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Review

Investigating the Potential of Nuclear Energy in Achieving a Carbon-Free Energy Future

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Abstract: This scientific paper discusses the importance of reducing greenhouse gas emissions to mitigate the effects of climate change. The proposed strategy is to reach net-zero emissions by transitioning to electric systems powered by low-carbon sources such as wind, solar, hydroelectric power, and nuclear energy. However, the paper also highlights the challenges of this transition, including high costs and lack of infrastructure. The paper emphasizes the need for continued research and investment in renewable energy technology and infrastructure to overcome these challenges and achieve a sustainable energy system. Additionally, the use of nuclear energy raises concerns, such as nuclear waste and proliferation, and should be considered with its benefits and drawbacks. The study assesses the feasibility of nuclear energy development in Latvia, a country in Northern Europe, and finds that Latvia is a suitable location for nuclear power facilities due to potential energy independence, low-carbon energy production, reliability, and economic benefits. The study also discusses methods of calculating electricity generation and consumption, such as measuring MWh produced by power plants, and balancing supply and demand within the country. Furthermore, the study assesses the safety of nuclear reactors, generated waste, and options for nuclear waste recycling. The transition to a carbon-free energy system is ongoing and complex, requiring multiple strategies to accelerate the transition. While the paper proposes that nuclear energy could be a practical means of supporting and backing up electricity generated by renewables, it should be noted that there are still challenges to be addressed. Some of the results presented in the paper are still based on studies, and the post-treatment of waste needs to be further clarified.

Keywords: decarbonization; carbon-neutral energy; power generation; nuclear power; sustainable energy; small modular reactor

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1. Introduction

The issue of climate change, characterized by the increase in global temperatures and associated impacts, requires a significant reduction in greenhouse gas (GHG) emissions [1]. One strategy to achieve this goal is to reach net-zero emissions and decrease dependence on fossil fuels [2]. This necessitates a shift in energy generation and consumption patterns. A widely recognized and practical solution to decrease GHG emissions and decrease dependency on fossil fuels is the electrification of all energy-consuming sectors [3]. This approach involves replacing fossil-fuel-based energy sources with electricity from low-carbon sources such as wind, solar, and hydroelectric power to power electricity generation, transportation, heating, and industry. This approach also provides a range of benefits, such as reducing air pollution, improving energy security, and creating new job opportunities in the renewable energy sector. The electrification of all energy-consuming sectors presents a practical and effective solution to reduce GHG emissions, decrease dependence on fossil fuels, and create a more sustainable and resilient energy system. While challenges such as the intermittency of renewable energy sources and the need for infrastructure upgrades and investments may exist, the benefits of electrification and the transition to low-carbon energy sources far outweigh the costs in terms of environmental, social, and economic benefits [4–7]. Transitioning to electric systems can significantly reduce emissions and improve energy efficiency, thereby slowing the pace of climate change. The electrification of energy-consuming sectors is widely considered as a key solution in mitigating the effects of climate change [8,9]. However, the transition to electric systems is not without challenges, such as high costs, a lack of infrastructure and technology, and a lack of political will [3,10]. Additionally, the availability of low-carbon energy sources may not be consistent or reliable in certain regions, making it challenging to rely solely on these sources for electrification. Despite these challenges, it is crucial to continue working toward the electrification of energy-consuming sectors, as it is an effective approach to addressing climate change.

Fossil fuels remain the primary source of electricity generation due to their abundance, established infrastructure, and relatively low cost. However, the negative impact of fossil fuels on the environment and human health is becoming increasingly apparent, leading to a growing demand for phasing out their use and transitioning toward cleaner and renewable sources of energy [11,12]. This shift is necessary to mitigate the effects of climate change, which is caused by the accumulation of GHG emissions in the atmosphere, primarily from the burning of fossil fuels. The implementation of renewable energy sources can significantly decrease GHG emissions and promote sustainable energy generation. It is essential to continue research and investment in renewable energy technology and infrastructure, to overcome the challenges and achieve a sustainable energy system.

The traditional method of electricity generation through fossil fuel power plants, which relies on the combustion of coal or oil to generate heat, is a significant contributor to GHG emissions and air pollution. Despite the growing awareness of the detrimental effects of fossil fuels on the environment and human health, they continue to be the primary source of energy worldwide, accounting for over 80% of global energy consumption [13–18]. This is due to a complex interplay of factors, such as the existing infrastructure, economic considerations, and political factors that have hindered the transition from fossil fuels to better energy sources. However, with the rapid advancements in clean and renewable energy technologies, the future of energy generation is shifting toward cleaner, sustainable sources. It is essential to continue the research and investment in these technologies, and develop the necessary infrastructure to facilitate the transition to a low-carbon energy system in order to mitigate the effects of climate change and improve air quality.

As technology advances and the need to reduce GHG emissions becomes increasingly apparent, the share of renewable energy in global energy consumption is increasing [19,20]. Among renewable energy sources, wind energy is currently the largest contributor, but solar energy is rapidly gaining ground [21–24]. With the decreasing cost of solar and wind energy, as well as the development of more efficient technology, their share in the energy mix is expected to increase in the future. This shift toward cleaner and sustainable energy sources is crucial for addressing the challenges of climate change and meeting the energy needs of a growing population. In 2019, in the United States (US), renewable energy surpassed nuclear energy in terms of its share of electricity generation for the first time in history, highlighting the growing potential of renewable resources to replace fossil fuels as the primary source of electricity generation [25]. However, it is important to note that while the use of renewable energy sources has been increasing in the recent years, they alone may not be sufficient to entirely replace fossil fuels with current technology solutions [26,27]. The power output of renewable energy sources is dependent on weather conditions, making it difficult to rely solely on these sources to meet the energy demands of the entire population. Achieving a fully decarbonized energy sector will require a combination of different clean energy sources and technologies, such as energy storage solutions, advanced grid systems, and carbon capture and storage (CCS).

Electricity is a fundamental and essential aspect of modern life and ensuring a constant and reliable supply of electricity is one of the most significant challenges facing the world today. The increasing global energy demand, the need to reduce GHG emissions, and the impacts of climate change make it increasingly important to develop clean and sustainable energy sources that can provide a reliable source of electricity. The transition to cleaner energy sources and technologies will be a complex and challenging process, requiring a combination of technical, economic, and policy solutions to achieve the goal of a sustainable energy future. To overcome the environmental and energy crisis caused by the extensive use of fossil fuels, and to establish a sustainable and clean energy system, it is vital to set in motion a new energy revolution focusing on electricity generated from renewable resources [28,29]. Renewable energy sources are increasingly being adopted, but the lack of advanced energy storage technology is a significant hurdle to overcome. Without sufficient energy storage, the full potential of renewable energy sources cannot be realized. Therefore, it is necessary to invest in advanced energy storage technologies, such as battery storage systems, to enable the integration of renewable energy into the power grid and ensure a reliable and consistent supply of electricity [30,31]. The development of advanced energy storage technologies must be a priority in order to achieve a sustainable and carbon-free energy system. Additionally, it is important to consider all viable options for providing a reliable and consistent supply of electricity, including nuclear energy, but with caution, considering the risks associated with it, such as safety concerns and the disposal of nuclear waste. The transition to a sustainable and clean energy future requires a holistic approach, considering all possible options and their associated risks to ensure a reliable, sustainable, and clean energy future.

The threat of climate change has reached a critical level and continues to escalate at an alarming rate. Mitigating the catastrophic effects of climate change requires immediate action, particularly in the energy sector, which is a major contributor to GHG emissions [32–34]. A holistic approach that considers the assorted options available and their associated risks is necessary to achieve a sustainable, clean, and reliable energy future. Phasing out the use of fossil fuels is a crucial step in combatting the climate crisis. Nevertheless, reaching net-zero emissions alone is insufficient, as the effects of climate change, such as increased flooding, coastal erosion, droughts, and wildfires, are already manifesting and will continue to affect the climate for years to come [35,36]. It is essential to take immediate action to reduce dependence on fossil fuels and transition to cleaner and sustainable sources of energy, to minimize the impact of climate change and ensure a safe and livable future for all. While further climate change is inevitable, phasing out fossil fuels can buy humanity more time to adapt to the new conditions [37–39].

Nuclear energy has the potential to be a valuable addition to the energy mix, as it can effectively be combined with renewable energy sources to provide stable and uninterrupted electricity without producing significant GHG emissions [40–42]. Nuclear energy can play an important role in the transition from fossil fuels to emission-free and clean energy. Furthermore, it is not necessary to build large nuclear power plants, as newer, smaller, and safer nuclear technologies, such as small modular reactors (SMRs), are already available and continue to improve [43,44]. SMRs can provide up to 300 MWh of carbon-free energy practically anywhere in the world, without the need for long-distance transmission of electricity. This approach allows for a quick and smooth transition to clean energy, while ensuring reliable and sustainable energy supply. In addition to providing a reliable source of carbon-free energy, SMRs have the potential to play a key role in addressing the climate crisis by powering technologies for carbon capture directly from the atmosphere. It is important to note that addressing the climate crisis requires not only the cessation of excessive emissions, but also the reduction of existing emissions in the atmosphere. Therefore, SMRs, combined with carbon capture technology, can be a powerful tool for achieving a low-carbon energy future and mitigating the effects of climate change [45,46]. However, it is important to take into account that SMRs are a relatively new technology, and more research is needed to determine the feasibility of the technology and its potential challenges. For example, a recent study by Stanford and the University of British Columbia suggests that SMRs would generate more radioactive waste than conventional nuclear power plants [47]. However, these findings have been disputed by other researchers, who argue that there are no additional major challenges to the management of SMR nuclear waste compared to traditional reactors [48]. Therefore, more pilot projects are considered necessary to determine the feasibility of the technology and its potential challenges. At the same time, it is generally accepted that nuclear power, including SMRs and other technologies, such as light water reactors (LWRs), boiling water reactors (BWRs), and high-temperature gas-cooled reactors (HTGRs), will continue to play an important role in the future energy mix, alongside other low-carbon energy sources, such as renewables, energy storage, and carbon capture technologies [49–51]. LWRs are a common type of pressurized water reactor (PWR) that use ordinary water as both a coolant and a moderator. LWRs are the most widely used type of nuclear power plant in the world, accounting for approximately 60% of global nuclear power capacity. The fuel used in LWRs is typically enriched uranium dioxide, which is fabricated into fuel rods that are loaded into the reactor core. Water is used to cool the reactor core and transfer the heat to a steam generator, where it is used to produce electricity. LWRs offer several advantages, including high thermal efficiency, low emissions, and relatively low operating costs. However, they also present certain challenges, such as the need for specialized fuel handling and storage facilities, and the risk of nuclear accidents and radiation leaks. Overall, LWRs have played a significant role in meeting the world's energy needs and will likely continue to be an important part of the energy mix in the future [49]. BWRs are a type of nuclear power plant that use enriched uranium fuel to heat water, producing steam that drives a turbine to generate electricity. Unlike PWRs, which use a separate water source to cool the reactor core, BWRs use the same water that is heated to create steam. This can make BWRs simpler and more efficient than PWRs. However, BWRs also present certain challenges, such as the need for specialized fuel handling and storage facilities, and the risk of nuclear accidents and radiation leaks. Despite these challenges, BWRs continue to play an important role in meeting the world's energy needs, particularly in countries such as Japan and the US, which have a large number of BWRs in operation. Recent advances in BWR technology, such as the use of passive safety systems, have also made them safer and more reliable [50]. HTGRs are a type of nuclear power plant that use helium gas as a coolant and graphite as a moderator. HTGRs can operate at much higher temperatures than other types of reactors, which makes them more efficient and potentially more versatile. They also have a relatively low risk of nuclear accidents and radiation leaks due to their inherent safety features, such as a ceramic-coated fuel that can withstand high temperatures. HTGRs can be designed for either electricity generation or industrial heat applications, such as hydrogen production. However, HTGRs also present certain challenges, such as the need for specialized fuel handling and storage facilities, and the risk of graphite oxidation. Despite these challenges, HTGRs have the potential to play an important role in meeting the world's energy needs, particularly in countries seeking to reduce their dependence on fossil fuels and decarbonize their energy systems [49,51].

The use of nuclear energy as a tool for decarbonizing the electricity grid and ending dependence on fossil fuels is a topic of ongoing debate within the scientific community [52–54]. While opinions on the role of nuclear energy in the future energy mix may vary, it is reasonable to suggest that it should play a significant role in achieving a clean and sustainable energy system. Simultaneously, it is crucial to address the issue of final disposal of nuclear waste if nuclear energy is to be included in any future energy mix. Critics of nuclear energy often fail to acknowledge the potential benefits of nuclear energy in terms of emission reduction and environmental sustainability. Furthermore, it is important to recognize that the risks associated with nuclear energy can be mitigated through the use of advanced technologies such as carbon capture and desalination equipment. Nuclear energy can not only provide emission-free energy, but also capture fossil emissions that have already entered the atmosphere, making it a valuable measure in the fight against climate change.

The objective of this paper is to assess the future perspectives of nuclear energy in the clean energy system, with a focus on safer, cheaper, and more compact options, particularly for small countries with limited funds to decarbonize their electricity grid or provide a local source of electricity. One such option is the use of SMRs, which are smaller, cheaper, and safer than traditional nuclear reactors. However, further studies and pilot projects are needed to assess the potential of nuclear energy as a tool for decarbonizing the electricity grid and ending dependence on fossil fuels, and determine the best options for different countries and regions.

This study provides a thorough examination of the advantages and limitations of both renewable and nuclear energy sources, with a focus on SMRs as a potential solution to the challenges faced by renewable energy. The analysis includes a detailed evaluation of the issues related to nuclear waste management and a comparison of the capabilities of SMRs in terms of providing reliable and sustainable energy. Furthermore, the study presents recommendations for the integration of nuclear energy, with technologies such as carbon capture and desalination, to mitigate the effects of climate change. The main goal of this paper is to offer a scientifically based, objective analysis of the potential role of nuclear energy in the transition toward a clean and sustainable energy system.

2. Materials and Methods

2.1. Feasibility Assessment of Nuclear Energy Development

For the purpose of assessing feasibility, the authors selected Latvia as a viable location for the implementation of nuclear energy in the future. Latvia is a country in Northern Europe, located on the eastern shore of the Baltic Sea. It is bordered by Estonia to the north, Russia to the east, Belarus to the southeast, and Lithuania to the south. The study has determined that Latvia is a suitable location for the establishment of nuclear power facilities for electricity generation in the future. This is due to a variety of factors, including the potential for energy independence, low-carbon energy production, reliability, and economic benefits [55–57]. Additionally, Latvia has a relatively small population and a relatively low need for electricity, which means that the energy generated by nuclear power plants could potentially be exported to other countries [58–61]. Nevertheless, it is important to weigh the potential advantages and disadvantages of nuclear power, as well as consider factors such as safety, waste management, and public acceptance, before deciding about the deployment of nuclear power plants in Latvia.

The study highlights several factors that make Latvia a viable location for the implementation of nuclear power plants:

- Energy independence: Latvia currently relies heavily on imported fossil fuels to meet its energy needs [62,63]. Building nuclear power plants in Latvia would reduce its dependence on foreign energy sources and increase its energy security;
- Low-carbon energy: nuclear power is a low-carbon energy source, which means that it emits less GHGs compared to fossil fuels [64]. This can help Latvia reduce its carbon footprint and meet its climate change goals;
- Reliability: nuclear power plants can provide a steady, reliable source of electricity to meet Latvia's energy needs, even during times of high demand [65];
- Economic benefits: nuclear power plants can create jobs and stimulate economic growth in the areas where they are built [66];
- Latvia has a relatively small population, and the need for electricity is not very high, so the energy generated by nuclear power plants could be used to export to other countries [59–62].

It is important to note that nuclear power has both advantages and disadvantages, and it is crucial to weigh them before deciding. Safety, waste management, and public acceptance are also critical factors to consider when it comes to nuclear power.

2.2. Calculating Electricity Generation

The calculation of electricity generation for a country can be achieved through various methodologies, but a common practice is to determine the total amount of electricity produced by all power plants within the country over a specific temporal interval, such as an annual period [67]. This can be accomplished by measuring the number of megawatt hours (MWh) produced by each power plant and subsequently summing these values to obtain the total for the country. Another approach to calculating electricity generation for a country is by utilizing the balance of electricity supply and demand within the country [68]. In this method, electricity generation for a country can be calculated as the sum of production from all power plants, minus the electricity lost in transmission and distribution, plus imports, and minus exports (Equation (1)). This can be mathematically represented as [69]:

$$\text{Electricity Generation} = \text{Production from all power plants} - \text{Transmission and distribution losses} + \text{Imports} - \text{Exports} \quad (1)$$

This methodology considers all the electricity that enters and leaves the country, providing a net generation value. It is important to note that the availability of data and methods of data collection may vary by country.

2.3. Calculating Electricity Consumption

The quantification of electricity consumption in a country can be performed through multiple techniques [70]. A prevalent method is to determine the aggregate consumption of electricity by all end-users within the country over a defined time frame, such as an annual duration [71]. This can be achieved by measuring the consumption of electricity in MWh for each consumer category, such as residential, commercial, and industrial sectors, and subsequently summing these values to attain the overall consumption for the country. This approach enables an accurate representation of the electricity consumption patterns in a country and provides a comprehensive overview of the energy consumption trends. Another method for determining electricity consumption in a country is through the analysis of the balance between electricity supply and demand. This approach calculates electricity consumption as the net result of electricity generated by domestic power plants, imports, exports, and transmission and distribution losses [72]. By considering all inflows and outflows of electricity, this method provides a comprehensive representation of the country's overall consumption. This approach enables a more accurate understanding of the country's energy consumption patterns and provides insight into the balance of domestic energy production and import dependency. This can be represented as the Equation (2):

$$\text{Electricity Consumption} = \text{Generation from all power plants} + \text{Imports} - \text{Exports} - \text{Transmission and distribution losses} \quad (2)$$

This method accounts for all the electricity that enters and exits the country, resulting in a net generation value. However, it is crucial to acknowledge that data availability and collection methods may vary across countries. This highlights the need for standardized and accurate data collection procedures to ensure the comparability and reliability of electricity generation and consumption calculations.

2.4. Calculating Electricity Demand

Calculating an increase in electricity demand can be done through various techniques, but a common method is to compare the current consumption to that of a previous period, such as the same month or quarter of the previous year [73]. This can be done by measuring the number of MWh consumed during the current period, and then subtracting the number of MWh consumed during the previous period. This will give the increase in demand. Mathematically, it can be represented as (Equation (3)):

$$\text{Increase in Demand} = \text{Current period's electricity consumption} - \text{Previous period's electricity consumption} \quad (3)$$

Another approach to calculate the increase in demand is by utilizing forecasting models [74–76]. These models can predict future demand based on historical data, weather patterns, and other relevant factors. The forecasting models use statistical and mathematical techniques to provide an estimate of future demand. It is important to note that the demand increase calculation is dependent on the data availability, accuracy and the data collection method used. The results of the calculation should be interpreted in the context of the underlying data and the method used for data collection.

2.5. Calculating Emissions from Electricity Generation

There are several ways to calculate emissions from electricity generation, but a common method is to use the emissions factor, which is a measure of the amount of GHG emissions produced per unit of energy generated [77,78]. This can be done by multiplying the emissions factor of the specific fuel source used by the total amount of energy generated from that fuel source. For example, if a power plant burns coal to generate electricity, the emissions factor for coal would be used to calculate the total emissions produced by the power plant. The calculation would be (Equation (4)):

$$\text{Emissions (in } CO_2e) = \text{Total electricity generation (MWh)} \times \text{Emissions factor (kg } CO_2e/\text{MWh)} \quad (4)$$

Another approach is to use data from the power plants regarding their fuel consumption and emissions, and then use that data to estimate the emissions from electricity generation. This can be done by using a tool such as the International Energy Agency's CO_2 Emissions from Fuel Combustion database, which provides detailed data on emissions from fuel combustion by country, fuel type, and sector. It is also important to note that emissions from electricity generation can also be calculated for other greenhouse gases besides CO_2, such as methane, nitrous oxide and others, depending on the specific fuel source and power plant [79].

2.6. Selecting the Optimal Evaluation Method for Power Plant Energy/Fuel Source

There are several methods available to determine the optimal energy/fuel source for a power plant, with the most widely used in practice being cost, efficiency, emissions, land usage, lifetime, waste generation, and reliability [80,81]. Selecting the appropriate evaluation method to assess the value of invested funds is crucial. The primary goal is to establish assessment methods that consider both positive and negative attributes in order to determine the most suitable type of power plant. In other words, the benefits should outweigh the drawbacks. For example, when evaluating the efficiency of power plants, calculating the amount of electricity generated relative to the fuel consumed would be an appropriate method. On the other hand, when evaluating waste production, evaluating the characteristics of the fuel used and its recycling potential may be a more suitable assessment option [82]. It is important to consider the specific context, goals and criteria of the energy planning or evaluation process to select the most appropriate methods.

2.7. Assessing Nuclear Energy as a Replacement for Fossil Fuels

To accurately determine the amount of nuclear energy necessary to replace fossil fuels in a country, a comprehensive analysis must be conducted. This includes evaluating the current electricity generation from fossil fuels and determining the total electricity generation for the country. Additionally, the capacity factor of proposed nuclear power plants must be analyzed [83–85]. The capacity factor, a metric that represents the actual output of a power plant over a period of time compared to its maximum potential output if it were to operate at full capacity during that same period, plays a crucial role in the feasibility of nuclear energy as a replacement for fossil fuels. Factors such as technology, efficiency, and operation and maintenance of the power plant impact the capacity factor and must be considered during the analysis. The nuclear energy needed can be calculated using Equation (5):

$$\text{Nuclear energy needed} = (\text{Total electricity generation from fossil fuels}/\text{Capacity factor of nuclear power plants}) \times \text{Total electricity generation for the country} \quad (5)$$

It is important to note that this calculation assumes that the capacity factor of the nuclear power plants will be the same as that of the fossil fuel power plants they are replacing and that the total electricity generation for the country will remain constant. In reality, the total electricity generation and the capacity factor may vary over time due to factors such as weather, economic conditions, and government policies. Furthermore, it is essential to consider safety, waste management, and public acceptance of nuclear power in the country before deciding to replace fossil energy with nuclear energy.

3. Results

3.1. Current Trends and Future Scenarios of Electricity Generation and Consumption

The current global primary energy mix is heavily reliant on fossil fuels, with 84% of the world's primary energy being sourced from fossil fuels such as oil (33%), coal (27%), and natural gas (24%) [86–89]. In contrast, only 16% of the world's energy is sourced from low-emission sources, including hydroelectric power (7%), renewable energy sources (5%), and nuclear energy (4%) [89]. The increasing demand for electricity (Figure 1) driven by technological advancements and population growth cannot currently be met solely by renewable energy sources, resulting in the continued reliance on fossil fuels for electricity generation and a corresponding increase in GHG emissions. Abandoning nuclear energy as a source of power would exacerbate this issue, as the missing energy would have to be generated using fossil resources. This would not only undermine efforts to decarbonize the energy sector, but also have a detrimental impact on global climate change mitigation efforts. Therefore, it is crucial to consider the continued use of nuclear energy as a viable option in the transition to a low-carbon energy system.

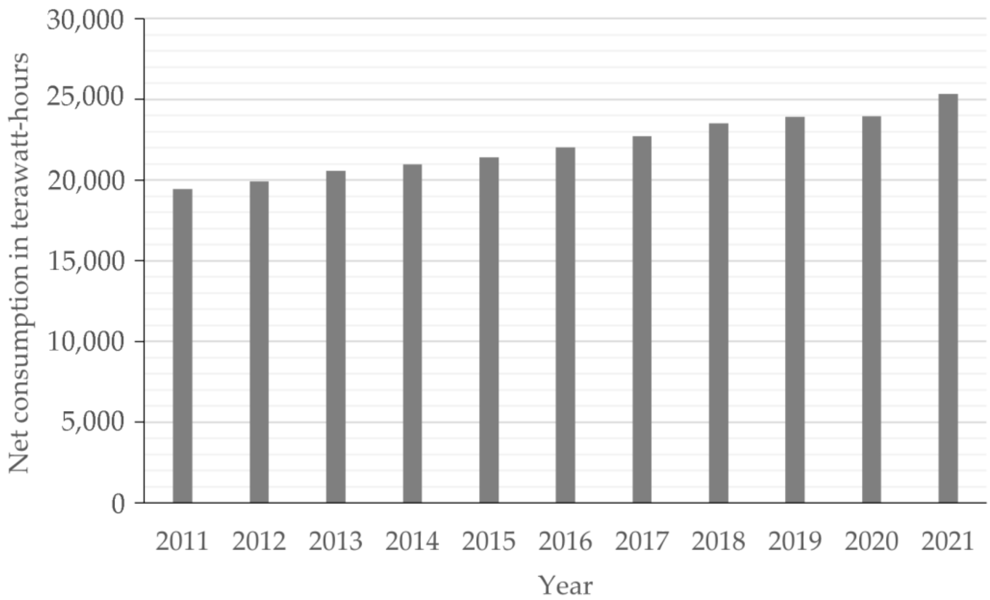

Figure 1. The net electricity consumption worldwide over the last decade (2011–2021), based on Statistica 2023 [90].

The histogram presented in Figure 1 illustrates the net electricity consumption of the world over the past decade (2011–2021). The vertical *Y*-axis represents the net consumption in terawatt hours (TWh), while the horizontal *X*-axis depicts the time period from 2011 to 2021. The data clearly demonstrate an exponential growth in net electricity consumption, increasing from 19,444 TWh in 2011 to 25,343 TWh in 2021. Notably, the data also indicate a period of relative stability in net consumption in the years 2019 and 2020, which may be attributed to the impact of the COVID-19 pandemic on global industrial activity [91]. Overall, the worldwide net electricity consumption is showing a gradual upward trend, and if this trend continues, it may result in an increase in fossil fuel emissions, as renewable energy sources are not yet able to keep up with this consumption. One example of this phenomenon can be observed in Lithuania, where the decommissioning of the Ignalina Power Plant resulted in a reduction of carbon-free nuclear energy production and an increased reliance on fossil fuels [92,93]. Despite the necessity of decommissioning the outdated and dangerous Soviet-era nuclear reactor, the situation highlights the potential benefits of investing in modern, state-of-the-art nuclear technology with advanced safety systems [94]. Given the existing legislation and the availability of qualified personnel, the primary challenge in this endeavor would be raising funds, given the negative perception of nuclear power.

The latest data from AST (Figure 2) indicate that Latvia's electricity consumption has exhibited a steady upward trend in the recent years [95]. However, this trend experienced a deviation in 2020 due to the implementation of COVID-19 restrictions, which resulted in a decrease in electricity demand. Similarly, in 2022, the increase in electricity prices also led to a drop in electricity demand. These data suggest that the overall trend of increasing electricity consumption in Latvia is subject to fluctuations caused by external factors such as pandemics and changes in electricity prices. The country has also been increasing its use of renewable energy sources, such as wind and biomass, to generate electricity [96]. However, Latvia still heavily relies on fossil fuels, particularly natural gas, to meet its energy needs. As of 2021, the majority of Latvia's electricity is generated by hydroelectric power plants, followed by natural gas and coal-fired power plants [97]. Latvia heavily relies on the imports of natural gas, oil, and coal to generate electricity. Latvia has committed to reduce its GHG emissions and increase the share of renewable energy in its energy mix, as part of its commitment to the Paris Agreement and the EU's climate change targets [98]. This would imply a decrease in the use of thermoelectric power plants in the future. Under the Paris Agreement, countries are required to submit Nationally Determined Contributions (NDCs) that outline their specific climate action plans and emission reduction targets. The NDCs are reviewed and updated every five years to reflect the country's progress towards achieving its goals. The Paris Agreement also established a mechanism for supporting developing countries in their efforts to mitigate and adapt to the impacts of climate change, including financial assistance, capacity building, and technology transfer to achieve its NDCs. Latvia has implemented several policies and measures, including a carbon tax, subsidies for renewable energy, energy-efficient building codes, and support for the use of electric vehicles. The EU has been a key supporter of the Paris Agreement and has set ambitious targets to reduce GHG emissions and increase the share of renewable energy in its energy mix. The EU has committed to achieving net-zero GHG emissions by 2050 and reducing emissions by at least 55% by 2030, compared to the levels in 1990. Additionally, the EU aims to increase the share of renewable energy to at least 32% by 2030 and increase energy efficiency by at least 32.5% by the same year [98].

The trend of electricity production and consumption in Latvia between 2015 and 2022 is illustrated in Figure 2. The data, presented in MWh, do not exhibit a clear trend of increasing or decreasing consumption. This lack of trend is likely due to the relatively short time frame, and the impact of the COVID-19 pandemic and electricity price increases on consumption patterns. Despite this, the overall consumption appears to be increasing. Additionally, Latvia's reliance on hydropower and fossil resources, which are subject to significant fluctuations in availability and cost, results in significant fluctuations in electricity production.

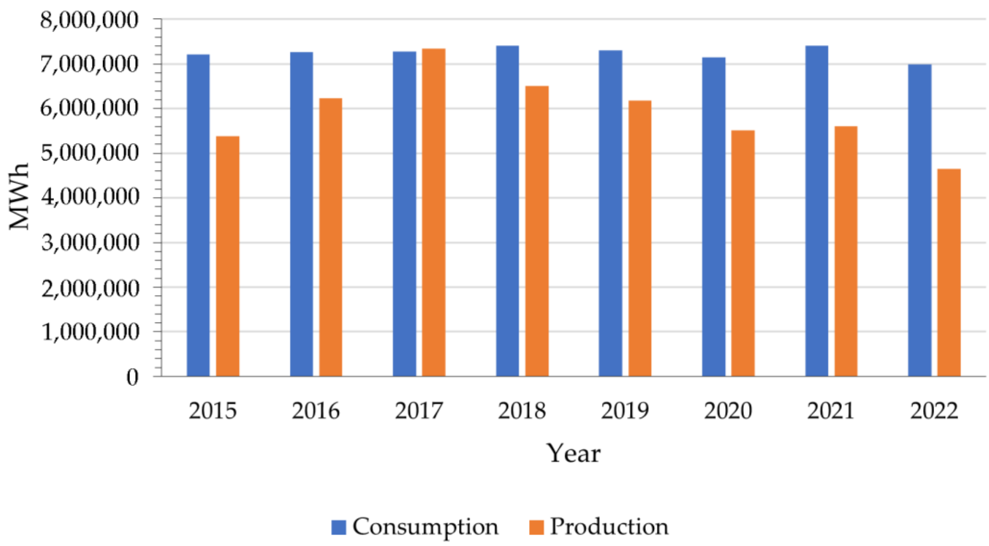

Figure 2. Electricity production versus consumption in Latvia (2015–2022), based on AST 2023 [95].

Latvia's electricity consumption is consistently increasing year-over-year and is projected to continue to rise in the future [99]. This fact must be considered when considering future energy scenarios. Currently, Latvia does not produce enough electricity to meet its consumption needs and this gap is expected to widen in the future. The amount of electricity generated in Latvia varies from year to year, depending on factors such as weather conditions and economic activity. According to data from the Latvian transmission system operator AST, the total electricity generation in Latvia in 2020 was approximately 8.2 TWh. Electricity in Latvia is primarily provided by Latvenergo, which is the largest electricity supplier in the country [95,97]. Latvenergo is a state-owned company and is responsible for the generation, transmission, and distribution of electricity in Latvia. Additionally, there are also several smaller private electricity suppliers operating in Latvia that provide electricity to customers. Some examples include [100]:

- Elektrum: a subsidiary of the international utility company, EON, which operates in several European countries;
- Enefit: a subsidiary of the Estonian state-owned energy company, Eesti Energia;
- Vattenfall: a Swedish power company that operates in several European countries, including Latvia;
- Baltijas gāze: a Latvian natural gas and electricity supplier;
- Nordea Elektrum: a subsidiary of the Nordea bank that provides electricity in Latvia.

Hydroelectricity is the main source of electricity generation in Latvia. The Latvian transmission system operator AST reported that the total electricity generation from hydroelectric power plants in 2020 was approximately 4.7 TWh [95]. Latvia has a relatively large number of rivers and lakes, which makes it well suited for hydroelectric power generation. The biggest hydroelectric power plants are located on the Daugava River, and include the Riga Hydroelectric Power Station, Plavinas Hydroelectric Power Station, and Kegums Hydroelectric Power Station (Table 1).

Table 1. Latvia's largest hydroelectric power plants on the Daugava River [97].

Name of the Power Station	Total Capacity (in MW)	Number of Generators	Commissioned Date
Riga Hydroelectric Power Station	690 MW	4	1977–1981
Plavinas Hydroelectric Power Station	440 MW	3	1980–1982
Kegums Hydroelectric Power Station	400 MW	4	1986–1987

Table 1 aims to give an overview of the hydroelectric power generation capacity in Latvia and the technical aspects of the hydroelectric power plants. The capacity of these power plants is a significant factor in understanding the power generation capacity of Latvia. The commissioning date also allows for a better understanding of how these power plants have been integrated into the national power grid.

In addition to conventional hydroelectric power, Latvia also generates a small amount of electricity from run-of-river hydroelectric power plants, which are smaller and have less environmental impact [97]. In addition to conventional sources, Latvia also generates a small amount of electricity from renewable energy sources, such as wind and solar power (Table 2).

Table 2. Renewable energy sources in Latvia [97].

Energy Source	Installed Capacity (MW)	Target for 2030 (Share in Energy Mix)
Wind Power	480 MW	6%
Solar Power	20 MW	1%

Table 2 provides a summary of the installed capacity of wind and solar power in Latvia. This table aims to give an overview of the current and future potential of wind and solar power in Latvia. It shows the installed capacity of both wind and solar power in the country, as well as the government's target for the share of these renewable energy sources in the national energy mix by 2030. It is important to note that these data are subject to change and are based on current policies and plans; therefore, future developments could change the actual figures.

The amount of solar energy generated in Latvia is relatively small compared to other sources of electricity. According to data from Eurostat, the share of solar energy in the total electricity generation in Latvia was around 0.5% in 2020 [101]. Latvia has a relatively low solar potential compared to other European countries due to its northern location and relatively short summer days. However, in the recent years, the Latvian government has been promoting the development of solar energy. Several private companies and organizations have begun to invest in solar energy projects in Latvia, and the number of solar panels installed in the country has been increasing. However, the overall capacity of solar energy is still relatively small, and the majority of electricity generated in Latvia is still coming from conventional sources, such as hydroelectricity, and combined heat and power plants.

The amount of wind energy generated in Latvia is also relatively small compared to other sources of electricity. According to data from Eurostat, the share of wind energy in the total electricity generation in Latvia was around 2.6% in 2020 [101]. Latvia has a relatively low wind potential compared to other European countries due to its location in the northeastern part of Europe, which is not as windy as the coastal areas and large parts of the continent. However, the Latvian government has been promoting the development of wind energy and has set a target to increase the share of renewable energy in the total energy mix to 40% by 2030, which includes the use of wind energy [102]. Several private companies have begun to invest in wind energy projects in Latvia, and the number of wind turbines installed in the country has been increasing over the years.

3.2. Energy Production Costs

Electricity generation involves both fixed and variable costs (Table 3). Fixed costs include capital expenses, such as the cost of constructing a power plant and the cost of land [103]. These costs can vary depending on factors such as labor costs and regulatory expenses, including permits and environmental approvals. Variable costs, also known as operating costs, include expenses for fuel, labor, and maintenance [103]. These costs can vary depending on the amount of electricity produced and the type of power plant used. For example, fossil-fuel-powered plants have higher fuel costs, while renewable energy sources have little to no fuel costs. Nuclear power plants have low fuel costs, but higher labor and maintenance costs [104]. The cost to generate each unit of electricity, known as the marginal cost, is influenced by these operating costs [103]. Table 3 provides a summary of the estimated capital, fixed, variable, and operating costs for electricity generation for different types of power plants. The data presented in this table are sourced from the International Energy Agency (IEA) and are based on estimates for the year 2020 [105].

Table 3. Electricity generation costs by power plant type [105].

Power Plant Type	Capital Costs (USD/MWh)	Fixed Costs (USD/MWh)	Variable Costs (USD/MWh)	Operating Costs (USD/MWh)
Coal	100–150	30–70	20–80	10–20
Natural Gas	50–80	20–50	15–30	5–10
Nuclear	150–200	50–100	30–50	10–20
Hydroelectric	50–80	20–50	10–30	5–10
Onshore Wind	40–80	10–30	10–20	5–10
Offshore Wind	80–120	20–40	10–20	5–10
Solar PV	50–100	10–20	10–20	5–10

Table 3 includes information on seven different types of power plants: coal, natural gas, nuclear, hydroelectric, onshore wind, offshore wind, and solar PV. Each type of power plant is represented by a row in the table, with columns displaying the estimated costs for capital, fixed, variable, and operating costs in USD/MWh. This table aims to give an overview of the approximate costs associated with different types of power plants and allows for comparison between them. For example, it can be seen that the capital costs for a coal-fired power plant are higher than those of a natural-gas-fired power plant, but the variable costs for a coal-fired power plant are lower. Similarly, it can be observed that the operating costs for hydroelectric power plants are lower than those for nuclear power plants. On the other hand, renewable energy sources, such as wind and solar power, are characterized by lower capital and operating costs than fossil fuel power plants. It is important to note that these costs are based on estimates and can vary depending on location and other factors. Additionally, these numbers are for reference and should be used as a rough guide, as the actual costs can vary depending on the specific conditions of each power plant and location.

SMRs can offer several benefits in terms of costs [43–45,57]. Since they are smaller and less complex than traditional nuclear power plants, the costs associated with building and installing SMRs can be lower. Additionally, the use of standardized designs and mass production can also reduce costs. Furthermore, SMRs can be used in a wide range of applications, including remote and off-grid locations, which can help diversify the energy mix in these areas [43–46,57]. While SMRs could potentially reduce the costs associated with nuclear power, this is not a guarantee, and more research and developments are needed to determine the actual costs and benefits of these new technologies. Furthermore, the cost of financing, insurance, and fuel supply, as well as the availability of skilled labor and the legal framework, are also factors that could affect the overall costs of a nuclear power project. It is important to note that SMRs are still in the research and development phase, and as a result, it is difficult to provide a precise estimate of their levelized cost of energy (LCOE). However, some studies and estimates have suggested that SMRs may have a lower LCOE than traditional nuclear reactors due to their smaller size, modular design, and potential for increased efficiency. For instance, a 2018 report by the IAEA indicated that the LCOE for SMRs could range from USD 60 to 90 per MWh, depending on the specific design and fuel cycle of the reactor. In contrast, larger traditional nuclear reactors typically have an estimated LCOE ranging from USD 90 to 150 per MWh [106]. It is important to emphasize that these estimates are based on a number of assumptions and are subject to change as SMR technology continues to develop. Additionally, the LCOE for SMRs may vary depending on several factors, such as the energy mix of the grid where the reactor is deployed, the cost of fuel, and regulatory compliance expenses. While it is challenging to provide an accurate LCOE estimate for SMRs at this stage, there is some evidence to suggest that these reactors may have a lower LCOE than traditional nuclear reactors, given their smaller size, modular design, and potential for increased efficiency [106]. Nonetheless, further research and development is needed to better understand the cost and feasibility of SMRs in practice. SMRs may be able to compete with renewables in certain applications, such as providing baseload power to remote or off-grid communities. While renewables may have a lower LCOE in some cases, they may also face challenges related to intermittency and grid integration. SMRs, on the other hand, can provide reliable 24/7 power, and may be more suitable for certain applications or locations.

3.3. Energy Decarbonization

Electricity decarbonization refers to the process of reducing the carbon emissions associated with the generation of electricity [107]. This can be achieved through a variety of means, including the increased use of renewable energy sources, the implementation of CCS technology, and the increased energy efficiency of power generation and transmission. One of the main strategies for achieving electricity decarbonization is the increased use of renewable energy sources. These sources of energy do not produce carbon emissions during operation, and can therefore help reduce the carbon intensity of the electricity grid. Another strategy for achieving electricity decarbonization is the implementation of CCS technology [108,109]. CCS technology captures CO_2 emissions from power plants and other industrial facilities, and stores them underground, effectively removing them from the atmosphere. Improving energy efficiency is also key for electricity decarbonization [110,111]. By reducing the energy consumption of buildings, industries, and the transportation sector, the demand for electricity is reduced, and the amount of energy that needs to be produced to meet that demand is therefore also reduced.

Many countries and international organizations have set ambitious targets for decarbonizing the electricity sector. For example, the EU has set a target to achieve a 32% share of renewable energy in its final consumption by 2030 and reduce emissions by at least 40% by 2030 compared to the levels in 1990 [102]. It is important to note that decarbonization is a complex and challenging process that requires a multifaceted approach and the cooperation of various stakeholders, including governments, utilities, and industry. It also requires significant investments in new technologies and infrastructure. Additionally, the implementation of policies and regulations to support the transition to a low-carbon electricity system, such as carbon pricing, renewable energy targets, and energy efficiency standards, will be crucial to achieve successful decarbonization. It is also worth mentioning that decarbonization of the electricity sector alone is not enough to tackle the climate change, as other sectors such as transportation, buildings, and industry, need to be decarbonized as well. Furthermore, it is not only about reducing emissions, but also about removing the already emitted CO_2 from the atmosphere. Overall, though, electricity decarbonization is a crucial step toward meeting global climate goals and addressing the impacts of climate change. It involves a transition from fossil-based power generation to low-carbon and renewable energy sources, as well as increasing energy efficiency, and the development and deployment of new technologies, such as CCS.

Businesses globally have varying focuses when it comes to decarbonization efforts, with some focusing on heating and cooling systems, and others on electricity generation [112,113]. This is due to the differing energy intensity of their operations, which can range from non-intensive to intensive. Decarbonization of heating and cooling in the industrial sector is a crucial step towards reducing GHG emissions. One of the main strategies for achieving this is through the use of low-carbon and renewable energy sources for heating and cooling [114]. This can include the use of geothermal heat pumps, solar thermal systems, and biomass boilers. Another strategy is the implementation of energy efficiency measures, such as insulation and efficient heating and cooling systems [115]. This can help reduce the amount of energy required for heating and cooling, thereby reducing carbon emissions. In terms of electricity decarbonization, it is also important to consider the intensity of operation of a corporation. For example, some industrial processes are more energy-intensive than others, and therefore may require more significant investments in low-carbon and renewable energy sources and energy efficiency measures. Additionally, some companies may have more opportunities to implement renewable energy and energy efficiency measures, depending on their location and access to resources. For example, a company that operates in a region with high potential for solar or wind power may find it easier to invest in these technologies than a company that operates in a region with less favorable conditions. It is important to note that the decarbonization of heating and cooling and electricity in the industrial sector is a complex and challenging process that requires a multifaceted approach and the cooperation of various stakeholders, including governments, utilities, and industry. It also requires significant investments in new technologies and infrastructure. Additionally, the implementation of policies and regulations to support the transition to a low-carbon system, such as carbon pricing, renewable energy targets, and energy efficiency standards, will be crucial to achieving successful decarbonization.

3.4. Challenges and Opportunities in Energy Storage

The transition to renewable energy sources has been met with both challenges and opportunities. One significant challenge is the high cost of energy storage devices, such as batteries (Table 4) [116,117]. Despite a recent decrease in costs, the initial investment required for these devices remains substantial for many corporations. In addition, the lack of standardization in energy storage technology creates difficulties for electricity generation projects that expand over time, as certain storage systems may not meet the specific requirements of the project and may need to be replaced. This lack of standardization also contributes to challenges in regulatory policy, as new technologies and designs may not be immediately recognized or accommodated by existing regulations. However, as energy storage technologies continue to improve and become more efficient and economically viable, they will play a crucial role in promoting flexible integration of renewable energy sources and baseload nuclear energy. Nuclear energy, in particular, has the potential to significantly contribute to a clean energy future and help combat climate change in conjunction with renewable energy sources. Therefore, more climate advocates should recognize the importance of including nuclear energy in any comprehensive climate solution.

Table 4. Solar energy storage possibilities [117–119].

Technology	Type	Description	Advantages	Disadvantages
Lithium-ion batteries	Chemical	Rechargeable batteries commonly used in consumer electronics and electric vehicles	High energy density, long life cycle, and low self-discharge rate	High cost, requires careful management to prevent overheating and fire
Lead-acid batteries	Chemical	Rechargeable batteries commonly used in automotive and backup power applications	Low cost, widely available, and well-established technology	Low energy density, short life cycle, and requires regular maintenance
Flow batteries	Chemical	Rechargeable batteries that use liquid electrolytes to store energy	Long life cycle, scalable and modular design, and ability to handle deep discharge	High cost, relatively new technology with limited commercialization
Compressed air energy storage	Mechanical	Uses compressed air to store energy, typically in underground caverns or repurposed natural gas storage facilities	Low cost, can be sited in a variety of locations, and has a long lifespan	Requires specific geographic conditions and high capital costs

Table 4 aims to give an overview of the different technologies used for solar energy storage and allows for comparison between them. For example, lithium-ion batteries have a high energy density and a long life cycle, but they are relatively expensive; while lead-acid batteries are low-cost, but have a low energy density and a short life cycle. It is important to note that each technology has its own advantages and disadvantages, and the most appropriate one will depend on the specific application and location.

3.5. Evaluating the Capability and Performance of a Proposed Power Plant

Energy planning, a process that encompasses decision-making related to energy demand and supply infrastructure, should be inclusive of all stakeholders and consider all possible options for energy supply and demand to align with the overall national goals for sustainable development [120–122]. This includes not just environmental protection, but also social and economic development, which are interconnected and overseen by competent regulatory bodies. The process of energy planning starts with the identification of a set of indicators that encompass all aspects of sustainable development. This is followed by an evaluation of all current and future energy supply options that meet demand within certain policy targets. The study of energy system analysis, considering a country's natural resource capacity, stage of infrastructure development, and sustainable development objectives, may or may not conclude the idea that nuclear energy should be included in the country's future energy mix. If nuclear energy is deemed a viable option, it may be beneficial to conduct a comprehensive assessment of the entire nuclear energy system to raise awareness of the associated issues, support the development of a national strategic plan for nuclear energy, and ensure that the proposed system meets sustainable development criteria.

The capacity factor of a power plant is a metric that quantifies the actual output of the power plant over a period of time, typically a year, as a ratio of its output if it were to operate at its maximum possible output, referred to as the nameplate capacity, over the same period of time [123,124]. It is a measure of the utilization of the power plant's capacity and is commonly used to compare the performance of different types of power plants. Here are some average capacity factors for different types of electricity production [123,124]:

- Coal: 60–65%;
- Natural gas: 55–60%;
- Nuclear: 90–92%;
- Hydroelectric: 40–60%;
- Wind: 30–45%;
- Solar photovoltaic: 15–25%.

It is important to note that the capacity factors provided are general and global averages, and may vary greatly depending on the individual power plant and its location. Factors such as technology, efficiency, operation and maintenance, weather conditions, and government policies can greatly impact the capacity factor of a specific power plant. Therefore, it is essential to conduct a detailed analysis of the specific power plant in question to obtain a more accurate representation of its capacity factor.

The efficiency of a power plant refers to the percentage of the energy content of the fuel that is converted into usable electrical energy [125–129]. Here are some average efficiencies for different types of power plants:

- Coal-fired power plants: 33–48%;
- Natural gas-fired power plants: 42–60%;
- Nuclear power plants: 33–48%;
- Hydroelectric power plants: 90–98%;
- Wind turbines: 25–45%;
- Solar photovoltaic power plants: 15–22%.

It is worth noting that the efficiencies provided are general averages and can vary significantly depending on the specific power plant and the technology used. Additionally, it is important to note that the efficiency and capacity factor are not directly related. Efficiency refers to the ratio of the amount of useful energy produced by a power plant to the amount of energy consumed, whereas capacity factor refers to the ratio of the actual output of a power plant to its maximum possible output.

3.6. Emissions from Nuclear Power Plants

Nuclear power plants do not produce emissions of CO_2 or other GHGs during their operation [130,131]. They generate electricity by using the heat produced by nuclear reactions, rather than burning fossil fuels. This means that nuclear power plants do not directly produce any emissions of GHGs that contribute to climate change (Table 5). However, there are other emissions associated with the nuclear power plants; they include the emissions produced during the mining and milling of uranium, the construction and decommissioning of the power plants, and the management of nuclear waste. Additionally, the emissions associated with the entire nuclear fuel cycle must be considered, including emissions from uranium mining, milling, enrichment, fuel fabrication, and transportation. The emissions associated with these processes are generally low, but can vary depending on the location and method of mining, milling, and fuel fabrication.

Emissions from uranium mining can vary depending on the specific mining method and location, but can include a variety of pollutants such as particulate matter, sulfur dioxide, nitrogen oxides, and GHGs [132,133]. The most common method for mining uranium is open-pit mining, which can generate emissions from the use of diesel fuel in equipment, as well as from the blasting and crushing of rocks. In situ leaching, another method of mining uranium which is widely used, involves pumping a leaching solution into the ground to dissolve the uranium, which can also result in emissions of the leaching agents and other chemicals used in the process. Emissions from uranium mining can also include the release of radioactive materials such as radon gas, which is a naturally occurring radioactive gas that can be released during the mining and milling of uranium. Additionally, the mining process can generate tailings, which are waste materials left over after the uranium is extracted. These tailings can contain radioactive materials and other pollutants, and can be a source of emissions if not properly managed. At the same time, it is worth noting that the emissions from uranium mining are generally much lower than those from coal mining, and the mining process has greatly improved over the recent years, with regulations and industry standards that aim to minimize the environmental impact and emissions [134]. Furthermore, the emissions associated with the entire nuclear fuel cycle are still much lower than those from fossil-fuel-based power plants, which are major contributors to GHG emissions and climate change.

Table 5. Emissions generated by different types of power plants [135–138].

Power Plant Type	CO_2 Emissions (kg/MWh)	NO_x Emissions (kg/MWh)	SO_2 Emissions (kg/MWh)
Coal	940–1100	0.10–0.40	0.10–2.00
Natural Gas	490–630	0.02–0.10	0.02–0.20
Nuclear	12	0.01	0.01
Hydroelectric	0	0.01–0.02	0.01–0.02
Onshore Wind	0	0.01–0.02	0.01–0.02
Offshore Wind	0	0.01–0.02	0.01–0.02
Solar PV	0	0.01–0.02	0.01–0.02

Table 5 provides a general overview of the emissions generated by different types of power plants per unit of electricity generated. It includes emissions of CO_2, NO_x, and SO_2, which are the most common emissions from power plants. As can be seen from the table, coal-fired power plants have the highest emissions of CO_2, NO_x, and SO_2 per unit of electricity generated, followed by natural-gas-fired power plants, which have lower emissions. On the other hand, renewable energy sources such as hydroelectric, onshore wind, offshore wind, and solar PV, have no emissions of CO_2, NO_x, and SO_2. It is important to note that these emission levels can vary depending on the specific conditions of each power plant, such as the type of coal or gas used, the age and efficiency of the equipment, and the level of emission control technology in place. Additionally, the emission level of a power plant can also vary depending on local regulations and standards. Overall, Table 5 illustrates the importance of transitioning to renewable energy sources in order to reduce the emissions generated by power plants and mitigate the impacts of climate change.

3.7. Nuclear Power Plant Safety

A nuclear accident is an event that results in significant consequences for people, the environment, or the nuclear facility. These consequences can include fatalities, substantial release of radioactive materials, and reactor core meltdowns. Despite the implementation of procedures to reduce the risk of accidents and minimize the release of radioactive materials, the potential for human error remains a concern [139].

The perception of the potential threat of nuclear accidents and the release of radioactive materials from nuclear power generation is prevalent [139,140]. However, it is important to note that the design and operation of nuclear power plants aims to minimize the likelihood of accidents and the impact on human health and the environment when they do occur. Throughout the history of commercial nuclear power operation, there have been only two major reactor accidents: Chernobyl and Fukushima Daiichi [139,141,142]. Both of these accidents resulted in significant radiation exposure to the public; however, it is important to note that these are the only major accidents to have occurred in over 18,500 cumulative reactor-years of commercial nuclear power operation in 36 countries [143].

To achieve optimal safety, nuclear power plants operate using a 'defense-in-depth' methodology, which includes multiple safety systems and redundancy to prevent equipment or operator failures from evolving into more significant problems [144]. This methodology includes high-quality design and construction, equipment that prevents operational disruptions, thorough supervision and routine assessment, redundant and diverse systems to control damage to the fuel, and the confinement of severe fuel damage to the plant itself. This approach ensures that physical barriers are in place between the radioactive reactor core and the environment, and multiple safety systems are in place, each with a backup and designed to accommodate human error. In conclusion, the use of nuclear energy for electricity generation can be considered exceptionally safe. The risk of accidents in nuclear power plants is low and declining, and the consequences of an accident or terrorist attack are minimal compared to other commonly accepted risks. Furthermore, nuclear energy saves lives by shifting fossil fuel from the electricity mix.

Safety in nuclear energy depends on factors such as rational planning, appropriate design with well-defined safety boundaries and backup systems, high-quality mechanisms, and a well-developed safety culture in operations [145,146]. The operational lives of reactors depend on maintaining their safety margins. Apart from the Chernobyl accident, no nuclear workers or members of the public have died as a result of exposure to radiation due to a commercial nuclear reactor incident. The serious radiological injuries and deaths that occur each year (2–4 deaths and many more exposures above regulatory limits) are the result of large uncontrolled radiation sources, such as abandoned medical or industrial equipment [147].

A commercial-type power reactor cannot, under any circumstances, explode like a nuclear bomb, as the fuel is not enriched beyond 5%, much higher enrichment is needed for explosives [148]. About 80% of all incidents in nuclear power plants are attributed to human error, which is lower than some other industries. Of the incidents, 20% involve equipment failures [149]. When the 80% human error is broken down further, it reveals that the majority of errors associated with events stem from suppressed administrative weaknesses, while about 30% are caused by the individual worker interacting with the equipment and systems in the facility. Focusing efforts on reducing human error will reduce the likelihood of nuclear incidents.

3.8. Small Modular Reactors

SMRs are a type of nuclear reactor that have a power capacity of up to 300 MW per unit (Table 6). Their design features include being smaller in scale compared to conventional nuclear power plants, modular in construction, and utilizing nuclear fission as the primary mechanism for generating heat and electricity, resulting in zero emissions. The advantages of SMRs include increased flexibility in deployment and operation, reduced capital costs, and improved safety characteristics [43–47,57]. Six distinct types of SMRs can be recognized [150]:

- Land-based water-cooled SMRs, which utilize pressurized water reactor (PWR), boiling water reactor (BWR), or pressurized heavy water reactor (PHWR) concepts, and are currently in operation in countries such as China, India, and Russia;
- Marine-based water-cooled SMRs, which are similar to land-based water-cooled SMRs, but are located on a barge or underwater. Russia currently has a two-unit 70 MW power plant in operation, and China is currently constructing a 60 MW unit;
- High temperature gas-cooled SMRs, which are cooled by gases such as helium and operate at temperatures as high as 1000 °C, resulting in high-temperature and high-pressure steam that increases the thermal efficiency of the generation process;
- Fast neutron spectrum SMRs, which utilize fast neutron spectrums for nuclear fission;
- Molten salt SMRs, which utilize a liquid salt coolant and fuel;
- Micro-sized SMRs, which have an extremely small power capacity.

Table 6. Small modular reactors in a conceptual and design development phase with potential for near-term deployment [150].

Prototype	Capacity (MW)	Type	Country
VBER-300	300	land/marine-based pressurized water reactor	Russia
NuScale	60	land-based pressurized water reactor	United States
SMR-160	160	land-based pressurized water reactor	Canada
ACP100	125	land-based pressurized water reactor	China
SMART	100	land-based pressurized water reactor	South Korea
BWRX-300	300	land-based pressurized water reactor	United states
PRISM	300	land-based sodium fast nuclear reactor	United States
ARC-100	100	land-based sodium fast nuclear reactor	United States
IMSR	192	land-based molten salt reactor	Canada
BREST	300	land-based sodium fast nuclear reactor	Russia
RITM-200M	50	marine-based pressurized water reactor	Russia

The cost of SMRs can vary depending on the design and size of the reactor, as well as the location and specific project. However, in general, SMRs are expected to be less expensive to build and operate than traditional large-scale nuclear power plants. The cost of an SMR can range from several hundred million to a couple of billion euros. The cost of the project depends on the technology and design of the reactor, the location of the project, and the regulatory environment. Additionally, the economies of the scale can affect the cost as well. It is worth noting that the cost of SMRs is still in the early stages of development, and it is hard to give an accurate estimate as the technology is still in the research and development phase, and it will take time for the cost to come down as the technology matures and economies of the scale increase [43–47,57,150].

Table 6 presents a list of 11 SMR designs that are in a well-developed phase and have the potential for near-term deployment. As the table illustrates, the majority of the proposed prototypes are land-based technologies, with the exception of the two Russian projects that are marine-based. Additionally, the majority of the technologies that are closest to being ready for release are PWRs, which is the simplest design among SMRs. In a PWR, nuclear fission heats the water in the nuclear core, which is then pumped into tubes inside a heat exchanger. The heat from these tubes is used to heat a separate water source, creating steam that powers an electric generator to produce electricity. Apart from PWRs, sodium fast reactor designs have also been relatively well-developed, with three prototypes offered by the US, Canada, and Russia. Furthermore, Canada is the only country that offers an innovative design for a molten salt reactor, which has the advantage of effectively eliminating the risk of steam explosions, hydrogen explosions, or a meltdown due to the nature of molten salt reactors. In general, SMRs offer a promising solution for the generation of safe, clean, and reliable nuclear energy, as well as provide the benefits of the large-scale reactors with the flexibility and scalability of smaller-scale reactors. Furthermore, they can be used in a variety of applications, including electricity generation, process heat, desalination, and hydrogen production [43–45,47,57,150].

SMRs make use of passive cooling systems that do not depend on the availability of electric power. No electrical supplies or pumps are needed to cool down the reactor in the event of an incident, as this is done by natural convection and the gravity coolant feed. This feature ensures that the reactor will remain safe under severe accident conditions. Furthermore, passive safety systems decrease the capital and maintenance costs compared to large power reactors, and fundamentally change the economic equation in favor of SMRs. However, innovative designs should still include reliable active backup cooling systems. Existing small modular reactor designs have smaller, less robust containment systems than conventional nuclear reactors, which may increase the probability of damage from hydrogen explosions. Therefore, modern designs should include measures to prevent hydrogen from reaching explosive concentrations. SMRs are expected to be installed underground, which reduces the risk of various negative environmental impacts [43–48,57,150].

In regard to SMRs, some researchers have raised concerns about a higher neutron leakage compared to conventional nuclear power plants due to their smaller size. As a result, this increased neutron leakage could increase the amount of produced nuclear waste. Additionally, the spent nuclear fuel from SMRs would also be discharged in greater volumes per unit than from conventional power plants. However, as previously mentioned, there are well-defined techniques for nuclear waste disposal. Conversely, some studies have shown that small modular reactors have reduced fuel requirements, hence power plants based on SMRs require less frequent refueling compared to conventional plants. Some designs of SMRs are intended to operate for up to 30 years without refueling. It is uncertain how many of the concerns are truly justified and how many are based on political considerations and 'greenwashing'. Nevertheless, it is clear that if managed appropriately, SMRs offer a lower initial capital investment, greater scalability, and siting flexibility for locations unable to accommodate more traditional larger reactors [43–48,57,150].

3.9. Nuclear Waste Production

The amount of nuclear waste generated by SMRs is currently uncertain and is based on experimental pilot projects. Nuclear waste metrics include the front-end waste generated during the nuclear fuel manufacturing process, the back-end waste arising from spent nuclear fuel, and the end-of-life nuclear waste from the decommissioning of SMRs [47,150–154]. In regard to front-end waste, the depleted uranium mass is proportional to enrichment and inversely proportional to burnup and thermal efficiency. VOYGR, the first SMR to receive design approval from the US Nuclear Regulatory Commission, generates 23% more depleted uranium mass than the reference pressurized water reactor, due to a higher fuel uranium enrichment, lower burnup, and lower thermal efficiency [155,156]. However, pilot designs such as Natrium and Xe-100 perform comparatively better in front-end waste generation due to a higher burnup and thermal efficiency.

With regard to back-end waste, VOYGR generates 1.1 times the spent nuclear fuel mass and 1.1 times the volume of the reference pressurized water reactor due to lower burnup and thermal efficiency [155]. Natrium and Xe-100 designs generally perform better than VOYGR and the reference PWR, generating 72% and 75% less spent nuclear fuel mass, respectively, due to higher burnup and thermal efficiency [157]. Decommissioning class A, B, and C low-level waste includes building materials activated by neutrons or contaminated by radioactive isotopes. Greater-than-class-C low-level waste includes reactor components located near the active core and activated above class C levels [158]. For PWRs, less than 1% of decommissioning low-level waste is greater-than-class-C. The decommissioning volume of class A, B, and C low-level waste for VOYGR is 10% smaller than the reference PWR [155]. However, the normalized greater-than-class-C volume for VOYGR is six times larger than that of the reference PWR. Natrium and Xe-100 designs include radial neutron reflectors and graphite blocks, respectively, that protect other core structures from activation, which may result in an increase in greater-than-class-C waste [155,157]. Further research and experimentation are necessary to determine the exact amount of nuclear waste generated by SMRs.

3.10. Nuclear Waste Disposal and Recycling

The energy density of nuclear fuel is significantly high, making it an efficient energy source that produces a relatively small amount of waste. Nuclear waste can be classified into three categories: low-level, intermediate-level, and high-level waste [159,160]. Low-level waste, accounting for 90% of all nuclear waste, represents only 1% of total radioactivity. This type of waste is often non-radioactive and can be stored in landfills or incinerated to reduce volume. Intermediate-level waste, representing 7% of the volume of nuclear waste and 4% of total radioactivity, typically contains contaminated metals and materials from the reactor core. This waste can also be stored in landfills or intermediate storage facilities until the radioactivity decreases. High-level waste, comprising 3% of the volume of nuclear waste and 95% of total radioactivity, is the used nuclear fuel containing uranium, thorium, and plutonium. This type of waste is highly radioactive and requires special disposal procedures, such as permanent disposal in a geological repository. This process includes placing the waste in iron and copper canisters, which are then buried deep underground and sealed with bentonite clay and cement seals. The borehole is then backfilled with a mixture of cement, crushed rock, or similar materials.

The issue of final disposal of nuclear waste is a complex and contentious one, and it is true that a universally accepted and fully implemented solution has not yet been achieved. At the same time, it is clear that all the waste generated by the nuclear industry has a defined method of disposal, and the methods are well-developed and thoroughly detailed; thus, there is no real basis for concern [161–163]. Furthermore, in addition to disposal, it is also possible to recycle and reuse most of the high-level waste as fuel in the same reactor from which it came, or using it elsewhere, meaning that it is necessary to extract the less radioactive ore, as the spent nuclear fuel still has more than 90% of its potential energy [65]. However, nuclear fuel recycling is a complicated and expensive process, and it is thus not a widely implemented approach [164]. Nevertheless, technology is constantly developing and may make this process easier and cheaper in the future. Additionally, some countries intentionally avoid reprocessing of nuclear waste because of the risk that the material could be diverted for weapons [165,166]. In addition, not all nuclear waste can be recycled: around 4% (the fission products) of the high-level waste cannot be recycled and would still require disposal in a geological repository. Usually, these fission products are immobilized through vitrification [167].

Currently, in countries that do not see a threat of proliferation (e.g., France, Japan, Germany, Belgium), the recyclable spent nuclear fuel is fed into a chemical processing system that separates actinide elements (e.g., uranium, thorium, plutonium) that can be recycled as mixed-oxide fuel to produce more electrical power. Recycling is mainly focused on the extraction of plutonium and uranium, as they can later be mixed with fresh uranium and made into new nuclear fuel rods [168].

3.11. Nuclear Energy as a Replacement for Fossil Fuels

Although Latvia currently heavily relies on natural gas and hydroelectric power for its energy needs, the Latvian government has formed a working group to assess the feasibility of SMRs and their potential impact on Latvia's energy security and decarbonization efforts [169,170]. Additionally, as a member of the EU, Latvia is under pressure to contribute to the EU's ambitious targets for the decarbonization of the energy sector by 2050. The authors believe that the principles used in this assessment can be applied to other countries as well. The study suggests that nuclear energy through SMRs might be a viable option for Latvia in the future, as it allows for achieving and exceeding net-zero emission goals and guarantees a reliable source of energy.

3.12. Assessing the Future Implications of Nuclear Energy Deployment

Nuclear energy has the potential to play a significant role in reducing GHG emissions and mitigating climate change. Nuclear power plants do not produce emissions of GHGs during their operation, making it a low-carbon energy source. Nuclear energy can thus contribute to the reduction of GHG emissions, which are a major contributor to global warming. However, it is important to note that the use of nuclear energy as a means of mitigating climate change is a complex issue and requires a thorough evaluation of various factors. The environmental, safety, and security risks associated with nuclear power plants are well known, and the management of nuclear waste is a technically challenging and costly endeavor. Additionally, the construction and decommissioning of nuclear power plants can also lead to significant environmental impacts. Furthermore, the availability of nuclear fuel is limited, and the risk of nuclear weapon proliferation is a concern. While nuclear energy has the potential to play a role in reducing GHG emissions and mitigating climate change, a comprehensive assessment of the potential risks and benefits of nuclear power is necessary to make a well-informed decision on its use as a means of addressing climate change.

Latvia does not currently have any nuclear power plants, and therefore does not have any specific regulations related to nuclear safety. However, as a member of the EU, Latvia is subject to the EU's nuclear safety regulations, which are designed to ensure the safe operation of nuclear power plants, and the protection of people and the environment from the potential risks associated with nuclear energy. The EU's nuclear safety regulations cover a wide range of topics, including design and construction of nuclear power plants, radiation protection, emergency preparedness and response, and the management of radioactive waste [171]. These regulations are enforced by the national regulatory authorities in each EU member state and are subject to a regular review and updates to reflect new scientific and technical developments. That being said, Latvia has a long history of opposition to nuclear power, and the public acceptance of the technology is quite low. Therefore, even if the country would consider the option of building a nuclear power plant, the public perception and the potential political opposition would have to be considered as well. The regulations require that waste management plans and the necessary waste management organizations are in place before the operation of any nuclear power plants. Additionally, the financing of nuclear waste management must be secured. It is important to note that the management of radioactive waste is a complex and costly issue that requires long-term planning and the involvement of various stakeholders, including the government, industry, and the public. While Latvia currently does not have any nuclear power plants, it is important for the country to be prepared for the management of radioactive waste should it decide to develop nuclear energy in the future.

3.13. Exploring the Use of Nuclear Energy in Carbon Capture and Water Desalination

Nuclear energy can be used in carbon capture and water desalination [172]. Carbon capture refers to the process of capturing CO_2 emissions from power plants or other industrial sources before they are released into the atmosphere. Nuclear power plants produce electricity without emitting CO_2, so they can be used to generate electricity for carbon capture systems. There are several ways in which nuclear energy can be used to capture carbon:

- Integrated gasification combined cycle (IGCC) with carbon capture: this technology uses nuclear energy to power an IGCC plant, which converts coal or other fossil fuels into a gas. The gas is then cleared of impurities, and the CO_2 is separated and captured before it is released into the atmosphere [173];
- Hybrid nuclear-renewable power plants: nuclear energy can be combined with renewable energy sources, such as solar or wind power, to generate electricity. The excess heat generated by the nuclear reactor can be used to power a carbon capture system, which separates and captures CO_2 emissions [174];
- Direct air capture (DAC): nuclear energy can be used to power DAC systems, which remove CO_2 directly from the air. These systems use a combination of chemical and thermal processes to capture CO_2, which can then be stored or used for various industrial applications [175];
- Advanced nuclear-based process heating: nuclear energy can also be used to provide process heat for industrial processes, such as hydrogen production, that require high temperatures. This can also produce CO_2 as a by-product and capture it [176].

It is worth noting that CCS is a complex process and is still under development, and it may not be the most cost-effective or efficient way to reduce CO_2 emissions. It is also important to consider the full life cycle of these systems, including the energy required to build and maintain them, as well as the potential environmental impacts of storing the captured CO_2.

Water desalination is the process of removing salt and other minerals from seawater to make it potable [177]. Nuclear energy can be used to power the desalination process, which typically involves heating seawater to create steam, which is then used to drive a turbine and generate electricity. The electricity generated can then be used to power the reverse osmosis process, which removes salt and other minerals from the seawater.

3.14. Nuclear Energy Versus Renewables

The three main sources of renewable energy are solar energy, wind energy, and hydropower, while the source of nuclear energy is fission power [178,179]. Nuclear energy is a stable and consistent source of energy, regardless of the location of the power plant, while the efficiency of renewables is highly dependent on various external factors, such as geographical location, seasonality, and time of the day, making them less reliable at a large scale.

Carbon emissions are a major problem in the energy sector, and both the nuclear power plants and renewable-based power plants produce zero carbon emissions during operation, making them climate neutral. However, the mining and processing of radioactive materials for use as fuel in nuclear power plants, as well as the mining and production of materials required for renewable energy systems, do produce carbon emissions [130,131]. Therefore, emissions cannot be used as a decisive argument for one option or the other.

Nuclear power plants have the advantage of requiring much less territory than renewable-based power plants to produce the same amount of electricity. This is particularly true for SMRs when compared to, for example, wind farms. Additionally, the lifetime of conventional nuclear power plants is around 40 years, with the potential for extension of up to 60 years, while the lifetime of renewable energy technologies, such as wind turbines and solar panels, is limited to around 20 years [180,181].

Another important aspect to consider when choosing an energy source is the waste generated as a result of energy production. Renewable energy sources generate a significant amount of waste due to the materials used to generate electricity and their comparatively shorter lifetime. In contrast, radioactive waste from nuclear power plants can be disposed of using deep geological repositories, and the radioactivity of the waste declines over time [182–184].

Reliability is an important factor when choosing an energy source for electricity production. Nuclear energy is a stable and consistent source of energy, while renewable energy does not provide a steady flow of energy. For example, solar power cannot generate electricity at night, and wind turbines do not generate electricity when wind is not blowing. Furthermore, the efficiency of hydropower generation decreases as the water level of rivers drops. Due to the unreliability of renewable energy, research is being conducted on energy storage approaches, but current battery technology is not yet advanced enough to provide a consistent energy source.

In conclusion, while renewable energy sources such as solar, wind, and hydropower are sustainable and renewable, they may not provide a consistent energy source for the growing demands of the civilization. Nuclear energy, on the other hand, is a stable and consistent source of energy and can provide a reliable source of electricity while also being climate neutral. However, it is important to take into consideration the environmental impact, waste generation, and safety risks associated with nuclear energy. An optimal energy mix would likely involve a combination of renewable energy sources and nuclear energy, with continued research and development in both areas to improve efficiency and reduce negative impacts.

4. Discussion

The transition to a carbon-free energy system is an ongoing and complex process, requiring the implementation of multiple strategies to accelerate the transition. One approach is to reduce dependency on fossil fuels by utilizing alternative sources of energy, such as nuclear energy, in situations where renewable resources are not readily available. Additionally, decreasing carbon emissions from the electricity grid beyond the capabilities of conventional clean energy sources can be achieved by accelerating the deployment of innovative technologies and phasing out fossil fuels. To achieve this, promoting the electrification of buildings, transportation, and other sectors and ensuring they are powered by carbon-free energy is crucial [2–9]. Improving grid resilience by incorporating a diverse range of carbon-free energy technologies to provide round-the-clock electricity, and directing support efforts to regions where access to carbon-free energy is limited due to policy or market constraints are also important considerations. Moreover, enhancing the health and living conditions of communities affected by fossil fuel production is also a crucial step.

Currently, the world's electricity generation is primarily reliant on fossil fuels (62%), with 28% coming from renewables and only 10% coming from nuclear energy [185–187]. This reliance on fossil fuels is driving an increase in GHG emissions. Despite the gradual shift toward low-carbon technologies and an increasing mastery of renewable resources, the pace of the transition is not sufficient to address the urgent need for decarbonization. Energy efficiency is a critical component in the process of decarbonization, as it involves using less energy to perform the same task. This not only reduces energy waste, but also brings a variety of benefits such as reducing GHG emissions, reducing the demand for energy imports, and lowering costs at both household and economy-wide levels, all which are essential in mitigating climate change.

The utilization of fossil fuels is posing an immediate threat to the climate and living conditions on Earth, is unsustainable in the long term due to finite resource availability. As a result, significant focus has been placed on the development and implementation of renewable energy sources. These alternative energy sources are viewed as a potential solution to the depletion of fossil fuels and have thus attracted significant investment, leading to advancements and innovations in the field. However, there is also a trend toward phasing out nuclear energy due to perceived risks [166,188]. It is important to note, however, that abandoning nuclear energy at this time, particularly in light of the current energy crisis and the need for sustainable energy development in the future, may not be a prudent decision.

While renewable energy sources are often touted as the future of energy production, current technological limitations, particularly in regard to energy storage, necessitate the use of supplementary, emission-free sources of power [116–119]. Nuclear energy, as a proven and efficient energy source, may serve as a viable option to support and backup electricity generated by renewables. Additionally, the excessive allocation of resources toward the development and implementation of renewable energy sources, such as solar and wind, may not be the most efficient use of resources due to the low efficiency and reliability of these energy sources. Therefore, increased investment in nuclear power may be necessary to bridge this knowledge gap, promote progress in the field, and ensure a reliable and efficient source of emission-free energy.

It is difficult to say whether Latvia can afford an SMR without more information on the specific costs and financing options for the project, as well as Latvia's current budget and economic situation. However, it is worth noting that SMRs are generally considered to be less expensive to build and operate than traditional large-scale nuclear power plants. This is partly because they are smaller and therefore require less initial investment and less complex infrastructure, and partly because they are designed to be factory-built, which can reduce construction costs [43–46]. Additionally, they can be built in smaller numbers than large reactors, which can also reduce costs. That being said, Latvia's economy is relatively small, and it may not have the financial resources to invest in a small modular reactor on its own. The country would likely have to secure funding from external sources, such as international organizations or other countries. Additionally, it is important to consider the regulations, laws and the public acceptance of such technology in Latvia as well.

5. Conclusions

The main objective of this review was to present a compelling argument for the utilization of nuclear energy in meeting the rapidly increasing demand for electricity, and to evaluate its potential role in the future of green energy. The findings of this review provide initial evidence of the beneficial properties of nuclear energy and support the development and implementation of SMR technology, which can both generate electricity and reduce carbon emissions. However, it is important to acknowledge that certain political considerations and strong opposition may hinder the practical application of these findings. Therefore, the authors argue that there is a fundamental need for public education about the benefits and safety of nuclear energy.

Nuclear energy is essential in addressing climate change and reducing GHG emissions, while providing a significant and growing amount of electricity. Society needs to be aware of the potential of this form of energy and how it can quickly transition away from fossil fuels. Additionally, SMRs can be combined with renewable energy sources to create a hybrid energy system, thus increasing the efficiency of renewable resources. Nuclear energy is a safe, sustainable, and carbon-free form of energy with enormous potential, but fear relating to nuclear energy is often irrational and based on political propaganda and "greenwashing". Together with renewables, nuclear energy is the only low-carbon source of energy that can replace fossil fuels with the current technology and discoveries.

Further research is needed to examine the potential of nuclear energy in the green energy mix at a local scale, as well as develop proposals for energy-efficient nuclear reactors and explore the nature of nuclear waste disposal and recycling in more detail. Additionally, assessing the potential of nuclear energy for small economies would be an important step in evaluating its significance in ensuring energy stability and independence for small countries. To further advance the utilization of nuclear energy as a low-carbon source of energy, potential recommendations for future work include conducting more research to explore its potential in the green energy mix at a local scale, developing proposals for energy-efficient nuclear reactors, assessing its significance for small economies, exploring nuclear waste disposal and recycling in more detail, and developing public education campaigns that emphasize the benefits and safety of nuclear energy to counteract political propaganda and "greenwashing." It is important to continue addressing limitations and expanding on the promising conclusions presented in the review paper to help meet the goals of the Paris Agreement, and provide a steady and reliable source of electricity necessary for running and growing advanced economies, as well as enabling developing countries to boost economic output and raise living standards.

In conclusion, the current review provides evidence of the high importance of nuclear energy in addressing the ongoing climate and resource crisis. In order to meet the goals of the Paris Agreement, the use of renewables will continue to grow; however, it is important to emphasize that nuclear energy already provides a steady and reliable source of electricity necessary for running and growing advanced economies, and for enabling developing countries to boost economic output and raise living standards. Future research should focus on addressing limitations and expanding on the promising conclusions presented in this review.

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