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Fossil fuel phase-out at a time of energy insecurity: Exploring the role that nuclear energy could play in Europe’s decarbonization.

Abstract:
In light of the European energy crisis, decarbonization efforts, and the recent Russian invasion of Ukraine, nuclear energy has gained renewed attention as a low-carbon, reliable energy source that can reduce reliance on fossil fuels and promote energy security. This thesis explores the potential role of nuclear energy in Europe's decarbonization, analysing its environmental, economic, and political dimensions using the energy trilemma framework. While nuclear energy offers great opportunities for decarbonization, it also poses significant challenges such as nuclear waste management. Nuclear energy's characteristics can also strengthen energy security by delivering reliable energy without geopolitical ties. The results of the analysis are quite positive for lifetime extension of existing nuclear reactors due to their low costs, while the results for commissioning new nuclear fission plants are less clear-cut. However, nuclear energy has in combination with renewables the opportunity to push the grid to a decarbonized reality and the prospects of nuclear fusion could help break our dependence on fossil fuels.

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Word count: 8724

Date: May 11th 2023

Table of Contents

1: Introduction

Decarbonization of the European power system is vital to achieving net-zero emissions and limiting anthropogenic climate to 1.5 and no more than 2 degrees by 2050 based on 1990 levels (IPCC, 2018). The European Union's (EU's) approach to achieving this has predominantly been to build large amounts of variable renewable energy technologies (VRETs) such as wind and solar, and to connect countries' electricity grids in order to synergise power systems (EEA, 2023). Nuclear power has in the last decade not been a large part of this debate, although it has historically been a large part of the European energy system. This is primarily due to concerns over the environmental impacts of nuclear waste, uncertainty over costs and a number of varying constraints that have emerged through political and societal preferences and pressures (Prăvălie & Bandoc, 2018).

In 2010 Samuel Apikyan and David Diamond wrote that a nuclear renaissance where it was seen as a clean and safe source of electricity might be close (Apikyan and Diamond, 2010). In 2011, a year after this publication, a tsunami hit the east coast of Japan which resulted in the Fukushima Daiichi nuclear accident. The live TV-pictures of hydrogen explosions at the nuclear plant not only contributed significantly to halting any form of "nuclear renaissance" but was a major step backwards. Not only did Japan suspend all their active nuclear plants but throughout Europe the anti-nuclear position gained traction. Nuclear phase-out plans were set in motion or sped up, ongoing projects were paused, with public opinion consisting of considerable, clear, and overwhelming opposition to the building of more nuclear power plants in most countries in Europe (Nuttall, 2022)

In the next ten years climate change mitigation and decarbonization became more important. In 2020 about 25% of the EU's electricity production came from nuclear sources (Eurostat, 2021). Despite the presence of a large amount of nuclear in the power system and its proven and tested role as a reliable base-load producer, nuclear energy was only partly mentioned in public mitigation strategy debates during this time. Experts were however more positive about nuclear either as an effective transition energy source towards net zero emissions, complimenting VRETs, or through helping manage the energy storage problems created by VRETs. All 4 mitigation strategy pathways to limit global warming to 1.5°C by 2100 with no or limited overshoot from the IPCC Report showed a huge increase in the share of energy provided by nuclear power. For example, pathway 3 in the report suggests a 501% increase from 2010 levels in energy globally provided by nuclear by 2050 (IPCC, 2018). The peak European level of gross nuclear electricity production was in 2004 with 928 438 gigawatt-hours (GWh). However, as of 2021, this figure has decreased by 21% (Eurostat, 2021). This shows a mismatch between the mitigation strategy pathways being developed by energy experts and the current reality where nuclear energy has not gotten the support or attention needed to realize these levels.

Since early 2021, however, the narrative around nuclear energy has begun to change considerably. The transition to a more renewable and decarbonized energy system is not going fast enough and Europe needs more clean energy to achieve their emissions reduction goals. High electricity prices and energy insecurity caused by the COVID-19 pandemic, and the subsequent supply chain shock that slowed down the delivery of gas and oil at the time of economic recovery, appear to be beginning to point towards the very nuclear renaissance that Apikyan and Diamond wrote about just over a decade ago. Nuclear power is now increasingly being discussed as a possible part of the solution to emissions reduction, thought of as a proven and reliable source of decarbonized energy. Given the current state of the European energy system and the narrative surrounding nuclear energy, this thesis looks to explore how the energy instability caused by the European energy crisis and Russia's invasion of Ukraine may not only lead to a partial realization of the nuclear renaissance that Apikyan and Diamond wrote about in 2010, but a more fundamental change in the role that nuclear energy could play in Europe's decarbonization.

This thesis has two main objectives. The *first*, is to explore how and why nuclear power finds itself in the position it does today by looking at how the nuclear narrative has changed in Europe in the last decade. Second, the thesis will discuss the role that nuclear energy could play in Europe's decarbonization. This will be analyzed using the energy trilemma introduced by the World Energy Council (2015) and used by scholars such as Sovacool et al. (2015) and Nuttall (2022) to highlight the opportunities and challenges nuclear face through three different analytical lenses: environment, economic, and political.

To support this thesis in its objectives, Chapter 2 provides a brief overview of nuclear power and its history to provide historical context and brings us up to 2021. This also contains a description of the Fukushima-Daiichi nuclear disaster and its ramifications, which to a large degree have shaped the nuclear narratives of the past decade (preceding 2021). Chapter 3 explores how and why a shift in the nuclear narrative is occurring today. In Chapter 4, the theory, methods, and analytical strategy for the thesis are elaborated upon. This entails empirical research with a review of the existing body of literature and relevant data which in turn will be analysed using the energy trilemma. The energy trilemma is a mid-range framework which is often used in energy-related research because it enables the user to summarize and compare the challenges regarding energy policy with a flexible approach. Results from the analysis conducted are reported in the fifth chapter and discussed in the sixth chapter. The last chapter will include a conclusion of the thesis.

2: Background & history

2.1 The process of nuclear fission and fusion

When nuclear energy is discussed, it is done so typically referring to nuclear fission which is where a nucleus of an atom splits into two or more smaller nuclei (IAEA, 2022). In nuclear power plants nuclear fuel is added because these materials do not only split into two or more nuclei but produces multiple new neutrons that can be split again. This makes the process self-sustaining and produces a large amount of energy. In nuclear power plants, whose main objective is to produce energy, the heat created by the nuclear reactor is cooled with a coolant. This coolant is then heated up by the nuclear reactor core and used to make steam which in turn powers a turbine which powers a generator that produces electricity. The most common type of nuclear reactor is the Water-Cooled Reactor (WCR) which accounts for approximately 95% of all operating civilian power reactors worldwide (IAEA, 2021).

Nuclear fusion is also a type of nuclear energy, but there are difficulties in achieving a positive energy gain, and is extremely costly, making the technology not currently viable for energy production on the scale of fission. The fusion process can be explained as simply being the process where two lighter atomic nuclei merge to form a heavier nucleus, and in the process release energy. The US National Ignition Facility managed for the first time to have a positive energy gain from this process in 2022 after 80 years of worldwide trial and error (US Department of Energy, 2022). Still, there are many hurdles to pass before we realistically could see nuclear fusion energy on the grid. Due to the uncertain extent of the impact that nuclear fusion may have in the next three decades, this thesis will concentrate on nuclear fission [1]

2.2 Brief history of nuclear power

In 1954 the first grid-connected nuclear power plant became operational. This was achieved at the Obnisk Power Plant located close to Moscow in today's Russia (Nuttall, 2022). Two years later in 1956, Calder Hall nuclear power station opened in England, becoming the first commercial power plant connected to a national electricity grid (Wydler, 1983). In the following years the USA (1957), France (1959), and Germany (1961) quickly followed by opening their first nuclear power plants (IAEA, 2004). In the 1970s the global capacity

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[1] The DNV Energy Outlook (2022) makes a similar argument, stating that although fusion technology has enormous potential, it is not expected to have an impact on their forecast period (until 2050) as it is still too far away from commercial maturity

quickly rose to 100 GW(e). The next decade followed the same trend with a huge increase in installed nuclear capacity. In 1983 the global capacity reached 200GW(e) (IAEA, 2004). An ever-increasing need for energy and a reliable source of base-load generation, coupled with the need to respond to the 1970s oil crisis, caused a peak in nuclear capacity under construction during the mid-1980s. After almost three decades of a continuous rise, the curve flattened after the Chernobyl disaster in 1986 (IAEA, 2004). The aftermath of the Chernobyl disaster, in combination with growing environmental concerns and cost-problems, caused a steep decrease in the number of commissioned nuclear power plants. Because of the longevity of nuclear power plants, the global generation capacity continued to rise, despite dramatically less growth in the construction of new power plants.

Up until the 2000s Europe and North America accounted for approximately 80% percent of the total global nuclear capacity (IAEA, 2004). In 2015, the countries with the most power plants under construction were China, India, Russia, and the United Arab Emirates (Prăvălie & Bandoc, 2018). These are countries that have experienced huge economic growth and an exponential need for energy. These are also countries that traditionally have been some of the biggest producers and users of oil, coal and gas, with China and India being 1st and 2nd in global coal production and Russia and the United Arab Emirates being among the top 5 biggest exporters of oil (BP, 2022). For China it is important to curb its reliance on coal because of air pollution, enabling them to maintain economic growth (Gil, 2017). In 2021 the net global electrical capacity from nuclear power was 374 GW(e) (PRIS, 2023).

2.3 Fukushima-Daiichi disaster and ramifications

In March 2011 a powerful earthquake with its epicenter outside the south-east coast of Japan created a 14-meter-high tsunami that hit the Oshika peninsula, which projects into the South-East of the Pacific Ocean. It’s estimated that more than 15,000 people were killed as a result of the earthquake and the tsunami it caused (National Police Agency of Japan, 2021). The tsunami hit the Fukushima-Daiichi Nuclear Power Plant in Japan and damaged the emergency backup generators which eventually led to meltdowns in several of the reactors. In the meltdown process hydrogen gas was created and several large hydrogen explosions subsequently occurred (Elliott, 2013). These explosions were broadcast on TV to 100s of millions of people. This caused a series of societal, political, and environmental reactions which contributed significantly to halting any form of “nuclear renaissance” (See Chapter 1.2 in Nuttall, 2022 & Chapter 7 in Elliott, 2013).

In Europe, nuclear was already a fiercely debated political topic and anti-nuclear groups gained traction from the Fukushima disaster as the general public's perception began to orientate back towards the skepticism that had characterized the years following the Chernobyl nuclear disaster of 1986. However, the need for additional energy production remained high in the 2010s. The EU's largest country, Germany, had begun to explore the possibility of building more nuclear after deciding to phase out coal (Rinscheid & Wüstenhagen, 2019). Germany has historically been a country with a highly divided opinion on its nuclear power production with a both strong and vocal opposition. In response to the Fukushima disaster, Chancellor Merkel, after large protests, shut down eight of the oldest nuclear power plants with immediate effect and issued several other plants a three-month moratorium (Nguyen, 2016). Germany's nuclear phase-out has however not been easy and started a long-lasting political tug-of-war (which we will revisit later in Chapter 6).

In Italy, a similar response was seen which resulted in a complete phase-out of nuclear, which would lead to having no operating plants only a couple of years later. France remains Europe's nuclear powerhouse and has historically had a large pro-nuclear position. Their response to the Fukushima-Daiichi disaster did not include phase-out policies but was mainly focused on re-investments for improved safety measures. However, poll results showed a 13% decrease in people favoring nuclear energy from 2008 to 2013 and increased debates within French society over the role of nuclear and its safety (Nguyen, 2016).

When summarizing the impact of the Fukushima disaster in continental Europe we can divide Europe in two. In Western-Europe we saw several dramatic policy changes in countries such as Germany, Italy, Belgium, and Switzerland. In Eastern-Europe there were no large policy changes but support for nuclear fell drastically at a crucial time when several countries were considering expanding their nuclear capacities (Elliott, 2013). In Figure 1 we can observe how the global net electrical capacity of nuclear dramatically fell after the Fukushima-Daiichi disaster. This decline is however mostly explained by Japan, the country with the third largest nuclear capacity, suspending all nuclear operations after the accident (Prăvălie & Bandoc, 2018). In Europe gross nuclear electricity production fell by only 3% from the end of 2010 to 2011, which for context is not a lot considering it fell almost 7% two years prior in the aftermath of the 2007/2008 global economic recession (Eurostat, 2021).

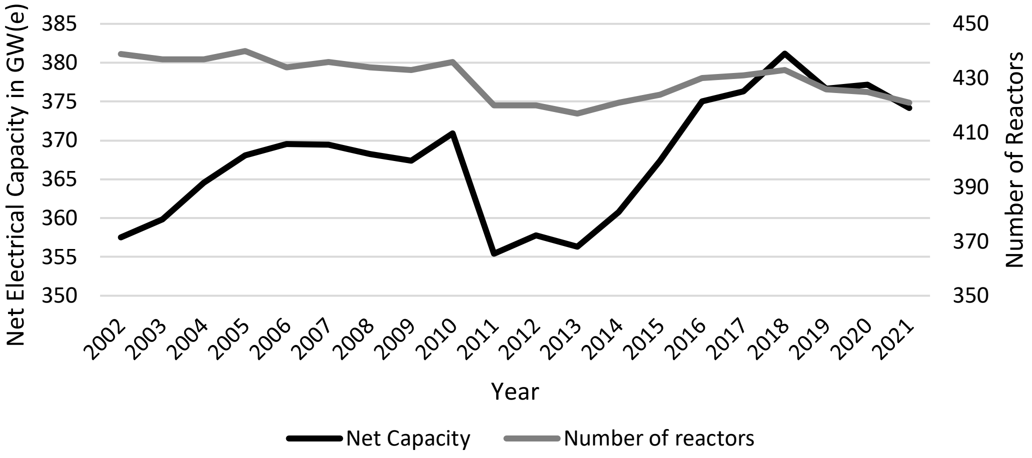


Figure 1: Global Nuclear Power Capcity Trends

Data Source: PRIS (2023). Power Reactor Information System. Nuclear Power Capacity Trend. International Atomic Energy Agency

3: Shift (the now)

In the last couple of years, we have seen a shift towards more pro-nuclear energy sentiments in Europe. This could be attributed to greater urgency with regards to the need to decarbonize the European energy system, coupled with the energy instability caused by the European energy crisis and made worse by the invasion of Ukraine by Russia. Furthermore, the Fukushima disaster occurred more than a decade ago, and its impact on the public perception of nuclear energy appears to have waned over time as memories of the event have faded, limiting criticisms and negative opinions. Whilst nuclear energy has found its development and implementation halted as a consequence of several disasters which have caused a decrease in both political and popular support, nuclear energy in Europe remains relatively steadfast with about half of the world's nuclear reactors still located and operational in Europe, with countries such as France, Slovakia, Belgium and Ukraine all sourcing more than 50 percent of their electricity from nuclear power as of 2021 (PRIS, 2023). Already before Russia's invasion of Ukraine, there was an extremely volatile energy market in 2021, with high prices in Europe caused by the COVID-19 pandemic and its subsequent supply shock (Kuik et al., 2022). The European energy market is complex, but the recent price surge can primarily be attributed to the unprecedented increase in gas prices. The EU imports about 50% of its energy and in 2021 the price of gas on the global markets increased by 170% (European Council, 2023a). When on the 24th of February 2022 as Russia Invaded Ukraine, Europe's liquefied natural gas (LNG) storages were already near record lows as the demand for LNG had a sharp increase in Asia (European Council, 2023a).

As Kuzemko et al. (2022) notes, the invasion highlighted two uncomfortable realities. The *first* is that even though the European energy system is currently undergoing rapid decarbonization, fossil fuels are still the foundation of its energy system. The *second* is that despite a push for more energy resilience and autonomy, the EU maintained high levels of dependency on Russian gas prior to February 2022 (Kuzemko et al., 2022). One of the main aspects of the EU's sanctions has been to quickly phase-out imports of Russian oil and gas in the aftermath of the invasion. This extraordinary geopolitical situation has led to a profound energy supply crisis amidst a time of decarbonization and at a pivotal point in the sustainable energy transition which has shown that Europe does not only need clean energy, but also reliable energy. This has led to a push to have "homegrown" energy solutions as the EU seeks to reduce its share of imported energy (European Council, 2023a). Because of this shift in the political landscape, a reorientation back towards nuclear energy is beginning to occur as policymakers look for possible solutions to these challenges (Davidson, 2022, Nuttall, 2022, Kuzemko et al., 2022).

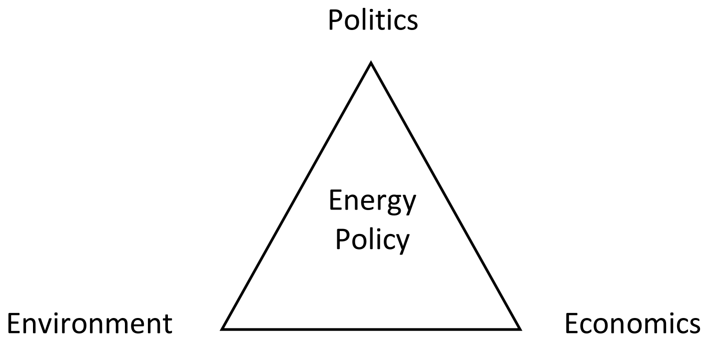
The more positive attitudes towards nuclear energy in the last few years can already be seen in policymaking. Some countries put short-term plans in motion, and most of these can be attributed to the European energy crisis. Germany extended the operation of the three of their remaining nuclear power plants into 2023 past their much-debated 2022 deadline (BASE, 2023). However, there have also been long-term schemes approved; In the UK they have announced the commission of 8 new reactors, Belgium has announced an extension of the lifetime of several of their current reactors, and in France and Finland a significant push for both upgrades of existing reactors as well as new reactor projects has been set in motion (Kuzemko et al., 2022). Even in Norway, a country where the nuclear debate hasn't been so publicly present because 91,5% of all energy production came from hydro in 2021 (Aanesen, 2022), a nuclear debate has emerged during the last year. There is now even a company that believes that they will be able to have Small Modular Reactors (SMR) operating in Norway in ten years' time (Valle, 2023). These all show how the nuclear narrative is changing, however, arguably the most important change of policy was the inclusion of nuclear in EU's taxonomy in March 2022. The EU's taxonomy is a classification system that provides policymakers, investors and companies with environmentally sustainable economic activities (Kuzemko et al., 2022). This was seen as a strong signal that the EU regards nuclear as part of the solution to reach their mitigation targets.

4: Theory, methods and analytical strategy

4.1 Mid-range analytical framework – Energy Trilemma

The energy trilemma is a conceptual framework that has been used to analyze the complex trade-offs and interactions between key dimensions of energy policy and sustainability. The trilemma was first introduced by the World Energy Council (WEC) to compare and guide countries regarding their sustainable energy transition and policy (WEC, 2015). Scholars have also utilized the trilemma as a mid-range analytical framework (Emblemsvåg & Österlund, 2023). The trilemma can be visualized as a triangle, as seen in Figure 2.

Figure 2: The Energy Trilemma



The World Energy Council considers the core dimensions of energy sustainability to be energy security, energy equity, and environmental sustainability of energy systems. The three dimensions of the trilemma are defined as follows: *Energy security* refers to the availability and reliability of energy supply and involves that energy systems are resilient to disruptions, such as geopolitical tensions and natural disasters. *Energy equity* relates to the social and economic aspects of energy policy, including issues of affordability, accessibility, and energy justice. *Environmental sustainability* focuses on the environmental impact of energy production, distribution, and consumption. This entails reducing greenhouse gas emissions, mitigating climate change, as well as addressing other environmental challenges associated with energy systems, such as air pollution and waste management (WEC, 2015).

The energy trilemma framework recognizes that these three dimensions are interconnected and that they involve both trade-offs and synergies. For example, policies aimed at enhancing energy security, such as decreasing dependency on energy imports, may have environmental sustainability implications. Similarly, policies aimed at promoting renewable energy sources for environmental sustainability reasons may have affordability and accessibility implications for energy equity.

The trilemma framework provides a structured and comprehensive approach to analyzing energy policy choices and understanding the complex interactions between energy security, energy equity, and environmental sustainability. It can be used to assess the performance of energy policies, evaluate different policy options, and inform decision-making processes in the context of energy transitions and decarbonization efforts. The trilemma has been used with different sets of variables, but they usually evolve around the same three core principles: politics, economics, and the environment. Each of these three principles come with each of their demands and the goal is to find policies or solutions that manage to balance these different demands and expectations.

4.2 Analytical Strategy

As mentioned earlier, this thesis looks to explore what role nuclear energy could play in the decarbonization of Europe's energy systems. The energy trilemma is widely used in energy transition studies. Examples of this are Gunningham (2012) and Oliver & Sovacool (2017), however, it has also been used specifically in the case of nuclear energy such as by Nuttall (2022) and Emblemsvåg & Österlund (2023). The rationale for using the trilemma framework is that it’s well aligned with the research questions of this study. Furthermore, looking at the role of nuclear energy through the three different dimensions from the trilemma can help to assess both the benefits and challenges associated with each dimension to get a better understanding of the role nuclear could play.

This thesis primarily utilizes qualitative methods to help understand the complex socio-political, economic, and environmental factors that shape the role of nuclear energy in the decarbonization process. In this regard, the data for this study is obtained from secondary sources, including relevant reports, scholarly literature, policy documents, and publicly available datasets. These data sources provide information on the current status of nuclear energy in Europe, including its contribution to energy security, energy equity, and environmental sustainability.

There are several limitations to this thesis. First, the analysis will be based on secondary data sources, which may be subject to biases and limitations of their own. Nuclear energy is a highly political theme and papers are often pro- or anti-nuclear, and thus it can be difficult to find balanced research. The best sources for data about nuclear energy are also often organizations such as the Nuclear Energy Agency and the International Atomic Energy Agency, which have an understandable pro-nuclear view. Whilst little can be done about these biases, the thesis attempts to provide a nuanced overview that takes from a wide variety of different sources to ensure that one perspective does not dominate another. Finally, the energy trilemma framework, while providing a comprehensive perspective, may not capture all the nuances and complexities of nuclear energy's role in Europe's decarbonization transition. This is typical of most frameworks, however, its utilization in Nuttall (2022), Gunningham (2012), Emblemsvåg & Österlund (2023) and Sovacool et al. (2015) to assess various states of nuclear energy, legitimizes its use when looking to explore the role of nuclear energy in the way that this thesis looks to.

5: Exploring the role that nuclear energy could play in Europe’s decarbonization

This section engages with the second objective of this thesis, specifically, to explore the role that nuclear energy could play in Europe’s decarbonization process using the framework explained in Chapter 4. Utilising the energy trilemma this analysis will first look at the environmental challenges and opportunities that nuclear energy poses. Then analysing the economic and practical implications of nuclear energy in the European energy system. Lastly, this chapter will look at the political challenges and opportunities for nuclear energy in Europe’s transitions towards decarbonization with a primary focus on energy security.

5.1 Environmental and climate

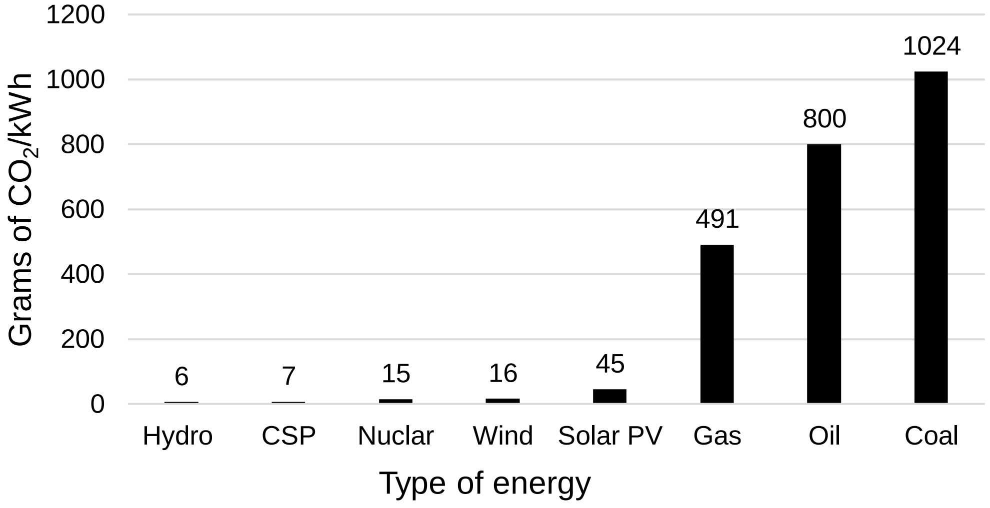
5.1.1 Decarbonization and capacity deployment

The EU has been leading the charge for a green energy transition and has legally committed to reducing their emissions by 55% below 1990 levels by 2030 (European Council, 2023b). However, in 2021, 76% of Europe’s total energy supply, including energy imports, still come from fossil fuels (gas 34%, oil 31%, coal 11%) (BP, 2022). This highlights how significant the reliance on fossil fuels is, and how the overwhelming majority of Europe's energy system still needs to transition to clean energy. Without nuclear power, energy decarbonization goals will be extremely difficult, if not impossible, to meet, according to analysis conducted by the energy firm BP (Bohdanowicz et al., 2023; BP, 2022). All 4 mitigation strategy pathways to limit global warming to 1.5°C by 2100 with no or limited overshoot from the IPCC Report showed a need to increase the amount of energy provided by nuclear power. If we look at the median of the 4 reported pathways, we can see a suggested 90% increase by 2030 and a 309% increase by 2050 relative to 2010 levels in energy globally provided by nuclear (IPCC, 2018). The median 2050 IPCC scenario would entail a global capacity of 1160 GW(e). If we assume that Europe will be keeping its share of 40% of the total global nuclear capacity, this would involve an increase from today's total capacity at 147,6 GW(e) to 456 GW(e) (PRIS, 2023). This growth would require an annual grid connection rate of approximately 10 GW(e) of installed capacity of a little more than 8.33 new nuclear plants every year, assuming that all new plants have an installed capacity of ~1200 MW(e), which is the current European average (PRIS, 2023). However, the reality is that the European nuclear capacity has been stagnant or slowly decreasing since the middle of the 1990s (Gospodarczyk, 2022).

5.1.2 Carbon footprint and emissions reduction

Nuclear energy's carbon footprint is comparable to that of several renewable energy sources. It's estimated that the average CO_2 emissions from nuclear energy are 15 grams of CO_2 per kWh (Prăvălie & Bandoc, 2018). The average estimated emissions per unit of electricity is illustrated in Figure 3. We can observe that nuclear has a similar emission profile to wind power (both on and offshore) and about 1/3 of solar photovoltaics (PV). Compared to fossil fuels the quantity of CO2 per kWh from nuclear energy is approximately 30 times smaller than gas, 50 times smaller than oil and 70 times smaller than coal.

Figure 3: Grams of CO_2/kWh per type of energy source



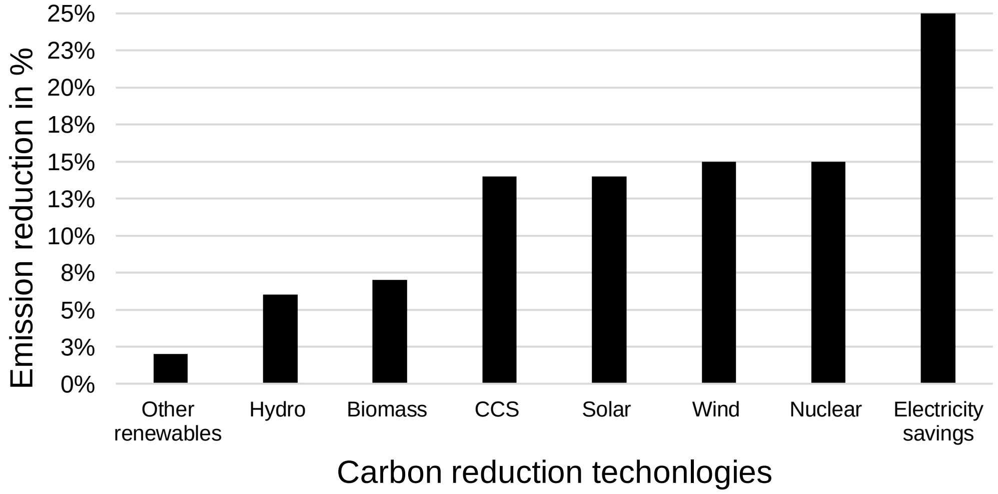
CSP: Concentrated Solar Power

Data Source: IEA (2015). Energy Technology Perspectives 2015.

It is however important to note that there are disputes about the emissions associated with the nuclear lifecycle. As Sovacool (2008) notes, different reactor designs, open or closed fuel cycle, fossil fuel infrastructure for commissioning/decommissioning and method of uranium mining greatly influence the life cycle emissions of nuclear making it difficult to accurately calculate. Still, Sovacool (2008) argues that most estimates for nuclear are too low and that the actual emissions including the indirect emissions are likely to be more comparable to solar PV. However, assuming the true emissions are higher than reported, would lead nuclear to still be considered a low-carbon source of energy.

In their Energy Technology Perspective report from 2015, the International Energy Agency (IEA) makes two different scenarios for mitigation strategy pathways (IEA, 2015). The first is an extension of current trends where no mitigation efforts beyond policy measures already implemented are included, which is called 6DS. The second follows a trajectory to limit global warming to 2 degrees and cut energy emissions by 60% by 2050 (based on 2012-levels) called 2DS. Figure 4 illustrates the percentage contribution of different technology areas to the cumulative CO_2 reduction moving from business as usual (6DS) to 2DS over the period 2012-2050. Electricity saving is the biggest contributor to emission reduction in this scenario. Nuclear and wind follows as the technologies with the biggest potential for emission reductions at 15%.

Figure 4: Emission reduction in % per technonlogies



CCS: Carbon Capture Storage

Data Source: IEA (2015). Energy Technology Perspectives 2015

5.1.3 Environmental concerns – Nuclear accidents

Despite the overwhelmingly positive picture of nuclear as a low-carbon source of energy with great potential for emission reductions, the overall environmental footprint of nuclear energy requires a more nuanced understanding. Even though nuclear is climatically considered beneficial for human society, the risk of radioactive contamination is a major environmental concern. The potential risk of radioactive contamination can be categorized into two parts: the threat of a nuclear accident and the challenges regarding nuclear waste management (Prăvălie & Bandoc, 2018).

Nuclear accidents are rare, but they could have catastrophic consequences for the environment. Concerns about the possibility of a major nuclear accident are a key factor for the negative public perception of nuclear energy (Nuttall, 2022). A nuclear power plant accident occurs when the reactor core melts which is most often caused by the failure of the cooling system, either through a direct technical fault or an external event such as human error or a powerful force e.g., earthquake, tsunami, etc. It's estimated that there have been 20 nuclear accidents in commercial reactors since the opening of the Obnisk Power Plant in 1954 (Prăvălie & Bandoc, 2018). Today the rules enforced by safety authorities have corresponds to a probability of a nuclear core melting to 1 in 100 000 per year per reactor. The probability of a significant radioactivity release to the atmosphere is further reduced to 1 in 1 000 000 (Berger et al., 2017). Berger et al. (2017) notes that neither Chernobyl nor Fukushima obeyed these types of safety requirements typically expected. In the case of Fukushima, the hydrogen explosion prevention and true confinement measures were significantly below par. The human element is thus often much more a concern than anything else when it comes to nuclear power.

If we look at deaths per 1000TWh of final energy for different production techniques globally, we can observe that nuclear has the lowest number with 90 deaths per 1000TWh (Table 1). It's interesting to look at this number from an environmental dimension since a large number of deaths from a nuclear accident almost guarantees a significant environmental event. 90 deaths per 1000TWh is approximately 5 times smaller than that of solar, 15 times smaller than hydro and 1100 times smaller than coal. Despite this low number of deaths per unit of energy produced, a severe nuclear accident has the most potential for mass casualties and environmental damage (see for example Lelieveld et al., 2012). Still, the United Nations Scientific Committee on the Effects of Atomic Radiation reported in 2021 that no adverse health effects could be documented as being directly attributable to radiation exposure after the Fukushima Daiichi disaster (UNSCEAR, 2021).

Table 1: Number of deaths per 1000 TWh of final energy for different energy production techniques

Production	Deaths per 1000 TWh
Coal	100 000
Oil	36 000
Biomass/biofuel	24 000
Natural gas	4000
Hydro	1400
Solar PV	440
Wind	150
Nuclear	90

Note: Nuclear data includes Chernobyl and Fukushima. The Nuclear US average is at 0,9 fatalities per 1000 TWh

Data source: Conca (2012); Berger et al. (2017)

5.1.4 Nuclear waste management

The generation of nuclear energy produces radioactive waste which needs to be carefully managed. The management of nuclear waste is controversial and is one of the major constraints on nuclear power's expansion (Findlay, 2010). Most nuclear waste has a relatively short half-life and is not hazardous for more than a couple of decades. However, about 3% of the waste has half-lives between a thousand and ten thousand years and therefore requires carefully controlled isolation. This waste is typically categorized as High-Level Waste (HLW) and despite its small quantity, accounts for 95% of the radioactivity from nuclear waste (WNA, 2022a). The construction of solutions for managing HLW could be said to be lagging behind the generation rate of HLW. There are two general approaches to management of high-level nuclear waste: reprocessing and storage in a deep underground repository.

Much of the nuclear waste can be reprocessed because it still possesses fissile materials that can be extracted and used again. It’s estimated that reprocessing of used fuel globally achieves 30% additional energy from the original uranium in the process (WNA, 2022a). Europe has been leading the charge for more reprocessing facilities in an attempt to close the fuel cycle with 73% of the reprocessing capacity situated in France and the UK (Prăvălie &

Bandoc, 2018). There is however a huge capacity gap between reprocessing facilitates and the generation of nuclear waste with a large potential for better maximizing the energy from fissile resources.

Reprocessing could also just be considered a partial solution to the problem as long-term waste disposal is still essential. Deep geological disposal has become the politically and scientifically favored method of long-term nuclear waste disposal. The essence of this method is to store the waste several hundred meters below the ground and seal it off with a multi-level concept, which consists of both anthropogenic barriers (such as stainless-steel drums) and natural barriers (such as areas that are especially tectonically stable and utilize particularly solid rocks and suitable debris) (Nuttall, 2022). As of today, there is no operational deep underground repository even though this is the preferred method of storage. However, France, Sweden, UK and Finland are all in the process of constructing deep geological storage facilities with the first repository scheduled to open later in 2023 at the Olkiluoto Nuclear Power Plant in Finland (Nuttall, 2022; Prăvălie & Bandoc, 2018)

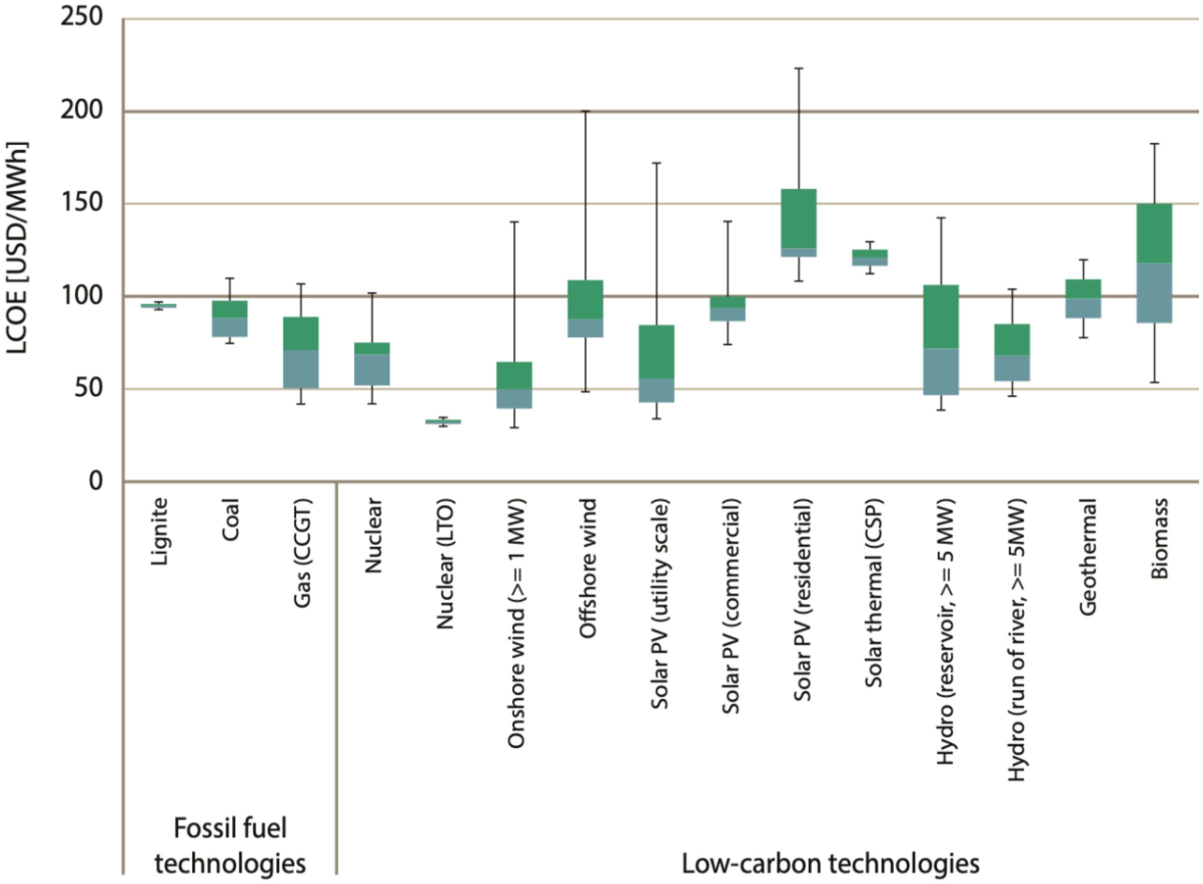
5.2 Economical implications

When summing up the overall European nuclear power plant construction story of the twenty-first century Nuttall (2022) describes it as a tale of cost overruns and construction delays. One of the main challenges for the economic dimension of nuclear energy is the large up-front capital costs, which accounts for approximately 60% of the levelized cost of electricity (LCOE). LCOE is a standard metric that consists of the total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period (WNA, 2022b). Advanced technology, expensive lienses and strict regulations regarding safety features also contributes to driving the LCOE up. The system costs are however much lower than that of VRETs and more similar to both gas and coal (WNA, 2022b). The main challenge for nuclear therefore lies in securing high-capital long-term investment for these large infrastructure projects in a market that is determined by short-term price signals.

Within Organisation for Economic Cooperation and Development (OECD) countries, the average nuclear plant took 12 years to construct (this does not include planning, permitting and licensing) in the period between1984-2000 (Nuttall, 2022). Recent European projects such as the Hinkley Point C reactor in England, Flamanville 3 in France and Olkiluoto in Finland have shown that there is no significant improvement in construction time from the 80s and 90s, with the average estimated construction time for these projects being 11 years (Nuttall, 2022). The global average construction time has however decreased, with Korea (5.3 years) and China (6 years) being below the median construction time (Eash-Gates et al., 2020; Schneider et al., 2017). In a liberalised market such as the European energy market the risks associated with nuclear power plant construction represent a massive hurdle. Especially in situations when the state is not simultaneously the constructor and the regulator. Because of how long the commission process is in Europe, investors are more exposed to changes in interest rates on debt, alterations in construction costs, changes in both public and political perceptions, and uncertainty regarding electricity and carbon prices. The power plant could be considered an unacceptable liability for many investors (and banks granting loans), since until it starts producing electricity there is no incoming revenue.

On the other hand, the marginalised costs of operating a nuclear power plant are relatively quite low and have the benefit of little price volitation. The plant operating costs of nuclear have a high fixed-to-variable cost ratio, meaning that changes in uranium prices just slightly affect the total operating cost. Gas and coal are, in stark contrast, highly affected by changes in the prices of raw materials since up to 90% of the marginal costs are fuel (WNA, 2022b). In Figure 5 the levelized costs of generating electricity (LCOE) for several technologies are presented. When we compare the total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period nuclear energy is competitive. This is due to its low operating costs, high capacity-factor and long lifetime which evens out the high capital costs.

Figure 5: Levelized costs of generating electricity by technology.



Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values.
The boxes indicate the second and third quartiles.
CCGT: combined-cycle gas turbines. LTO: long-term operation

Source: IEA (2020)

A key observation is that long term operation (LTO) of nuclear power plants by lifetime extension is the least costly option across the board. With the high costs of constructing new power plants in mind, the IEA suggests that investments in lifetime extensions and upgrading capacity would be one of the most cost-effective energy investments that can be made (IEA, 2020). Investments for long-term operation are also far less sensitive to a potential increase in discount rate compared to new nuclear power plants which means fewer economic risks.

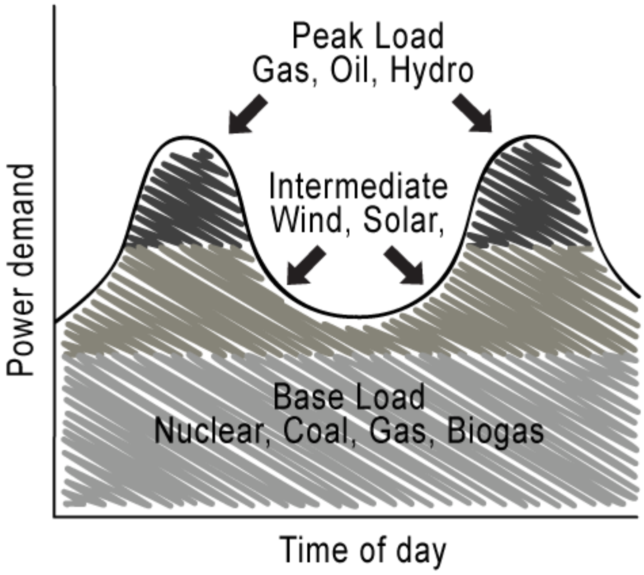
One valid criticism of the well-established LCOE analysis ties to the fact that all power is not of equal value, and the LCOE does not capture the relative value of the electricity generated (Nuttall, 2022). In other words, VRETs like solar and wind might generate less value since they do not follow demand. It can also be useful to assess the different technologies in different mixes since the energy mix usually includes many different sources of energy. In the report "The costs of decarbonisation" by the Nuclear Energy Agency it's shown that the total installed energy capacity would have to be doubled in a potential move from 30% to 75% VRETs. The move would also entail a change in total costs of electricity provision from 43 to 69 billion dollars per year (NEA, 2019). The biggest driver for the price increase is the large increase in profile costs to compensate for variability and intermittency. There are some uncertainties in these estimates, but it does however provide some indications that nuclear is much more valuable than simply comparing energy generation and unit prices due to its reliability and role as a non-intermittent and decarbonized energy form.

5.3 Politics – Security of supply

The dimension of politics regarding nuclear energy is multifaceted, complex, and entails many of the environmental and economic concerns discussed in the previous parts. However, several authors argue that energy security is the most important motivation for states to pursue nuclear energy, and thus its most political aspect (Davidson, 2022). Additionally, in the book "The Politics of Nuclear Energy in Western Europe" by Wolfgang C. Müller and Paul W. Thurner, they highlight changes in energy security conditions as one of the main reasons for political parties holding pragmatic views on nuclear in terms of their changing preferences (Müller & Thurner, 2017). The invasion of Ukraine by Russia highlighted the importance of energy security for the entire European continent. Russia perceives energy as a strategic tool in foreign policy, with the EU maintaining high levels of dependency on Russian gas prior to February 2022 (Kuzemko et al., 2022).

Energy security has a broad spectre of definitions but is usually referred to as low vulnerability to vital energy systems (Jewell & Brutschin, 2021). Sovacool & Brown (2010) finds that when examining the broad field of energy security literature the most mentioned components are accessibility, affordability, efficiency, and environmental stewardship. However, what energy security entails varies considerably from country to country with focus on imports or exports, the geopolitical ties a country has and the energy mix, all being important variables influencing energy security and how it is perceived (Davidson, 2022).Nuclear energy has characteristics that can strengthen a country's energy security,

Figure 6: Illustration of energy loads

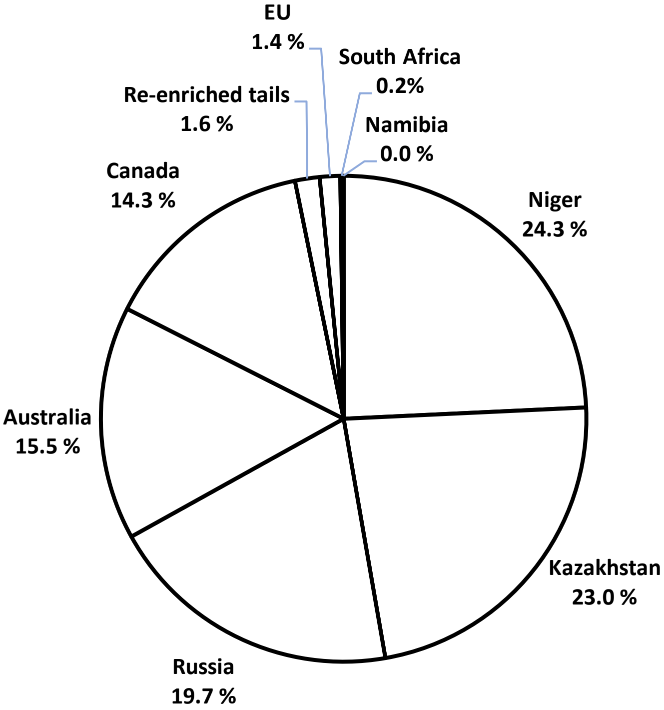


especially regarding availability. In Figure 6 and example of the different daily energy loads is illustrated along with the most common fuels for each demand. Capacity factor is a measure of reliability that is calculated as the ratio of the actual output to the maximum possible output. Nuclear energy has a high capacity-factor of 92% compared to some intermittent renewable sources of energy such as solar (24,8%) and wind (24,8%) (EIA, 2023). You would need almost four times the capacity of solar, and almost four times the capacity of wind to produce the same amount of energy to the grid as nuclear does over time. Data from the PRIS database shows that European nuclear reactors have produced between 83% and 90% of the maximum possible output since 2017 (PRIS, 2023).

VRETs such as solar and wind are important for providing the intermediate load during the day and are an essential part of Europe’s mitigation strategies. However, these sources of energy are not well suited for providing base load as they are intermittent, and the output is dependent on weather conditions and daily variations. Nor for providing peak load as the energy is not dispatchable or available throughout the entire day. This means nuclear energy could play a role in stabilizing European energy grids, preventing power outages with non-intermittent energy and supporting stabilization of the electricity grid.

Availability is, according to Sovacool & Brown (2010), closely tied to import dependencies, with the EU and its REPowerEU framework seeking to decrease external imports (Kuzemko et al., 2022). Nuclear power plants usually operate for 60+ years and thus could provide the EU with a reliable low-carbon, long-term replacement of the 155 billion cubic meters of Russian natural gas that European countries imported in 2021 (WNA, 2022c). Belgium is an example of a European country that decided to extend the lifetime of its current nuclear capacity to cut its ties with Russian gas (Kuzemko et al., 2022). Unlike many other sources of energy, nuclear power plants can be built in quite diverse locations, with a water source for cooling being the main physical requirement (Davidson, 2022).

Figure 7: EU Uranium supply sources in % for 2021



Source: Eurostat (2021)

With energy self-sufficiency being more important, there might be some issues with the supply of Uranium, since only 1,4% of the EU's supply comes from within EU (Figure 7). Uranium also has an extreme energy density which enables nuclear power plants to store about 2 years of fuel (WNA, 2022c). Imported raw materials is also a challenge for other sources of energy with 70% of the world's cobalt used in gas turbines and batteries, coming from the Democratic Republic of Congo, and 90% of rare earth elements (REEs) used in the refining of petroleum and in generators for wind turbines processed in China (WNA, 2022c).

As previously discussed in Chapter 5.2, the question of whether nuclear energy can provide energy for a competitive price is an important one. Concerning affordability, it's interesting to look at the IEA LCOE analysis (Figure 5) which shows that the long-term operation of existing nuclear reactors would give very low costs per unit of electricity. The high fixed-to-variable cost ratio for generation of nuclear energy leads to a quite predictable price of electricity being supplied, which could help stabilize other more volatile energy forms within the electricity and energy markets. Efficiency is explained by Sovacool and Brown (2010) as reducing per capita electricity usage and is by that definition not directly applicable to sources of energy. However, innovation is also mentioned as an underlying value of efficiency, and the field of nuclear energy is a promising and well-funded field, especially concerning the technology with the greatest future potential: nuclear fusion. The environmental dimension has been discussed in Chapter 5.1 and can be seen as a dichotomy. Nuclear energy has great potential as a low-carbon source of energy which can help the European energy system to decarbonize and facilitate for the increase in VRETs. At the same time, nuclear energy will always pose a risk of radioactive contamination and there are challenges concerning radioactive waste management.

6: Discussion

To discuss the results of the analysis conducted in the previous chapter I focus on three elements: Can, should, and will nuclear fission energy have a role in Europe's decarbonization process?

6.1 Can?

Nuclear energy is a low-carbon energy source having a quantity of CO_2 per kWh comparable to wind and lower than solar PV (Figure 4). LCOE analysis (Figure 6) has shown that the cost of nuclear energy is competitive, especially if measures for long-term operation are made. One of the main reasons why momentum for a positive nuclear narrative has gained traction can be explained by the qualities nuclear energy possesses as a reliable and consistent base-load provider, which can maintain grid stability as more intermittent renewable energy sources are added to the energy mix. VRETs will play a major role in helping limit anthropogenic climate to no more than 2 degrees by 2050, but understanding their limitations enables us to see the importance of having a reliable base load provider like nuclear as part of the energy supply mix. Nuclear is one of the very few low-carbon options that is almost always available everywhere. With this in mind, I believe it’s reasonable, to say that nuclear can play a role in Europe’s decarbonization process.

6.2 Should?

The decision of whether to use nuclear energy as part of the decarbonization process is a complex one that involves weighing the benefits, such as low-carbon electricity, energy security and stabilizing the energy grid, against the risks of radioactive contamination and costs associated with construction of nuclear power plants. To examine this question further it might be useful to take a look at the case of nuclear energy in Germany.

Germany has had one of the most vocal debates about nuclear power in Europe. The Green Party, along with most other environmental organizations, has framed nuclear power as an environmental concern, primarily through the risk of radioactive contamination and nuclear waste disposal, rather than being positive towards it as a low-carbon source of reliable and energy. As described in Chapter 2.3, the Fukushima disaster was the final blow for the pro-nuclear movement in Germany at the time. Over the last 10 years Germany's nuclear capacity has diminished to 1/5 of what it was in 2010, with the last nuclear power plants going off the grid in 2023 (WNA, 2023b). The Energiewende, Germany's energy transition policy, entails a 95% reduction in GHG emissions with solar and wind gradually replacing fossil fuels and nuclear. However, today coal remains Germany's main energy source in electricity production, accounting for 33% of the country's energy mix, with 8.4% more coal-generated electricity fed into the grid than in 2021 (Federal Statistical Office of Germany, 2023). Coal releases 70 times more CO_2 per kWh than nuclear and there is an estimated 1100 times more deaths per 1000 terawatt-hour of energy generation related to coal than nuclear (Prăvălie & Bandoc, 2018; Berger et al., 2017).

The Energiwelde has brought an impressive roll-out of solar and wind, there are however concerns about Germany staying reliant on coal past their phase-out time since the energy mix will not contain any energy sources that could help substantially with the intermittency issues caused by so many renewables (see for example Law et al., 2019; Bohdanowicz et al., 2023). It does seem strange for a country with ambitious climate mitigation goals to choose a transition strategy that has led to coal being the go-to non-renewable energy form above nuclear energy. Especially considering that they had the technical capacity to have nuclear as a transition energy, since lifetime extensions until 2036 were agreed upon in 2010 but later reversed after Fukushima (WNA, 2023b).

With fossil fuels still accounting for 76% of Europe's total energy supply in 2021, the transition to a decarbonized energy system is still a long way from done (BP, 2022). Arguably the most important climate mitigation pathways provided by the IPCC (2018) show a 309% increase by 2050 relative to 2010 levels in energy globally provided by nuclear. It is difficult to give one universal answer to the question of should nuclear energy (fission) have a role in Europe's decarbonization process, however, the data provided throughout this thesis shows that countries with existing nuclear capacity should certainly invest in and take measures to extend the lifetime of nuclear reactors, rather than phase them out. The analysis does not provide a clear-cut answer for investments in building new reactors since they are more costly and include more risk than long-term operation There are however good arguments for nuclear energy to replace coal in the European energy mix, since they both possess the quality of providing reliable base-load energy but nuclear would provide the same energy with 70 times less CO_2 emissions, in addition to replacing Russian gas (with 30 times less CO_2 emissions) and reducing geopolitical dependencies. It is however important to note that nuclear should not be considered as a substitute for renewables, but rather as a facilitator for continued growth towards a low-carbon energy mix that can meet demand throughout the day. A mix would be cheaper, include less risk for radioactive contamination and less pressure on the waste disposal facilities than a scenario where nuclear is the sole provider (NEA, 2019).

6.3 Will?

This question is for obvious reasons the most difficult to answer. In Finland, large investments have been made towards the maintenance and upgrading of existing nuclear power plants and plans so operating licenses can be extended until 2050. This year, in 2023, the construction of the new Hanhikivi 1 power plant started. Public opinion in Finland has also changed drastically. Polling data from 2014 shows that 24% of Finns were negative to nuclear power, and updated data from 2022 show a decrease to only 11% against, with 60% in favour of nuclear power (WNA, 2023a). The case of Finland, as well as Belgium and France, shows that nuclear energy most likely will have a future in Europe's decarbonization efforts in at least some countries. The EU has also sent strong signals that they regard nuclear energy as an important source of energy in the decarbonization process, for example through the inclusion of nuclear in EU's taxonomy (Kuzemko et al., 2022). At the same time, countries like Germany have shown that despite the experts and data providing a convincing argument towards the opportunities presented by nuclear energy, public opposition fuelled by the fear of nuclear accidents continues to influence politicians to exclude nuclear energy from the energy mix. And after all, a potential nuclear renaissance requires support from the people to be achievable in European democracies.

7: Conclusion

It's important to analyze the potential of nuclear power potential in the European decarbonization process from a multidimensional perspective due to its complex nature. When it comes to the environmental dimension, we can see the duality of nuclear energy. Climatically there are huge opportunities for nuclear energy to enable Europe to decarbonize.

The IEA finds in its analysis that nuclear (along with wind) has the biggest potential for emissions reduction of all the energy sources available (Figure 5) (IEA, 2015). The other side of the environmental dimension relates to arguably the biggest hurdle for a nuclear renaissance: radioactive contamination through nuclear accidents or nuclear waste disposal. There are vast amounts of high lever waste that needs to be stored safely, however, European countries have been hesitant in their approach to this. Economically, nuclear energy is competitive from the perspective of a complete life cycle. However, high capital costs and long construction times result in a high risk for investors which have proved difficult to secure financing from for the construction of new plants. Lifetime extensions of already existing nuclear power plants are seen as one of the best investments regarding the costs per unit of electricity produced. Nuclear energy possesses characteristics that enhance a country's energy security through the provision of dependable and stable energy, which in turn stabilizes the grid and ensures more predictable prices. The Russian invasion of Ukraine has brought the need for energy without geopolitical ties to the forefront of politics and has been part of the reasons why nuclear energy has received renewed interest in the last 3 years.

Based on the findings in this thesis, it seems counter-productive for countries like Germany to rely on coal, or other high-carbon sources, as their base-load provider when life-time extensions of existing nuclear reactors were possible. By phasing out nuclear, Germany’s chances of reaching its emission goals are severely diminished. Starting the work with commissioning new fission-based nuclear energy plants will be expensive in Europe, also posing questions about nuclear waste management. For European countries without any nuclear capacity, it’s difficult to say if building fission-based nuclear power plants or solely focusing on renewables is most beneficial for decarbonizing their grids. This is especially true in countries with a large share of fossil fuels. Technological advancements could prove to help with the challenges of costs and waste. Small modular reactors could lower the financial risk associated with nuclear plants with shorter construction times and substantially lower costs. Sodium-cooled fast reactor could also potentially reduce the amount of nuclear waste made from the generation process. However, the prospect of nuclear fusion is more tempting given its potential, and if energy from nuclear fusion becomes commercially available in the next 20 years a future energy mix of nuclear fusion and different types of renewables sounds not only promising but a highly likely development.

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