, require metals such as lithium and cobalt. These resources are finite and their deposits need to be considered too. A solution to this problem is to take into account the consumption and reserves of finite resources that are key to energy industries, such as lithium, cobalt and rare earth metals.

Despite the various unrealistic assumptions, the results provide a rough estimation and indication of how long each energy type can sustain our energy demand. The rationale for such assessment is that, even if an energy source has substantial benefits by many criteria, if it cannot sustain our energy demand in the foreseeable future, policy makers cannot rely on it as the primary means of power generation in a country.

Conclusion

To sum up, governments in industrialised countries should consider using nuclear energy as a major means of electricity generation, as the results from the various criteria show that nuclear energy boasts tremendous benefits over other types of energy sources. Both hydropower and nuclear energy have the lowest per unit costs of electricity in the entire lifecycle. Nuclear energy also results in the lowest number of per-unit fatalities. Nuclear, wind and hydropower release the lowest amounts of GHGs per unit electricity. Nuclear power also has the highest mean capacity factor, making it a reliable and efficient means of power generation. Lastly, nuclear fuel (uranium) can potentially last the longest among non-renewables. Although there is still a long way to go, future developments in nuclear fusion technology may make nuclear power more accessible and sustainable. As our world's "carbon budget" rapidly depletes, the environment-energy dilemma is becoming ever more prominent. In the search for alternative energy sources, nuclear power can play a momentous role.

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