An Examination of the Future of Nuclear Energy in the Context of Climate Change

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Abstract

This paper intends to explore whether nuclear power plants can serve as a sustainable alternative to thermal power plants powered by coal and natural gas, and as a legitimate and much needed supplement to currently popular sustainable energy sources such as wind, solar, and hydropower. A brief analysis of the French nuclear system will provide historical background to the most significant commitment of a state to the utilization of nuclear energy as a means to produce electricity. Interviews with relevant experts will shed light on mistakes made in the French nuclear project to serve as lessons for future nuclear projects, particularly in terms of maximizing the efficiency of future nuclear power projects. In the primary analysis of the viability of nuclear energy as a means to produce electricity, a comparison of lifetime greenhouse gas (GHG) emissions will provide support for the future utilization of nuclear energy, while a comparison of the overall financial cost of nuclear power will explain the economic complexities involved with investing in the construction of new nuclear projects. Finally, propositions for the future of nuclear energy in the context of reducing GHG emissions in the electricity sector will be provided with additional concluding remarks.

Acknowledgements

I would like to thank Dr. Curgai for inspiring me to research nuclear energy, and Dr. Matilla for providing invaluable guidance early in my research process. I would also like to express my gratitude to Mr. Marc Finaud for both helping me narrow down my research topic, and for referring me to relevant experts whom I had the privilege of interviewing.

I would also like to thank Muhlenberg College for approving my request to study abroad with SIT here in Geneva. The experience has been nothing short of fantastic.

Abbreviations in Alphabetical Order

CO_2 - Carbon Dioxide

EI - Economic Index

EU - European Union

GHG - Greenhouse Gas(s)

kWh - Kilowatt Hour

LCOE - Levelized Cost of Electricity

MIVES-Monte Carlo - Modelo Integrado de Valor para una Evaluación Sostenible

mWh - Megawatt Hour

TMR - Total Material Requirement

OCC - Overnight Construction Cost

UN - United Nations

US - United States

U_3O_8 - Triuranium Octoxide

Introduction

The topic of nuclear energy has been a widely discussed, heavily polarized, and generally vaguely understood topic since the first nuclear reactor began operations in the 1940s. Naturally, the usage of atomic weapons at the end of the second World War and the nuclear arms race that followed surrounded the idea of nuclear power with a fog of misunderstanding and fear. Several high profile incidents including the disasters at Chernobyl and Three Mile Island, both of which having been exacerbated by human error and disinformation, further deteriorated the public perception and support for nuclear power during the second half of the 20th century. Late 20th century environmentalism further marginalized the acceptance of nuclear energy, with advocates calling for the shutdown and decommissioning of looming plants which they saw as threats to the earth itself. Today, the world of energy policy and environmental advocacy is split between those who support nuclear power, and those who very much do not. Though electricity generated by nuclear power plants produces no direct greenhouse gas (GHG) emissions as a byproduct, the fear of a nuclear meltdown, an atomic-level explosion, or radiation poisoning still remains at the forefront of the laypersons' oppositional arguments to nuclear power. The production and storage of nuclear waste is a further anxiety commonly presented by skeptics, though such an argument exposes a lack of understanding, as nuclear waste has the potential to be eliminated by reprocessing into usable nuclear fuel (World Nuclear Association, 2020). In general, nuclear energy is a controversial topic championed by some, and disparaged by many others.

This article will explore the scientific basis for the argument which claims nuclear power to be a valuable, sustainable, and viable source of energy in the electricity production sector, particularly in the context of the collective responsibility of the world to confront and combat the climate crisis, while continuing to meet the electricity needs and demands of over 8 billion people. The production of electricity through various means including both renewable and non-renewable sources will be discussed, with statistics regarding their accompanying GHG emissions provided from several sources including the United Nations (UN), the country of Canada, and independent researchers. As a case study, the (mostly) nuclear powered electricity grid of France will be discussed as a means to analyze the effects of a country which, since the oil crisis of 1973, committed strongly to the utilization of nuclear power to produce electricity. The case of France will be referenced in the forthcoming policy recommendations. The economic cost and financial investment required for the construction and operation of nuclear power plants will also be discussed, as despite the low GHG emissions produced from nuclear power plants, the required construction costs have historically proven to be significant. Whether nuclear power is a sustainable and economically viable means to generate the electricity that will take the world deep into the 21st century is a burning question that must be answered by energy policy experts. As such, it is the aim of this article to contribute to the conversation and explore the future of nuclear energy in the electricity production sector.

Research Methodology

Prior to initiating the research process for this project, I considered several potential topics in which to engage. I was initially inclined to continue my research from my SPS essay regarding the position of Israel in the Ukraine conflict in the context of its operations in Syria and the necessity to appease both Russia and the West. I was dissuaded, however, from continuing with this topic as I had already spent a significant amount of time exploring Israeli defense policy and it had been recommended to me that I expand my research-related horizons.

As such, I cast around for inspiration, and soon felt drawn in by the prospect of exploring the viability of nuclear energy as a means to reduce GHG emissions in the electricity sector. I had a degree of background knowledge on the subject of climate change, GHG emissions, and energy policy, though I lacked the critical understanding of these topics to substantially back up a claim. I am passionate about finding solutions to the climate crisis and I strongly believe humanity to be in possession of the necessary tools to fix our most pressing collective problem. Therefore, after briefly considering researching the protection of nuclear power plants in conflict zones as initially suggested by Professor Curgai, I settled on deepening my understanding of energy policy by exploring the viability of expanding nuclear energy capabilities for the sake of reducing GHG emissions in the electricity sector. My research was intended to be general, in the sense that I would not limit my analysis to a single country. I believe that since reducing GHG emissions to the extent that we limit global temperature rise to 1.5 degrees Celsius, as agreed upon in the 2015 Paris Agreement, is a collective responsibility for all of humanity and is not possible to achieve by a single state, it would be ineffective to limit my research to a single country.

Upon confirming my topic with Dr. Mattila, I began exploring potential interview candidates in order to incorporate professional insight into my finished product. On the advice of a peer, I reached out to Mr. Marc Finaud, with whom I had a highly productive conversation and who referred me to several experts whom I then interviewed as well. I discussed energy policy and the French nuclear energy system with Professor Giacomo Luciani, and some of the oppositional arguments to expanding nuclear power with Mr. Mycle Schneider. Mr. Schneider also explained operational aspects of nuclear power and wind power plants, which contributed to my overall understanding of the issue I was approaching.

Following my discussions with Mr. Finaud, Professor Luciani, and Mr. Schneider, I felt confident in my understanding of nuclear energy to begin my independent research. I spent time developing an understanding of the French nuclear energy system, including various mistakes made by France since the Messmer plan[1], after which I researched the lifetime GHG emissions of various power plant types. Finally, I researched the economic viability of producing electricity with nuclear energy using two methods of analysis. The two methods gave two different answers to the question of economic viability- the MIVES-Monte Carlo method analyzed the degree to which an investment in different energy types would yield sustainable development potential, and the LCOE method produced cost figures for electricity generated by source.

Literature Review

Existing literature on the topic of nuclear energy is plentiful, though there lacks consensus among the community of relevant academics regarding whether nuclear energy usage should be expanded or even continued at all. The report from the United Nations Economic Commission for Europe clearly shows the sustainability factor of nuclear energy with regards to its low lifetime GHG emissions, and exemplifies the call by international organizations including the UN and EU to combat the ongoing climate crisis by lowering GHG emissions on a planetary level (Gibon, 2021). Of the best historical examples of the impact of a wide usage of nuclear power to generate a significant portion of a state's electricity is that of France. The French energy company, Electricité De France, owns and operates all nuclear reactors in the country, as explained by Grant (2001). The French nuclear project is not without fault however, and the mistakes and missteps of the nuclear program are discussed in Grubler (2010).

[1] The Messmer Plan was the nuclear initiative put forth by Pierre Messmer following the 1973 oil crisis.

The comparison between energy sources and their accompanying GHG emissions are discussed in several sources, each with their own particular specialty and focus. Parker et al. (2016) studies the effect of uranium mining and refining in Canada, which possesses large natural uranium deposits and currently is both an exporter of uranium, and a major producer of electricity from nuclear power. The United Nations report mentioned above (Gibon, 2021) offers a comparison of several electricity generation options and their resulting emissions, similar to the research produced by Li et al. (2021) and Nakagawa et al. (2022). The benefit of utilizing several sources with similar data sets is the ability to analyze the consistencies between the three, while diversifying the sources of data. Between the UN, the Canadian government, and independent researchers, several consistencies with regards to the efficacy and sustainability of nuclear power plants are proven later in this article.

The analysis shifts from focusing purely on the emissions produced by nuclear power plants and their overall environmental impact, to the financial investment required to construct and the overall economic sustainability of nuclear power plants. Two methods of analysis are examined in this article, notably the MIVES-Monte Carlo (Cartelle Barros et al., 2016)(Pujadas et al., 2016) and LCOE analysis by several sources including Cartelle Barros et al. (2016), Kemp & Doren (2022), Sung & Jung (2019), and Bilicic & Scroggins (2023). As this data can be impacted by the sources of primary data and potentially impacted by the respective articles political intentions, utilizing several data sets to explore consistencies was deemed prudent and necessary.

French Nuclear Power: A Brief History

Following the oil crisis of 1973, the French government, at the time headed by Prime Minister Pierre Messmer, decided to drastically reduce its reliance on foreign energy exports so as to protect the state from potential future energy crises. The French mainland possesses limited natural energy resources which can be extracted locally and had historically relied heavily on imports of foreign energy resources such as oil and coal. France already possessed local expertise in nuclear science, having first tested a nuclear weapon in 1968, roughly 21 years after the opening of the first French nuclear reactor, 'La Pile Zoé,' in 1947 (Cea, 2019). As such, nuclear energy was an obvious option for France to reduce its consumption of imported energy resources, especially considering its lack of natural resources. Following the implementation of the Messmer Plan in 1974 which aimed to produce a significant majority of French electricity using nuclear power, the French energy company 'Electricité de France', owned and operated by the French government since 1946 (Grant, 2001), initiated construction of 58 Pressurized Water Reactors. The reactors were constructed in phases until 2000, at which time nuclear power supplied roughly 80% of French electricity. Most of the reactors were built in a roughly 20 year period between 1974 and 1993 (Grubler, 2010).

In an interview with Professor and energy policy expert Dr. Giacomo Luciani, he stated that the degree to which France committed to nuclear power could have been somewhat excessive, as a significant event destabilizing the availability of refined uranium could result in a major catastrophe for the French energy grid. Despite providing safe, stable, and relatively cheap energy for the French population for the past 40 years, problems arising in recent years have exposed some of the shortcomings of the French nuclear program. Professor Luciani discussed the relatively short amount of time in which most of the French nuclear reactors were built, which has led to steadily increasing maintenance costs, and the recent need to extend the life of nuclear power plants rather than decommission them, which is both costly and potentially dangerous as the plants continue to age past 50 years (Makovsky, Luciani, 2023).

Furthermore, in an exchange with international energy and nuclear policy consultant Mycle Schneider, we discussed the relative efficiency of the French nuclear system compared to other low-emission renewable energy sources. By comparing the load factors of the French and US nuclear power systems with a relatively high-efficiency offshore wind farm in Scotland, he showed how the lack of reliability and increasing need for maintenance across French nuclear reactors had resulted in the wind farm example proving more efficient and significantly cheaper. While, in 2022, still producing 63% of all electricity, the French nuclear power fleet only operated at 52% of its nominal capacity, which, for nuclear power plants, should ideally be over 90%. The US nuclear power system operated at roughly 90% of nominal capacity over the past decades, though it provided a significantly smaller portion, about 20%, of commercial electricity to the grid. The Scottish Hywind floating offshore wind farm (Equinor, 2022) discussed by Mr. Schneider, operated over the past five years at an average of 54% of nominal capacity, higher than the French nuclear power fleet and at a drastically lower cost. While wind turbines obviously have varying output, they generate some power most of the time. A nuclear power plant that is down for refueling, inspections, maintenance, repairs, climate impacts, or strikes does not produce anything. Five French reactors (7,140 MW) did not produce a single kWh in 2022 (Makovsky, Schneider, 2023).

Increasing penetration levels of variable renewables like solar and wind will need increasing availability of highly flexible response options, like demand-response approaches, peak-capable production plants like hydro, gas (preferably biogas) and storage. The latest Lazard comparative cost estimates show that solar and wind combined with ‘firming’ measures (mainly storage) undercuts peaking natural gas plants anywhere in the US (Bilicic & Scroggins, 2023) (Makovsky, Schneider, 2023).

Despite the shortcomings of the French commitment to nuclear power since the 1970s as referenced by Mr. Schneider, carbon emissions per capita are still significantly lower for France than fellow European economic powerhouses such as Germany (Our World in Data 2, 2023). The largest emitter of CO2 in Germany is the electricity and heat sector, powered mostly by natural gas (Our World in Data 1, 2023). As such, the French commitment to nuclear power has resulted in significantly lower carbon emissions per capita, potentially proving the efficacy of nuclear power as a low-carbon energy source. The issues currently faced by the French nuclear power system need not be repeated in future nuclear endeavors, however. Diversification of energy sources and chronologically spreading out the construction of nuclear plants so as to avoid rapid collective decommissioning in the future is key for maximizing the efficiency of a nuclear power system.

Emissions Comparison of Electricity Production Methods

In order to analyze the actual lifetime emissions produced by a nuclear power plant, consideration must be given to all the processes required for operation, including the mining and refining of nuclear fuel. In an assessment of three uranium mine-mill operations in Saskatchewan, Canada, the mining and processing of locally produced uranium was determined to generate 81, 64, and 34 kg CO2e/kg U3O8 for respective uranium ore grades of 0.74%, 1.54%, and 4.53%. In general, lower grade uranium is more accessible and exists in higher quantities, though it requires more energy to process and hence releases more greenhouse gas per kilogram to produce usable nuclear fuel. With an average ore grade of 3.81%, the average GHG emissions for the Canadian uranium ore studied was 42 kg CO_2e/kg U_3O_8. However, this number is reduced substantially when factoring in the strict utilization of local hydroelectric power as opposed to the wider grid. The total emission intensity when using local hydroelectric power is 24 kg CO_2e/kg U_3O_8, almost half of that using electricity from the grid. The results of this study show that the mining and milling process of Canadian uranium contribute roughly 1.1 g CO_2e/kWh in the context of the "total life cycle GHG emissions from the nuclear fuel cycle," and only 0.7 g CO_2e/kWh when utilizing the local hydroelectric power rather than the grid. Considering these factors and the significantly low levels of CO_2 emissions resulting from locally mined and milled uranium, especially when utilizing local hydropower which would need to be present at the premises of a nuclear power plant for cooling purposes, it would greatly benefit Canada to invest in their nuclear energy sector for the purpose of reducing their reliance on natural gas and coal (a total of 18% of yearly electricity production) and for the purpose of expanding economic opportunities for Canadians working in the nuclear sector (Parker et al., 2016).

Canada already utilizes Uranium for 15% of its yearly electricity production (Government of Canada, 2023), though as seen in the case of France, the future of this production will require robust maintenance and upgrading of older power plants, construction of new power plants, and substantial energy storage and transportation capabilities for isolated communities. A significant majority of GHG emissions in the electricity sector of Canada come from the usage of coal and natural gas, which make up a combined 18% of total electricity production, as previously mentioned. While total GHG emissions from these sources have been effectively halved since 2000 (Canada, 2022), it is likely that increased utilization of locally produced and refined uranium would further decrease these levels. Furthermore, it would be in the interest of the United States to explore the possibility of expanding their nuclear energy sector by importing uranium from Canada, either already refined or to be refined locally, in order to reduce its reliance on fossil fuels for electricity generation, to strengthen North American trade cooperation and the US-Canadian relationship, and to re-establish American energy independence in the near future.

This case is unique to Canada and the United States, as together they possess both the raw materials and the financial resources needed to invest in the local nuclear sector. However, this case could hypothetically be applied to additional potential partnerships between states with local uranium resources and correspondingly high electricity needs with relatively short transportation requirements for raw materials. Examples of potential future partnerships and uranium trade corridors could be Kazakhstan and western China, or Australia and Indonesia. Both Kazakhstan and Australia possess large amounts of uranium resources, and China and Indonesia produce high amounts of greenhouse gasses from their respective electricity sectors.

The United Nations Economic Commission for Europe published a report in 2021 assessing the life cycles of electricity generation options, considering several factors such as their respective effects on climate change, local water resources, and land occupation, as well the required resources needed to produce electricity from the various sources included the building of power plants, transportation of physical resources and raw materials, and the processing and/or storage of resulting byproducts. The study showed consistent results with regards to life cycle GHG emissions which are widely understood across the energy sector today. First and foremost, electricity produced from the burning of coal produces the most CO2 per kWH, followed by natural gas combined cycle plants. Renewable energy sources such as hydropower, photovoltaics, and wind power produce significantly lower GHG emissions compared to the aforementioned conventional electricity production methods, and nuclear energy produces the least GHG emissions, most of which are produced in the extraction, refining, and transportation of raw materials and in the construction of new plants. The UN reported 5.1-6.4 g CO2 eq./kWh emitted from electricity produced from nuclear power, compared to over 1000 g CO2 eq./kWh for some coal power plants. Even natural gas power plants equipped with carbon capture technology produce roughly 20 times the amount of carbon per kWh than nuclear power plants, exposing the significant environmental sustainability potential of nuclear energy. Figure 1 shows the overall average lifecycle GHG emissions according to the results of the UN study (Gibon, 2021).

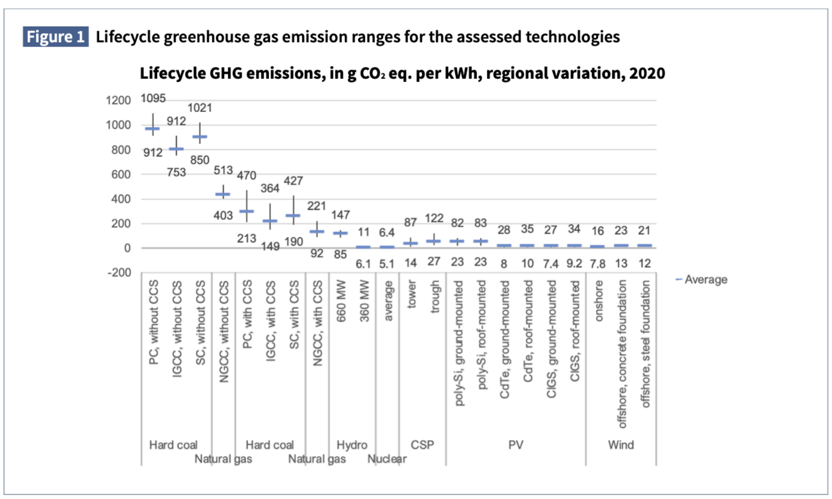

Figure 1. Source: Gibon, 2021

In a life cycle assessment of a 40 MW wind farm in China by Li et al. (2021), an analysis of GHG emission intensity was provided, comparing GHG emissions in g CO2 eq./kWh. Li et al. (2021), produced a valuable chart (Fig. XY) showing the corresponding GHG emissions from various power plant types. Nuclear power was noted to produce a similar amount of g CO2 eq./kWh as wind power, slightly more than hydropower and slightly less than photovoltaic power (Li et al., 2021)(Wang et al., 2019)(Zhao et al., 2017)(Gao et al., 2019)(Dong and Qi, 2019). The

Statistics presented by Li et al. (2021) are similar to those produced by the UN, though some variation does exist. Despite slightly higher emission output statistics by nuclear power according to Li et al. (2021), the numbers are still drastically lower than thermal (coal) power plants, and even amount to less than those of wind power.

Electricity type	GHG emissions intensity (g CO_2 eq./kWh)
Wind power	16.4–28.2
Nuclear power	10.9–13.9
Hydropower	3.1–3.9
Thermal power	810.0–820.0
Biomass power	206.0
Photovoltaic power	16.0–40.0

Figure 2. Source: Li et al. 2021

The variation in statistics between the UN (Gibon, 2021) and Li et al. (2021) can be understood through the differentiation in the samples being analyzed. Li et al. (2021) strictly studied Chinese electricity generation sources while the UN study assessed electricity production around the world. Regardless, the results are clear in that nuclear power produces substantial amounts of electricity with a corresponding GHG emission intensity similar, and sometimes lower, than that of renewable energy sources such as wind, hydro, and photovoltaic power. Furthermore, the space taken up by nuclear power plants is relatively little, and they have correspondingly low impact on the local environment and ecosystems. As stated by Mycle Schneider, for obvious economic and technical reasons, a capital-intensive nuclear power plant should run at a maximum load factor (e.g. over 90%)

(Makovsky, Schneider, 2023); if a state can maintain its nuclear power capabilities to sustain a load factor of over 90%, nuclear power becomes a highly attractive solution to produce high amounts of electricity with GHG emissions drastically lower than their thermal counterparts (Li et al., 2021)(Gibon, 2021).

The total material requirement (TMR) is a further applicable metric for analyzing the sustainability and overall environmental impact of constructing and operating a nuclear power plant. Nakagawa et al. (2022) explores the TMR of nuclear energy in depth, considering the varying factors which affect the lifetime sustainability of mining and refining uranium, as well as constructing and operating power plants. Nakagawa et al. (2022) analyzes different mining methods and their accompanying TMR, eventually showing that In Situ Leaching (ISL) is the most environmentally friendly way of extracting uranium from the earth, followed by underground and open pit mining methods. Nakagawa et al. (2022) compares their findings[2] with estimates of the TMR of coal, oil, and liquified natural gas power plants, along with photovoltaic solar cells and wind power plants. As seen in figure Q, nuclear energy has a significantly lower TMR than conventional thermal energy sources, and a similar TMR to photovoltaic solar cells.

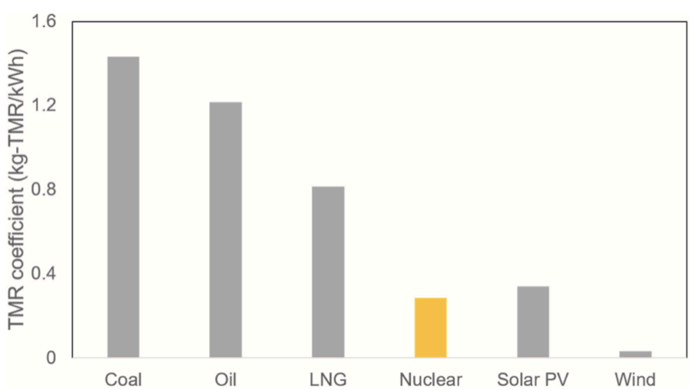

Figure Q. Source: Nakagawa et al. 2022

Economic Viability of Nuclear Power

Two methods of analysis will be presented in the following section. The goal of these analyses will be to examine whether nuclear power is or has the potential to be an economically viable alternative to conventional fossil fuels for generating electricity. The two methods utilized

[2] Comparative calculations shown in Figure Q assume 25% open pit and underground mining, and 50% ISL mining, with an even split between open and closed cycles (Nakagawa et al. 2022)

will be the MIVES[3]-Monte Carlo method and the Levelized Cost of Electricity (LCOE) method (Mari, 2014). Cartelle Barros et al. (2016), presents both methods in their 2016 article (Cartelle Barros et al., 2016), both of which will be presented in the forthcoming section. Kemp & Doren (2022) present their own LCOE calculations in their analysis of whether a carbon tax would make nuclear power a more economically viable form of alternative energy. The LCOE values produced from Cartelle Barros et al. (2016), will be compared to that of Kemp & Doren (2022), as well as a third LCOE source (Sung & Jung, 2019) comparing nuclear, coal, and wind in order to analyze consistency in the various statistics.

Cartelle Barros et al. (2016), combines the deterministic MIVES simulation with the Monte Carlo simulation in order to factor uncertainty into the results of their study. The purpose of the MIVES simulation is to analyze the contribution to sustainable development as a result of a particular investment (Pujadas et al., 2017). The MIVES-Monte Carlo model has nine phases: the selection of probabilistic variables[4], estimation of values for deterministic variables, estimation of values for probabilistic variables, evaluating the model using the (deterministic) MIVES method, the repetition of phases four and five until the resulting relative error is below 0.0001 three times consecutively, a statistical analysis of the output, an interpretation of the statistical analysis, and the collection of real data.

Cartelle Barros et al. (2016), use a probabilistic LCOE method in addition to the MIVES-Monte Carlo simulation as an additional means to evaluate the economic benefits/drawbacks of nuclear power compared to various other energy sources. In a general sense, the LCOE method is an analysis of the total life cycle cost divided by total lifetime energy production. The total life cycle cost is determined by incorporating several factors including

[3] Modelo Integrado de Valor para una Evaluación Sostenible/Integrated Value Model for Sustainability Assessment
[4] Variables with the most influence on the model and most uncertainty are considered probabilistic.

costs and revenues, either nominal or real. Nominal costs and revenues represent the actual currency flows in and out of the power plant, while real costs and revenues are adjusted for inflation using a dedicated base year as the basis for adjustment (Cartelle Barros et al., 2016)(Hannon, Bolton, 2021)

The results of the MIVES-Monte Carlo simulation are presented in terms of the global assessment parameter called the economic index (EI). The EI exists between 0 and 1, representing the lowest and highest levels of economic satisfaction respectively. Cartelle Barros et al. (2016), ran several simulations with varying levels of uncertainty. The following table (Figure 3) contains the results of the seventh iteration which takes into consideration uncertainty throughout every phase of the simulation. In addition to the EI, the average LCOE calculations are contained in the following table, presented in terms of € per mWh.

	Coal	Lignite	Oil	Natural Gas	Onshore Wind	Offshore Wind	Photovoltaic	Hydropower	Biomass	Nuclear
EI Mean	.45	.43	.42	.39	.49	.43	.45	.50	.32	.59
LCOE mean /mWh	66€	71€	98€	92€	84€	142€	124€	121€	102€	69€

Figure 3. Source: Cartelle Barros et al., 2016

The results of the MIVES-Monte Carlo simulation show nuclear power to be the most effective investment for sustainable development, as it scores a 0.59 in the EI category. This does not imply that nuclear power is the most efficient or cost effective way of producing electricity in a sustainable way, however. Rather, the EI shows that there is high development potential resulting from an investment in nuclear power, and that such development will be sustainable (Cartelle Barros et al., 2016). This is consistent with the high amounts of electricity produced by nuclear power plants with extremely low GHG output (Gibon et al., 2021).

A study published in 2021 (Kemp & Doren, 2021) produced an original LCOE analysis comparing the hypothetical construction of three new power plants in the US. The three types of plants considered were a nuclear reactor, a coal power plant, and a combined cycle natural gas power plant[5]. The power plants were all assumed to be baseload generators which translates to a high load factor (load factor was modeled at 85% for all three plants). Baseload generators need to operate almost constantly in order to support the electricity needs of the grid. All power plants were assumed to have a capacity of 1000 MW. Power plant lifetimes and modeled construction times were consistent with analyses by the International Energy Agency and Nuclear Energy Agency published in 2020. The nuclear power plant is modeled to have an initial lifetime of 40 years, with an additional 20 years added as a license renewal. The coal plant is modeled to operate for 40 years, and the natural gas plant for 30 years. The primary variables factored into the LCOE estimates are (nuclear) overnight construction cost (OCC)[6], the discount rate[7], and fuel costs.

Three OCC values were presented in the study, ranging from $4000 and $9000 per kW. The discount rate was considered used as the "opportunity cost of capital, the expected rate of return on the capital invested in the power plant" if it were instead invested in the S&P 500. As

[5] "Combined-cycle natural gas plants generate electricity both through a combustion turbine and by using the waste heat from combustion to create steam that is then converted to electricity by steam turbines" (Kemp & Doren, 2021)
[6] Overnight Construction Cost (OCC) considers the total cost of constructing a nuclear power plant as if it were constructed overnight, without taking into consideration Interest During Construction (IDC), which are additional financial costs which arise prior to the start of commercial operation (Lovering et al., 2016).
[7] The value of money changes due to inflation, which must be factored into the LCOE. A high discount rate is detrimental to the economic benefit of constructing a nuclear power plant as the large initial construction costs come to be valued higher than the future benefits from low operating costs.

such, the discount rate used for this model was 7%, which is approximately equal to the annual average rate of return of the S&P 500 from 1972 to 2021. Fuel costs are a distinctly important factor in comparing coal and natural gas power to nuclear power. While a majority of lifetime costs of a nuclear power plant incur during construction, natural gas and coal plants are significantly cheaper to build. That being said, nuclear power plants benefit from relatively low lifetime fuel costs while coal and natural gas plants can be significantly affected by volatility in their respective fuel markets. The fuel prices used for the LCOE model are projections of average fuel costs during the time in which the plants are operating. It should be noted that both uranium and coal are generally more stable in price compared to natural gas, as they are bought in longer term contracts. The nuclear fuel costs are projected annual costs calculated from historic nuclear fuel costs from the EIA. The results of this LCOE model are presented in Figure 4.

Levelized cost estimates (cents/kWh) at 3, 7, and 10 percent costs of capital

	Cost of capital		
	3%	7%	10%
Nuclear			
Low OCC* (4,000 $/kW)	5.3	7.9	10.4
Middle OCC (6,700 $/kW)	7.1	11.4	15.7
High OCC (9,000 $/kW)	8.6	14.4	20.2
Coal			
	5.8	7.9	9.8
Natural gas			
Low fuel price (3.10 $/MMBtu)	3.3	3.8	4.2
Middle fuel price (3.80 $/MMBtu)	3.7	4.2	4.7
High fuel price (5.80 $/MMBtu)	5.0	5.5	6.0

Figure 4.

Source: Kemp & Doren, 2022

The results of the LCOE model by Kemp & Doren (2022) show how high nuclear construction costs and current natural gas fuel costs do not make nuclear energy an economically beneficial source of electricity. The economic difficulties with nuclear power plants are currently being further exacerbated by rising interest rates to combat inflation across much of the world. Kemp & Doren (2022) note that future carbon taxes may result in increased economic competitiveness for nuclear power, though even with a relatively high carbon tax and relatively low OCC, natural gas remains a cheaper, albeit more volatile, alternative to nuclear power. Furthermore, according to recent data concerning the construction of new nuclear power plants in the West, achieving a low OCC is somewhat unlikely. Nuclear power plant construction projects experience an estimated time overrun of roughly 64%, resulting in an overall cost increase of about 117% due to financing. The time overrun statistics are similar to that of hydropower projects, though conventional thermal power plants experience significantly lower time overruns on average. It is estimated that 97% of nuclear power projects overrun their initial cost projections (Kemp & Doren, 2022).

The third and final LCOE analysis was published in 2019 in an evaluation of the economic competitiveness of various energy sources in the “Energies” journal. The resulting LCOE figures were consistent with those previously presented by Cartelle Barros et al. and Kemp & Doren (2022). The following figures (Figure 5) are presented in order to assert the findings of the previous studies, and to show that nuclear energy should not be entirely excluded from future energy ventures and development projects as it is not far from economically viable.

Table 4. Median LCOE values of Coal, Wind, and Nuclear at 3%, 7% and 10% *IR*.

Rank	3% *IR*		7% *IR*		10% *IR*	
1	Nuclear	47.87$/MWh	Coal	61.76$/MWh	Coal	72.91$/MWh
2	Coal	48.83$/MWh	Nuclear	75.31$/MWh	Wind	94.49$/MWh
3	Wind	63.82$/MWh	Wind	80.47$/MWh	Nuclear	98.15$/MWh

Figure 5. Source: Jung, Sung, 2019

As shown in the graphic, Jung and Sung (2019) explored to what extent the interest rate during construction affected the cost of electricity from each of the plants. As shown through the data set, nuclear energy experiences the most price volatility from changes in the interest rate, which is consistent with the high OCC required to construct a nuclear power plant. This is particularly relevant in 2023 as many of the world's central banks, those in the US and Europe included, have increased interest rates in recent months in response to increased rates of inflation. As such, even economically powerful countries such as the United States would need to plan their construction projects strategically, investing heavily in initiating nuclear power projects during times of economic growth and low interest rates so as to accomplish at least a significant portion of the necessary cash spending prior to the inevitable downturn of the business cycle. During times of low interest rates, however, Jung and Sung's (2019) data shows just how competitive nuclear energy can be. Coal has historically been a widely utilized source of energy given its low cost in areas with significant natural deposits, particularly in China in recent years. While producing high amounts of relatively cheap electricity, however, coal power plants release by far the most GHG per electricity produced, especially compared to nuclear energy (Gibon, 2021).

The most recent LCOE analysis published by Lazard earlier this month offered valuable insight into the effect of tax subsidies on energy prices from renewable sources. Compared to the $141-$221 LCOE for nuclear power as contained in the recent Lazard publication, most renewable energy sources provided cheaper electricity than nuclear power plants, as seen in figures 6 and 7.

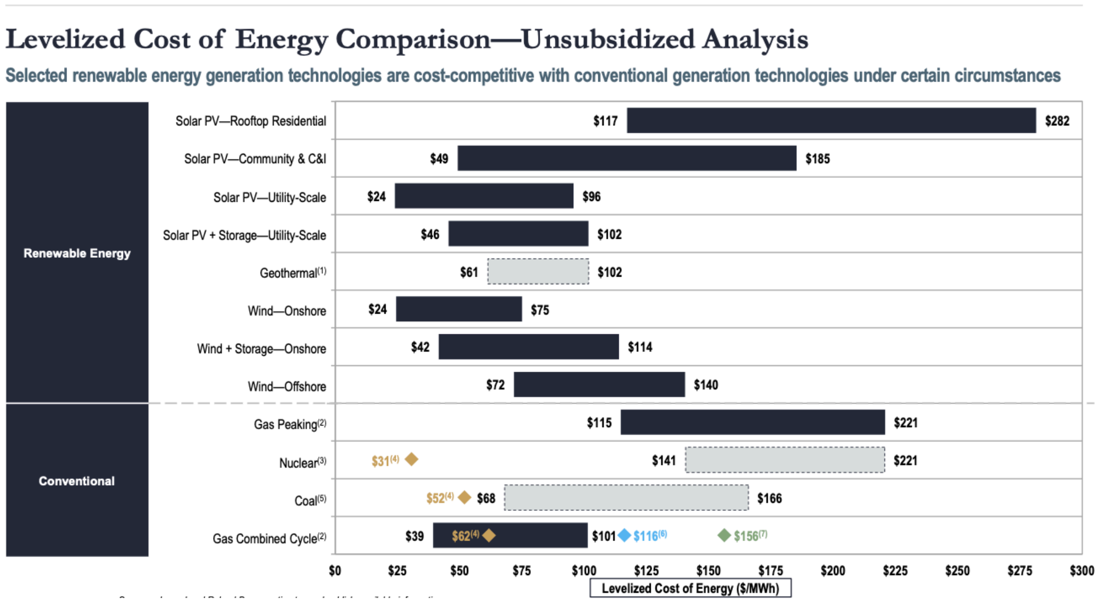

Figure 6.

Source: Bilicic & Scroggins, 2023.

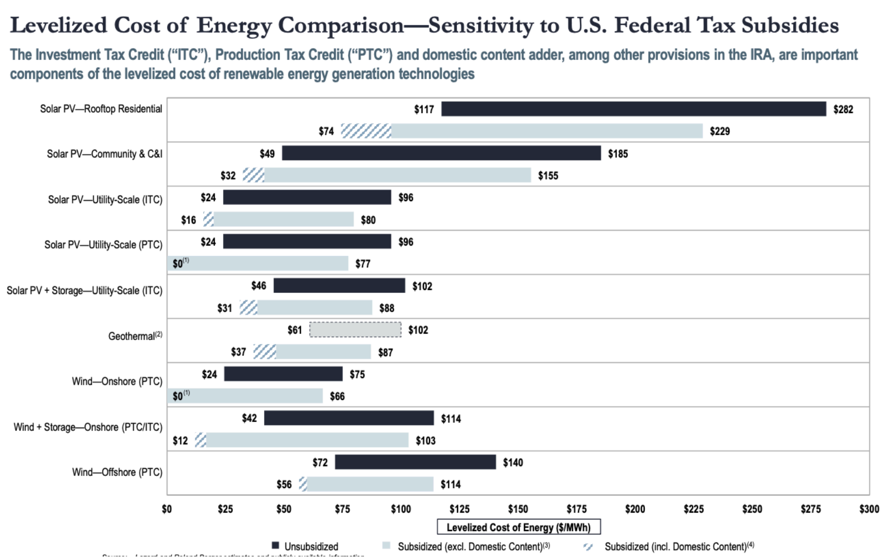

Figure 7.

Source: Bilicic & Scroggins, 2023.

Of course, capital cost is not the only cost to be considered when building power plants; environmental and aesthetic impact are both important variables to be considered, particularly with regards to solar, wind, and hydro power plants. Solar and wind farms would require massive amounts of land to produce the equivalent electricity as the average nuclear power plant, which takes up a significantly smaller amount of space. Moreover, hydro power plants can disrupt the local environments of local fish and plants. The politicization of “green” energy has further hindered the progression away from fossil fuels, and many conservative voices across the US and Europe still cast doubt on the necessity to reduce GHG emissions.

Based on the data provided in the figures above, residential solar panels prove to be somewhat expensive, even with US federal tax subsidies. However, the installation of solar panels by private homeowners or developers does not require direct government spending (other than tax subsidies) and reduces overall reliance on the grid, lowering energy costs across the board. Furthermore, the aesthetic and environmental impacts associated with massive solar farms become significantly reduced, as the land on which residential solar panels are built are already being used, effectively multiplying the efficiency with which the land is being utilized. Finally, installing solar panels offers a relatively affordable means through which the private individual can positively contribute to electricity production and the overall transition away from fossil fuel-generated electricity, relieving some of the responsibility of the government at large.

Unfortunately, due to the variation in construction and capital costs around the world, and the limited data available regarding new nuclear construction projects in the US, the LCOE numbers presented by the various aforementioned sources are relatively spread out. That being said, the differences between nuclear power and the various other power sources discussed in this section, are fairly consistent, with nuclear power proving to be an expensive, yet potentially consistent producer of electricity. Due to the massive scale with which nuclear power plants can produce electricity, larger economies, particularly those producing high amounts of GHG and especially those with access to nuclear fuel resources such as the US, Russia, and China, should invest in nuclear energy to meet a portion of their electricity demands. Construction of plants, however, should be spread out so as to avoid the rapid collective aging of plants such as the case with France, and massive investment into renewable energy should continue, with the eventual goal of these larger economies to produce most of their electricity with renewable energy sources, followed by nuclear and gas (both bio and natural, preferably in combined cycle plants).

Concluding Remarks and Policy Recommendations

As shown in the preceding research, nuclear energy has the capability of producing massive amounts of electricity with relatively low accompanying GHG emissions, including from both the mining and refining processes, and through the actual construction of power plants themselves. The analyses provided by Gibon (2021) and Li et al. (2021) clearly show that the lifetime GHG emissions produced by nuclear powered electricity are comparable to that of renewable energy sources such as wind and hydropower. Despite these findings, however, the massive economic investment, particularly in terms of OCC and the large amounts of cash needed to initiate the construction of nuclear power plants, has inclined many policy analysts to conclude that nuclear power may not be a necessary aspect of future energy policy, at least for most countries. Moreover, the case of France sheds light onto the potential downsides of committing too strongly to nuclear energy particularly without adequate plans for the future of the grid.

Taking into consideration the aforementioned points presented in this article, it can be concluded that nuclear energy should in fact play a role in the future of electricity generation, but only under specific circumstances and with meticulous planning for the future of the power plants themselves. First and foremost, the goal of the future of electricity generation should be the maximization of electricity produced with the lowest possible GHG coefficient. The financial investment required for this energy transition should be considered, but not prioritized by the states with the highest electricity needs. China, for example, should invest in nuclear energy projects so as to reduce the country's dependence on coal for electricity, and should incorporate the trade of nuclear energy resources into its Belt and Road Initiative. The United States, on the other hand, should look for ways to both appease its population, and simultaneously lower emissions substantially. Electric cars and renewable (“green”) energy has become highly politicized in a country with polarized politics and where low gas prices are crucial for securing votes. As such, despite inevitable short term pushback from investors in the coal industry (politicians included), the US should ban the burning of coal for the production of electricity, and initiate the construction of nuclear power plants in nearby areas, promoting the plants as job replacements and healthier alternatives for local residents, particularly considering the reduction of the release of air pollutants. Furthermore, the US should continue to strongly encourage the electrification of both the manufacturing and transportation sectors, while simultaneously increasing electricity production through both renewable and nuclear means. The reduced consumption of oil in both sectors will reduce demand for oil, both lowering gas prices for consumers and reducing the impact of foreign energy exporters on the US economy.

On the other hand, as seen through the case of France, a commitment to one single energy source, whether fossil fuels, nuclear, or renewable, is an inherent liability. Any country deciding to invest in its energy sector needs to build a system of diverse energy sources, particularly to avoid significant volatility in energy prices due to uncontrollable events. For example, following the outbreak of the War in Ukraine, energy prices in Germany skyrocketed due to its unbalanced commitment to Russian-supplied natural gas. Germany has a history of aversion to nuclear power, and a significant lack of hydropower or solar power resources due to its geography, leaving it unable to meet its electricity demand without importing massive amounts of foreign fossil fuels. Instead of shutting down its last three nuclear reactors as it did in April 2023, Germany should invest in building new nuclear reactors over an extended period of time, while continuing to invest in its renewable energy sector as well. Diversification is the key to a stable energy economy, and nuclear power deserves to be a part of that conversation.

The future of energy and electricity production is a highly relevant and widely debated topic in governments around the world. If humanity is to reduce its GHG emissions collectively while continuing to improve as a species, change is more than necessary. Nuclear power will provide a healthier future for both the Earth and its inhabitants, and as such it must not be ruled out. Further research into the production of electricity by atomic means is more than necessary as well, though opposition to nuclear energy has significantly slowed research and development breakthroughs since the late 20th century. States need to encourage research into small nuclear reactors (modular nuclear reactors), combined power plants such as nuclear/hydro plants on major waterways, and energy storage solutions such as Tesla MegaPack. Additionally, states should encourage relevant educational tracks for university students by funding nuclear engineering and innovation programs at universities.

It is more than clear that humanity possesses the tools to solve the climate crisis. Whether we have the will to invest our time, energy, and resources into developing those tools is yet to be seen. Nevertheless, it is vital that nuclear energy continue to be pursued in the coming decades.

☢

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SIT Study Abroad: Switzerland

International Studies and Multilateral Diplomacy

ISP INTERACTIVE RESEARCH

INTERACTIVE LOG

(4 interviews are required: 3 formal + 1 informal)

Name Max Makovsky Semester Spring 2023

Organization	**Contact name**	**Address/email**	**telephone**	**Date(s) & time of interview**	**Formal/informal interview**
GCSP	Marc Finaud	m.finaud@gcsp.ch		3/20/23	Formal
Geneva Graduate Institute	Giacomo Luciani	giacomo.luciani@graduateinstitute.ch		3/24/23	Formal
Independent	Mycle Schneider	mycle@orange.fr		3/27/23	Formal

ISP Work Journal

Date	Location	Contents
3/19	Ex Machina Cafe	Began initial research into nuclear energy, gathering understanding of existing literature
3/20	UMEF University	Met with Mr. Finaud, discussed the future of nuclear energy and further refined my topic
3/21	Tete de Course Cafe	Began gathering relevant sources.. A process
3/24	Cafe near Grad. Institute	Interviewed Professor Luciani about nuclear energy and whether it has a place in the future of electricity generation.
3/25	Ex Machina Cafe	Continued preliminary research and the finding of sources
3/27	Another Geneva Cafe (unsure of which)	Interviewed Mr. Schneider about nuclear energy and whether it has a place in the future of electricity generation. He did not think so for economic reasons.
3/29	Cafe Milo	Organized info from interviews, continued finding sources
3/30	Tete de Course Cafe	Finished finding sources, began to read and annotate
3/31	Home	Continued annotating sources
4/2	Ex Machina Cafe	Continued annotating sources
4/3	Ex Machina Cafe	Continued annotating sources, created a rough outline. Break for Passover.
4/14	Cafe Milo	Finished outline, began to initiate the writing process.
4/16	Ex Machina Cafe	Wrote about French nuclear

		program and Canadian mining
4/17	Ex Machina Cafe	Wrote about GHG statistical comparison
4/18	Tete de Course Cafe	Wrote about economic statistical comparison
4/19	Ex Machina Cafe	Wrote intro, conclusion, policy recommendations
4/20	Train	Editing, title page, abstract. etc.
4/23	Ex Machina Cafe	Final touches
4/24	SIT Office	Turned in final draft