Resende PR, et al., J Nucl Ene Sci Power Generat Technol 2023, 12:2

Journal of Nuclear Energy Science & Power Generation Technology

Review Article

A SCITECHNOL JOURNAL

The Contribution of Nuclear Technology to the Sustainability of the Global Energy Matrix and the Mitigation of Climate Change

Pedro R Resende[1], Maria LP Antunes[2], Leandro C Morais[2] and Leonel JR Nunes[1,3,4*]

[1]Prometheus, Unidade de Investigação em Materiais, Energia e Ambiente para a Sustentabilidade, Escola Superior Agrária, Instituto Politécnico de Viana do Castelo, Rua da Escola Industrial e Comercial de Nun'Alvares, 4900-347 Viana do Castelo, Portugal

[2]São Paulo State University (UNESP), Institute of Science and Technology, Sorocaba/SP - CEP 18087-180, Brazil

[3]Departamento de Economia, Gestão, Engenharia Industrial e Turismo, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

[4]GOVCOPP, Unidade de Investigação em Governança, Competitividade e Políticas Públicas, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

***Corresponding author:** Leonel JR Nunes, PROMETHEUS, Unidade de Investigação em Materiais, Energia e Ambiente para a Sustentabilidade, Escola Superior Agrária, Instituto Politécnico de Viana do Castelo, Rua da Escola Industrial e Comercial de Nun'Alvares, 4900-347 Viana do Castelo, Portugal; E-mail: leonelnunes@esa.ipvc.pt

Received date: 27-Mar-2023, Manuscript No. JNPGT-23-92934;

Editor assigned date: 29-Mar-2023, PreQC No. JNPGT-23-92934 (PQ);

Reviewed date: 13-Apr-2023, QC No. JNPGT-23-92934;

Revised date: 21-Apr-2023, Manuscript No. JNPGT-23-92934 (R);

Published date: 01-May-2023 DOI: 10.4172/2325-9809.1000332.

Abstract

Nuclear energy is generated through the fission of atomic nuclei in nuclear reactors. The produced energy is extremely concentrated, which signifies that the amount of fuel needed to generate substantial quantities of electricity is relatively small compared to other energy sources. Furthermore, nuclear energy is highly reliable and stable, providing a consistent energy source. However, safety remains a significant concern in nuclear power generation. The Chernobyl accident in 1986, and the Fukushima disaster in 2011, illustrated the perils of poorly managed nuclear energy. Security failures in nuclear plants can result in radioactive leaks, environmental contamination, and threats to public health. Although technological advancements have enhanced nuclear energy safety, nuclear waste management remains a substantial challenge. Upon usage, nuclear fuel becomes hazardous nuclear waste that must be safely stored for hundreds of years. Secure management of nuclear waste is crucial in minimizing the environmental impact of nuclear energy. Another concern is the utilization of vast amounts of water for cooling nuclear reactors. While water is essential for maintaining reactor operations, excessive water usage may have negative impacts on the environment and local communities. In comparison to other energy sources, such as oil, coal, and natural gas, nuclear energy emits significantly fewer greenhouse gases. This is because nuclear energy does not burn fossil fuels to generate electricity. Nevertheless, nuclear energy also has other environmental impacts, including the release of small amounts of radiation during the normal operation of a power plant.

Keywords: Nuclear energy; Safety concerns; Nuclear waste management; Environmental impacts; Climate change mitigation

Introduction

Nuclear energy is an energy source that has been utilized worldwide for over half a century [1]. Nuclear technology employs the process of atomic nucleus fission, wherein atoms are split into two smaller parts, releasing a vast amount of energy in the form of heat, as shown in Equation 1 [2]. This heat is used to generate steam, which drives turbines that power electricity generators [3]. One of the advantages of nuclear energy is that it can be a cleaner and more efficient alternative to other forms of energy, such as coal, oil, and natural gas, which are responsible for a significant amount of greenhouse gas emissions [4]. Nuclear energy can produce substantial amounts of energy with a relatively small amount of fuel, making it an economical option [5]. Another advantage of nuclear energy is that it is a baseload energy source, meaning it is capable of generating electricity in a stable and reliable manner, regardless of weather conditions or seasonality [6]. This implies that nuclear energy can provide continuous and predictable electricity, which is essential for ensuring energy security and preventing power supply disruptions [7]. However, nuclear energy also presents significant challenges and risks, including the possibility of nuclear accidents, the production of hazardous radioactive waste, and nuclear proliferation [8]. It is therefore crucial that nuclear energy be managed with care and that safety remains the utmost priority at every stage of the process.

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3\,{}_{0}^{1}n + Energy \quad (1) $$

There are currently around 440 nuclear reactors in operation worldwide, generating approximately 10% of global electricity [9]. Countries such as the United States, China, and Japan are significant producers of nuclear energy. The main nuclear energy producers in Europe are France, Russia, Germany, Sweden, Spain, Ukraine, and the United Kingdom. Nuclear energy is also used in other European countries, including Belgium, Switzerland, the Czech Republic, Finland, Hungary, Slovakia, and Slovenia. However, some countries, such as Austria, Denmark, Ireland and Portugal, do not have nuclear power plants and do not produce nuclear energy. Nonetheless, countries without nuclear power plants consume nuclear energy purchased from other countries that produce nuclear energy. This energy can be imported *via* interconnected electricity grids or through energy purchasing and trading contracts. For example, Portugal does not have nuclear power plants, but imports nuclear energy from countries such as France or Spain.

Nuclear energy presents several advantages over other forms of energy. One of the primary advantages is the high energy density of nuclear fuel, which is far greater than other forms of energy, such as coal and oil [10]. Nuclear energy production is stable and reliable, making it an important energy source for countries that require constant and dependable power [11]. Another significant advantage of nuclear energy is the substantial reduction in greenhouse gas emissions compared to other energy forms [12]. However, nuclear energy is controversial due to concerns about safety and environmental impact. The Chernobyl nuclear disaster in 1986 and the Fukushima nuclear accident in 2011 underscored the potential risks associated with nuclear energy. The Chernobyl disaster is considered the worst nuclear accident in history [13]. It occurred on April 26, 1986, at the Chernobyl nuclear power plant in Ukraine. During a safety test, an explosion occurred in nuclear reactor number 4, releasing large amounts of radioactive material into the atmosphere. The explosion destroyed the reactor and caused a fire that continued to burn for several days. The accident resulted in the immediate death of two plant workers. Subsequently, about 134 people were diagnosed with acute radiation syndrome, and 28 of these individuals died within the first few months following the accident. The total number of deaths related to the accident is difficult to estimate, but it is believed that the number of fatalities related to the accident could reach around 4,000. The Chernobyl disaster had a significant impact on the environment and public health. The area surrounding the power plant was evacuated and remains uninhabitable until now. The radiation released by the accident contaminated vast areas in Ukraine, Belarus, and Russia. The radioactive contamination adversely affected people's health as well as wildlife and the environment. It is estimated that the radiation exposure caused by the Chernobyl disaster has increased cancer risk throughout the region. The Chernobyl disaster highlighted the importance of nuclear safety and nuclear waste management. Since the disaster, more stringent safety measures have been implemented in nuclear power plants worldwide to minimize the risk of accidents. Furthermore, the proper management of nuclear waste is a growing concern as more countries seek to expand their nuclear capacity.

The Fukushima disaster is considered the second-worst nuclear accident in history, following Chernobyl [14]. It occurred on March 11, 2011, when a magnitude 9.0 earthquake struck the northeastern coast of Japan, followed by a tsunami. The earthquake and tsunami caused significant damage to the Fukushima Daiichi nuclear power plant, resulting in a series of explosions and radioactive leaks. There were no immediate radiation-related deaths, but several plant workers were exposed to radiation. The radioactive contamination of the area surrounding the plant led to large-scale evacuations. The disaster caused a humanitarian and economic crisis in Japan. The Fukushima disaster highlighted the importance of nuclear safety and nuclear waste management. Since the disaster, more stringent safety measures have been implemented in nuclear power plants worldwide to minimize the risk of accidents. Proper management of nuclear waste is also a growing concern, and Japan has faced difficulties in dealing with the large volume of nuclear waste generated by the disaster. The Fukushima disaster also had a significant impact on the environment. The radioactive contamination of air, water, and soil in the area surrounding the plant has caused ongoing concerns about public health and food safety. Local fishing and agriculture have been severely affected by the disaster, and the cleanup of the area remains a significant challenge.

Since the Fukushima accident in 2011, there have been no significant large-scale nuclear accidents. However, there have been some smaller incidents that have raised safety concerns at nuclear power plants worldwide. For example, in 2016, one of the reactors at the Flamanville nuclear power plant in France experienced a fire, which caused safety concerns and led to the suspension of the plant's operations [15]. Although the fire did not result in deaths or injuries, it underscored the importance of safety at nuclear power plants.

Prior to the Chernobyl disaster in 1986, there were other significant nuclear accidents around the world. In 1957, an accident occurred at the Mayak nuclear facility in Russia, resulting in an explosion that released large amounts of radioactive material into the atmosphere [16]. Approximately 200,000 people were affected by the resulting contamination, leading to the evacuation of several villages. In 1961, there was an accident at the SL-1 nuclear power plant in Idaho, United States [17]. The accident resulted in an explosion that killed three plant workers, marking the first fatal accident at a nuclear power plant in the United States. In 1979, an accident occurred at the Three Mile Island nuclear power plant in Pennsylvania, also in the United States [18]. The accident was caused by a failure in the reactor's cooling system, leading to a partial core meltdown. Although the accident did not result in immediate deaths, it caused significant concerns about the safety of nuclear power plants and led to a suspension of new nuclear power plant construction in the United States.

These disasters have raised concerns about the safety of nuclear reactors and nuclear waste management. Uranium mining and nuclear waste management can have a significant impact on the environment [19]. The process of nuclear power generation produces highly radioactive nuclear waste, which remains hazardous for thousands of years [20]. While some countries opt to store nuclear waste in underground facilities, others choose to reprocess used nuclear fuel to recover uranium and plutonium [21]. Nuclear power also raises concerns about nuclear proliferation [22]. Nuclear energy can be used for military purposes, and the enrichment of uranium and the production of plutonium for use in nuclear reactors can be employed to produce nuclear weapons [23].

The construction of nuclear power plants is an expensive and complex process, making nuclear energy less accessible for some countries [24]. The cost of nuclear waste management is also significant and adds to the overall expense of nuclear power [25]. Although, nuclear power can reduce dependence on fossil fuels, the use of fossil fuels is still required to produce enriched uranium and construct nuclear power plants [26]. The mining of uranium and other materials necessary for nuclear power can also have a significant environmental impact [27]. Due to these concerns, many countries are seeking alternative energy sources, such as wind and solar power, to reduce their reliance on nuclear energy [28]. However, nuclear power remains an important energy source worldwide and will continue to play a significant role in global energy production in the future.

The aim of this article is to provide a detailed analysis of nuclear energy, comparing its advantages and disadvantages with other energy sources. Furthermore, the key components of nuclear technology, including nuclear reactors, nuclear fuel, cooling systems, and nuclear waste storage, will be assessed. Safety concerns related to nuclear power, such as nuclear accidents, waste management, and storage security, will be discussed. The environmental impact of nuclear energy in comparison with other energy sources, such as oil, coal, and natural gas, will also be evaluated. The ultimate goal is to provide a comprehensive review of nuclear energy, discussing the pros and cons of this form of power generation and analyzing its potential contribution to climate change mitigation and the sustainability of the global energy matrix.

Technology, Fuels and Safety

Energy production

There are various different types of nuclear reactors in use today, each with its own design and characteristics. Pressurized Water Reactors (PWRs) are the most common type of nuclear reactor in use today [29]. They use water as a coolant and moderator, and enriched uranium is inserted into fuel rods. The water circulates through the reactor core to remove the heat generated by nuclear fission and transfer it to secondary circulating water, which is used to generate steam and drive electricity-generating turbines. Boiling Water Reactors (BWRs) are similar to PWRs but use water as both coolant and moderator, and the water that circulates through the reactor cores are used directly to generate steam and drive electricity-generating turbines [30]. Heavy water reactors (CANDU) utilize heavy water (deuterium oxide) as a coolant and moderator, and natural uranium is inserted into fuel elements of tubes [31]. The use of heavy water allows the reactor to utilize natural uranium without the need for enrichment, making it more cost-effective than reactors that use enriched uranium. Molten Salt Reactors (MSRs) employ a molten salt as both fuel and coolant [32]. The salt is pumped through a closed loop to remove the heat generated by nuclear fission and transfer it to a secondary salt stream, which is used to generate steam and drive electricity-generating turbines. MSR reactors have the ability to reprocess their spent fuel while still in operation, making them potentially more efficient than other types of nuclear reactors. Small Modular Reactors (SMRs) are smaller, modular nuclear reactors that are less sizeable than traditional nuclear reactors [33]. They are designed to be more flexible and easier to construct than larger nuclear reactors. SMR reactors typically use enriched nuclear fuel in a water-cooled reactor core, which is used to generate steam and drive electricity-generating turbines.

The different types of nuclear reactors have distinct advantages and disadvantages [34-36]. PWRs have low fuel costs and can produce a large amount of electricity efficiently. However, they can be vulnerable to cooling system failures and may generate hazardous nuclear waste. BWRs, similar to PWRs, can also produce electricity efficiently but share the same vulnerabilities and nuclear waste risks. CANDU have the advantage of being able to use natural uranium as fuel, which is more abundant than enriched uranium. Also produce less hazardous nuclear waste than other types of reactors and can be used in remote areas without access to enriched uranium. However, the use of heavy water makes the process more expensive and difficult to manage, and the tubular fuel elements are more costly and challenging to manufacture. The CANDU is less tested than other types of reactors. MSR are potentially more efficient than other types of nuclear reactors and can reprocess their used fuel while still in operation. They can also use either natural or enriched uranium fuel. However, they are less tested than other types of reactors and may experience corrosion issues with the prolonged use of molten salts. They can also be costly to construct and maintain. SMR are less expensive to construct and maintain than traditional nuclear reactors and can be installed in areas with limited space. They generate less hazardous nuclear waste but produce less electricity than traditional nuclear reactors.

Although nuclear power is a clean and efficient source of energy, nuclear technology still faces many challenges and concerns [37]. In addition to the issues already mentioned, nuclear technology faces questions related to safety and nuclear proliferation. The enrichment of uranium and the production of plutonium for use in nuclear reactors can also be used to produce nuclear weapons, raising concerns about security and nuclear proliferation. The utilization of nuclear technology has also been subject to critical scrutiny for its dependence on fossil fuels for the production of enriched uranium and construction of nuclear power plants [38]. The mining of uranium and other essential materials in the nuclear industry may result in a substantial environmental impact, encompassing the release of radioactive waste [39].

Nuclear fuels

Uranium is the most commonly used nuclear fuel for electricity production, and its exploration and extraction are carried out in mines across the world [40]. Natural uranium is primarily composed of the isotope U-238, which is relatively stable, and the isotope U-235, which is fissile, meaning it is capable of sustaining a nuclear chain reaction [41]. Natural uranium is processed and enriched to increase the proportion of U-235 for use in nuclear reactors [42-44]. The enriched uranium is then fabricated into nuclear fuel, which is inserted into nuclear reactors. Plutonium is produced as a byproduct of the nuclear fission process that occurs in the core of a nuclear reactor when uranium is bombarded by neutrons. Plutonium can be recycled and reused as fuel in some types of nuclear reactors, such as fast neutron reactors. Plutonium can be used as a material for nuclear weapons, which has led to international concerns regarding the control and monitoring of nuclear materials. Aside from uranium and plutonium, there is ongoing research into the use of other elements as alternative nuclear fuels. Thorium is one such alternative fuel being investigated [45]. Thorium is more abundant in the Earth's crust than uranium and has the advantage of producing less radioactive waste. However, thorium is not yet widely used in nuclear power production and is considered an experimental fuel.

The management of nuclear waste from power plants is a critical and complex process that requires careful planning, implementation, and monitoring to ensure the safety of workers, the public, and the environment [46]. The process typically involves waste classification, storage, treatment, transportation, and disposal. Nuclear waste is categorized based on its radioactivity levels, half-life, and heat generation into Low Level Waste (LLW), Intermediate Level Waste (ILW) and High Level Waste (HLW) [47-50]. LLW consists of items such as protective clothing, tools, and filters contaminated with radioactive materials, while ILW includes resins, sludge, and reactor components. HLW primarily consists of spent nuclear fuel and waste produced from reprocessing spent fuel. Initially, nuclear waste is stored on-site at the power plant, often in spent fuel pools or dry storage casks. Spent fuel pools are large, water-filled basins that provide cooling and radiation shielding, while dry storage casks are large, robust containers that store spent fuel after it has cooled sufficiently in the pools. Various treatment methods are used to reduce the volume, stabilize the form, or remove contaminants from the waste, depending on its type. For example, LLW can be compacted, incinerated, or encapsulated in concrete or other materials. ILW may undergo processes like solidification or vitrification, where waste is mixed with glass and melted to create a stable, solid product. HLW is often vitrified as well. When off-site disposal or storage is necessary, nuclear waste is transported using specialized containers designed to provide radiation shielding and prevent leakage in case of accidents. Transportation is carefully regulated, and security measures are in place to protect against theft or sabotage. The final disposal of nuclear waste depends on its classification. LLW and ILW are typically disposed of in near-surface repositories, such as engineered landfills or concrete vaults, designed to isolate the waste from the environment and protect against intrusion. HLW requires deep geological repositories, where waste is placed in robust containers and buried several hundred meters underground in stable geological formations, designed to prevent the release of radioactivity for thousands of years.

Nuclear safety

Safety is a major concern in the nuclear industry, and nuclear accidents have demonstrated the devastating potential of a nuclear incident [51]. Nuclear reactors must be built with stringent safety measures to ensure that an accident does not occur [52]. These measures include redundant safety systems, radiation sensors, protection against overload, and automatic shutdown mechanisms. Proper training of plant workers is also essential to ensure that safety procedures are followed correctly. In addition to nuclear accidents, the safe management of nuclear waste is a significant challenge [53]. The storage of nuclear waste must be managed carefully to ensure that there is no leakage of radioactive material into the environment [54]. Highly radioactive nuclear waste is stored in steel and concrete containers and, in some cases, buried deep in underground storage facilities [55]. Storage facilities must be built to withstand natural disasters, such as earthquakes and floods, and must be continuously monitored to ensure safety. Nuclear safety is an ongoing concern in the nuclear industry and requires the careful attention of engineers, technicians, and managers to ensure that nuclear reactors are safe and that nuclear waste is stored securely [56]. With proper awareness and management, it is possible to produce nuclear electricity safely and efficiently [57].

Nuclear waste management is a crucial issue in the nuclear industry. Among the challenges associated with nuclear waste management, the safe and effective storage stands out, involving the use of robust and sealed containers to prevent leakage into the environment. This process is long-term and requires significant planning and investment. The transportation of nuclear waste is a significant security risk, requiring strict measures to protect against accidents and ensure public safety. Nuclear waste management is also expensive and complex, with significant costs for storage and long-term financing to ensure coverage of these costs [58].

Decommissioning a nuclear power plant is a complex and costly process that involves several stages, each requiring careful planning, extensive resources, and adherence to strict regulatory standards [59]. The process of dismantling the nuclear reactor and removing all associated equipment and materials can take years, even decades, and poses a significant challenge in nuclear waste management [60-62]. The first stage of decommissioning is pre-decommissioning planning, which involves assessing the plant's condition, determining decommissioning strategies, estimating costs, and developing a detailed decommissioning plan. This plan must address various aspects, such as radiological assessments, waste management strategies, environmental impact, and health and safety considerations. Next comes the safe shutdown and defueling of the reactor. The spent fuel is removed from the reactor core and transferred to a spent fuel pool or dry storage casks, which is crucial for reducing the radiological risk associated with the decommissioning process. Following shutdown and defueling, the plant undergoes decontamination and dismantling. This stage involves removing radioactive contaminants from the surfaces of structures, systems, and components within the plant. Decontamination methods may include chemical, mechanical, or thermal techniques. Once decontamination is complete, the dismantling of the reactor and other plant structures can begin, with the careful segregation of radioactive and non-radioactive waste. Waste management is a critical aspect of the decommissioning process. All waste generated, including radioactive and non-radioactive materials, must be managed according to regulatory requirements. Radioactive waste must be categorized, packaged, and transported to appropriate storage or disposal facilities. Non-radioactive waste can be recycled or disposed of in conventional waste facilities. Site remediation follows waste management and involves restoring the site to meet environmental and radiological criteria for its intended future use. Contaminated soil and groundwater may need to be remediated, and the site may be subject to ongoing monitoring to ensure that no residual radioactivity remains. The final stage is the release of the site. Once all decommissioning activities are complete and regulatory requirements have been met, the site can be released for unrestricted or restricted use, depending on the levels of residual radioactivity. Decommissioning a nuclear power plant is a challenging and resource-intensive process that requires careful planning, execution, and oversight to ensure the safety of workers, the public, and the environment. The cost of decommissioning can be significant, but it is an essential aspect of responsible nuclear power management, ensuring that nuclear facilities are safely and effectively retired at the end of their operational lives.

Nuclear Energy and the Global Energy Mix

Nuclear energy is one of the available options for reducing greenhouse gas emissions and mitigating climate change [63]. This is because nuclear energy is a clean source of energy that does not emit carbon dioxide or other greenhouse gases during electricity production [64]. Nuclear energy can be used to produce electricity more sustainably and with less environmental impact. It is also a reliable and safe source of energy that can help ensure energy security and diversify the energy mix. This is particularly important in a world where dependence on fossil fuels can lead to energy security issues such as supply disruptions and price volatility. Nuclear energy can reduce dependence on fossil fuels and protect against fuel price volatility [65].

Another way in which nuclear energy can contribute to sustainability is through its capacity to be used for non-electric purposes, such as desalination of water [66]. Desalination is a process that requires a significant amount of energy and can be facilitated by the use of nuclear energy [67]. This is particularly important in regions of the world where the availability of potable water is a challenge. While nuclear energy has its benefits in terms of sustainability and decarbonizing the global energy mix, it is important to note that nuclear energy is not a perfect solution. The safe and effective management of nuclear waste is a significant challenge, and the development of more advanced nuclear reactor technologies and nuclear waste management methods is still needed. Nuclear energy can be expensive and complex compared to other forms of renewable energy [68].

Public perception and trust are significant challenges for nuclear energy, especially in the aftermath of nuclear accidents such as Chernobyl and Fukushima [69-72]. These events have had a lasting impact on public opinion and have led to skepticism and opposition towards nuclear power [73]. This can make it difficult to secure the necessary political and financial support for the development and expansion of nuclear energy. One reason for public skepticism towards nuclear energy is the potential for catastrophic accidents. The risk of nuclear accidents, though relatively low, can have severe consequences for public health and the environment. Moreover, the long-term impacts of nuclear waste and the potential for nuclear weapons proliferation can also contribute to public concerns about the safety and security of nuclear energy [74]. In addition to safety concerns, public perception of nuclear energy can also be influenced by issues of transparency and accountability. The nuclear industry must be open and transparent about its activities, including nuclear waste management, safety procedures, and the potential risks associated with nuclear energy [75]. This can help build public trust and confidence in the industry. Public perception of nuclear energy can also be influenced by political and economic factors [76]. Nuclear energy requires significant government support and financing, and political opposition to nuclear energy can make it difficult to secure the necessary funding and resources. The high upfront costs of building nuclear power plants can be a significant barrier to the development and expansion of nuclear energy, especially in developing countries.

Nuclear power plants require significant capital investment and can take years to plan and construct, making them less flexible and adaptable than other renewable energy sources such as solar or wind power [77]. The complexity of nuclear power plants and the regulatory requirements associated with their construction and operation can add to the overall cost and lead time [78]. This can make nuclear energy less accessible to smaller-scale energy providers or developing countries that may not have the financial resources or regulatory infrastructure to support nuclear power generation. The high capital costs associated with nuclear energy can have a significant impact on energy prices. These costs must be factored into the price of electricity generated by nuclear power plants, making them less competitive than other forms of energy that have lower capital costs and shorter lead times [79]. This can limit the market demand for nuclear energy, particularly in regions where energy prices are a key consideration for consumers [80].

Despite the challenges associated with nuclear energy, there are some who argue that it is a necessary component of a low-carbon energy mix [81]. Nuclear power plants have the capacity to generate large amounts of reliable, base load power that can complement the variability of solar and wind power [82]. This can help ensure a stable and resilient energy system that can meet the demands of modern societies while reducing greenhouse gas emissions. Ongoing research and development efforts in nuclear technology, such as SMRs, could potentially reduce the cost and lead time of nuclear power plants and make them more accessible to a wider range of energy providers [83]. SMRs are designed to be smaller and more flexible than traditional nuclear power plants, with the potential for faster construction times, lower capital costs, and greater scalability. Some also argue that SMRs could be used to power remote or off-grid communities, providing a reliable source of energy where traditional grid infrastructure is unavailable or unreliable. Advancements in nuclear fuel technology, such as the development of thorium-based nuclear reactors, could potentially increase the efficiency and safety of nuclear power generation while reducing the amount of nuclear waste produced. These technologies could help address some of the environmental and safety concerns associated with traditional nuclear power generation and make nuclear energy a more viable option for the future.

The Environmental Impact of Nuclear Energy

With the growing global demand for electricity, nuclear energy can be an important solution to help meet this need. Nuclear reactors can operate for longer periods than coal or gas-fired power plants, requiring fewer interruptions and maintenance, which makes them a cost-effective and safe option [84]. Another advantage of nuclear energy is its high energy density, meaning that a small amount of nuclear fuel can generate a large amount of electricity [85]. This makes nuclear energy more resource-efficient and can help reduce dependence on non-renewable fossil fuels. However, nuclear energy presents significant challenges related to safety and nuclear waste management. Nuclear accidents, such as the Chernobyl disaster in 1986 and the Fukushima accident in 2011, highlight the potential danger associated with nuclear energy.

The issue of nuclear proliferation is a major concern surrounding nuclear energy, and it is one that has been the subject of much debate and controversy [86]. Nuclear proliferation refers to the spread of nuclear weapons, technology, or materials to states or non-state actors who do not currently possess them [87]. It is a complex issue with far-reaching implications for global security and stability [88]. To mitigate these risks, it is essential that countries with nuclear technology take measures to ensure that access to nuclear materials is strictly controlled and that rigorous security measures are in place to prevent unauthorized access. This includes measures such as background checks, physical security measures, and the use of advanced technology to detect and deter potential threats. It is essential for nations with nuclear technology to work together to promote nuclear non-proliferation and disarmament. The Nuclear Non-Proliferation Treaty, signed by over 190 countries, is a vital tool in preventing the spread of nuclear weapons and technology [89]. The treaty requires states to pursue disarmament, maintain safeguards to prevent the diversion of nuclear materials for military purposes, and facilitate the peaceful use of nuclear energy.

Despite its potential benefits, the nuclear energy industry has continued to face environmental criticisms due to its significant environmental impact [90]. The production of nuclear energy involves the mining and processing of uranium, which is an energy-intensive process and can have a negative impact on the environment [91]. Uranium mining involves the extraction of uranium ore from the earth, which can result in soil and water pollution [92]. The use of heavy machinery and equipment during the mining process can also lead to the emission of greenhouse gases and other pollutants into the atmosphere [93]. The health of miners may be at risk, as they may be exposed to radioactive materials during the mining process [94]. In addition to the environmental impact of uranium mining, the processing of uranium also poses environmental risks [95]. The conversion of uranium ore into nuclear fuel involves several processes, including milling, enrichment, and fuel fabrication. During these processes, there is a risk of radioactive materials being released into the environment, which can cause long-term harm to both human health and the environment [96-99].

The storage and disposal of nuclear waste is another significant environmental concern associated with nuclear energy [100]. Nuclear waste is highly radioactive and can remain hazardous for thousands of years [101]. Safe and effective disposal of nuclear waste is critical, as any leakage or release into the environment could have severe consequences. Therefore, it is crucial that the nuclear energy industry implements effective measures to minimize its environmental impact. Governments and companies must ensure that uranium mining is carried out responsibly, with proper measures in place to prevent soil and water pollution and protect the health and safety of workers. Additionally, the industry must prioritize the development of safe and secure methods for the storage and disposal of nuclear waste.

The management of nuclear waste presents yet another significant environmental challenge associated with the nuclear energy industry. Safe storage of highly radioactive nuclear waste is a major technical and regulatory challenge [102]. Currently, there is no final solution for the management of nuclear waste, and long-term storage remains a contentious issue. The challenge is to ensure that nuclear waste is stored securely and effectively for the duration of its hazardous life span. This requires the development of safe, stable, and long-lasting storage facilities that can isolate the waste from the environment and prevent the release of radioactive materials. One of the main difficulties in managing nuclear waste is the sheer volume of waste produced by the nuclear industry. Spent nuclear fuel and other radioactive waste materials continue to accumulate, and the capacity of current storage facilities is limited. The construction of new nuclear waste storage facilities is a complex and lengthy process that requires significant technical expertise and regulatory approval [103]. The nuclear energy industry must prioritize the development of safe and effective methods for the management and disposal of nuclear waste. This involves not only the development of new storage facilities but also the implementation of strict regulatory standards and continuous monitoring to ensure the safety of workers, the public, and the environment.

In addition to the aforementioned challenges, nuclear energy also presents other significant environmental impacts. One of the primary concerns is the use of large amounts of water to cool nuclear reactors [104]. This is because water is used as a coolant to absorb the heat generated by nuclear fission in the reactor core. The water circulates through the reactor and is then released back into the environment at higher temperatures. This process can have a negative impact on the water quality of the receiving body, particularly if used in areas with water scarcity. The release of warm water can affect aquatic life and flora in the vicinity of the nuclear power plant [105]. Another environmental impact of nuclear energy is the release of small amounts of radiation during normal plant operation [106]. While these amounts are insignificant compared to the risks associated with nuclear accidents, they still pose a risk to public health and the environment. Radiation can affect local flora and fauna, as well as humans living in the vicinity of the nuclear power plant [107].

Although nuclear energy production can generate negative environmental impacts, such as soil and water contamination and energy consumption for nuclear fuel production, it is one of the available options for reducing greenhouse gas emissions and mitigating climate change. This is due to the fact that nuclear energy is a clean source of energy that does not emit carbon dioxide or other greenhouse gases during electricity production. Nuclear energy can provide a reliable source of electricity that can help replace electricity production from fossil fuels, which are responsible for a significant portion of greenhouse gas emissions. Nuclear energy can help diversify the energy mix, reduce dependence on fossil fuels, and ensure energy security. With effective management of environmental impacts and nuclear waste, nuclear energy can be an important part of the global energy mix to meet the increasing demand for electricity in a more sustainable manner. It is important to note that nuclear waste management and nuclear safety are important issues that need to be addressed to ensure that nuclear energy can be used safely and sustainably. Nuclear energy may not be appropriate or feasible in all regions of the world due to issues of cost, resources, and infrastructure. To minimize the environmental impacts of nuclear energy, responsible and sustainable uranium mining and processing must be adopted. It is important to adopt mining and processing technologies that minimize soil and water contamination and reduce the risk of exposure to radioactive materials. Additionally, nuclear fuel production should be carried out using renewable energy sources to minimize greenhouse gas emissions.

Future Developments of Nuclear Energy

Future developments in nuclear energy include technological advancements in various areas. One of these areas is the design of safer and more efficient nuclear reactors, such as fourth-generation nuclear reactors [108]. These reactors are designed to operate more efficiently, produce less nuclear waste, and be safer in the event of accidents. Another future development is the research of new nuclear fuels, including thorium and other elements that could be used as alternative fuels. Additionally, research into new nuclear reactor technologies, such as molten salt reactors, graphite core reactors, and high-flux reactors, may enable more efficient and safer nuclear power generation [109-111]. Other areas of research include the use of nuclear energy for desalination of water and the development of new techniques for nuclear waste storage.

Nuclear energy can also play an important role in integrating renewable energy sources into the energy mix. As renewable energy sources such as solar and wind are intermittent in nature, energy storage systems such as batteries and thermal storage systems are essential for balancing electricity supply and demand. Nuclear energy can be used to support these energy storage systems and provide a stable source of base load power to complement the variability of renewable energy sources [112]. For example, nuclear energy can be used to power the production of hydrogen through the electrolysis of water, which can be stored and used as a fuel for transportation or industrial processes. This can help reduce the dependence on fossil fuels in these sectors and contribute to de-carbonization efforts. Nuclear energy can be used to power Carbon Capture and Storage (CCS) technologies, which can capture carbon dioxide emissions from industrial processes and store them in underground [113]. This can help mitigate the environmental impact of these industries and reduce greenhouse gas emissions. Nuclear energy can also be used in hybrid energy systems that combine different energy sources, such as nuclear and renewable energy, to provide a more reliable and sustainable source of electricity. These hybrid systems can take advantage of the complementary strengths of different energy sources, such as the stable base load power of nuclear energy and the variability of renewable energy sources. This can help reduce the overall cost and environmental impact of the energy system and improve energy security.

The production of hydrogen using nuclear energy is a promising area of development for nuclear energy [114]. Hydrogen is a clean and versatile fuel that can be used in a wide range of applications, from industry to transportation. Currently, hydrogen production is dominated by processes that use fossil fuels, resulting in significant greenhouse gas emissions. However, the production of hydrogen using nuclear energy can be a viable and sustainable alternative [115]. Nuclear energy can be used to produce hydrogen in two ways: thermochemical electrolysis and electrochemical electrolysis [116]. Thermochemical electrolysis involves using heat generated by nuclear fission to break water into hydrogen and oxygen. Electrochemical electrolysis uses electricity generated by a nuclear reactor to split water into hydrogen and oxygen. Hydrogen production from nuclear energy can help to reduce dependence on fossil fuels and mitigate climate change. However, there are some challenges associated with hydrogen production from nuclear energy. One of the main challenges is cost. Hydrogen production from nuclear energy is currently more expensive than conventional methods, which limits its commercial viability. The transportation and storage of hydrogen present significant challenges and require additional investments in infrastructure [117]. With continuous advancements in technology and infrastructure, hydrogen production from nuclear energy could become a viable and sustainable alternative to fossil fuels in the near future.

Discussion and Conclusion

Nuclear energy offers several significant advantages over other forms of energy, including the ability to generate large amounts of electricity reliably, safely, and without greenhouse gas emissions. Additionally, nuclear technology is highly efficient and capable of operating for long periods of time, reducing the need for frequent maintenance and equipment replacement. However, nuclear energy also presents significant challenges in terms of safety and environmental impact. The risk of nuclear accidents, such as the Chernobyl disaster and the Fukushima accident has highlighted the importance of rigorous safety in the nuclear industry. Nuclear waste management remains a major challenge, with highly radioactive waste remaining hazardous for thousands of years. The assessment of the environmental impact of nuclear energy compared to other forms of energy is complex and controversial. While nuclear energy does not emit greenhouse gases during operation, uranium mining and the construction and decommissioning of nuclear power plants can have a significant environmental impact, including the release of greenhouse gases and the production of toxic waste. The use of large amounts of water to cool nuclear reactors can affect water availability in some areas. Overall, nuclear energy is a viable energy option but must be carefully managed to ensure safety and minimize environmental impact. Nuclear technology will continue to evolve and improve, but it is important that environmental and safety concerns are considered at all stages of nuclear energy production, from uranium mining to safe storage of nuclear waste. The implementation of rigorous safety and environmental practices and policies is essential to ensure that nuclear energy is a sustainable and safe energy option.

Funding

L.J.R.N. was supported by proMetheus-Research Unit on Energy, Materials and Environment for Sustainability-UIDP/05975/2020, funded by national funds through FCT-Fundação para a Ciência e Tecnologia.

References

1. Zhiznin SZ, Timokhov VM, Gusev AL (2020) Economic aspects of nuclear and hydrogen energy in the world and Russia. Int J Hydrogen Energy 45(56):31353-31366.
2. Rest J, Cooper MW, Spino J, Turnbull JA, van Uffelen P, et al. (2019) Fission gas release from UO2 nuclear fuel: A review. J Nucl Mater 513:310-345.
3. Darwish MA, Al Awadhi FM, Amer AO (2010) Combining the nuclear power plant steam cycle with gas turbines. Energy 35(12):4562-4571.
4. Petrescu FI, Apicella A, Petrescu RV, Kozaitis S, Bucinell R, et al. (2016) Environmental protection through nuclear energy. Am J Appl Sci 13(9):941-946.
5. Brook BW, Alonso A, Meneley DA, Misak J, Blees T, et al. (2014) Why nuclear energy is sustainable and has to be part of the energy mix. Sustain Mater Technol 1:8-16.
6. Muradov NZ, Veziroğlu TN (2008) "Green" path from fossil-based to hydrogen economy: An overview of carbon-neutral technologies. Int J Hydrog Energy 33(23):6804-39.
7. Bielecki J (2002) Energy security: is the wolf at the door? Q Rev Econ Finance 42(2):235-250.
8. Slovic P, Flynn JH, Layman M (1991) Perceived risk, trust, and the politics of nuclear waste. Science 254(5038):1603-1607.
9. Cattant F, Crusset D, Féron D (2008) Corrosion issues in nuclear industry today. Mater Today 11(10):32-37.
10. Cheng VK, Hammond GP (2017) Life-cycle energy densities and land-take requirements of various power generators: A UK perspective. J Energy Inst 90(2):201-213.
11. Prăvălie R, Bandoc G (2018) Nuclear energy: Between global electricity demand, worldwide decarbonisation imperativeness, and planetary environmental implications. J Environ Manage 209:81-92.
12. Weisser D (2007) A guide to life-cycle Greenhouse Gas (GHG) emissions from electric supply technologies. Energy 32(9): 1543-1559.
13. Berger EM (2010) The Chernobyl disaster, concern about the environment, and life satisfaction. Kyklos 63(1):1-8.
14. Beyea J, Lyman E, von Hippel FN (2013) Accounting for long-term doses in "worldwide health effects of the Fukushima Daiichi nuclear accident". Energy Environ Sci 6(3):1042-1045.
15. Ming Z, Yingxin L, Shaojie O, Hui S, Chunxue L (2016) Nuclear energy in the Post-Fukushima Era: Research on the developments of the Chinese and worldwide nuclear power industries. Renew Sustain Energy Rev 58:147-156.
16. Akleyev AV, Krestinina LY, Degteva MO, Tolstykh EI (2017) Consequences of the radiation accident at the Mayak production association in 1957 (the'Kyshtym Accident'). J Radiol Prot 37(3):R19.
17. Mendoza ZT, Stevens CA, Ritzman RL (1981) Radiation releases from the SL-1 accident. Nucl Technol 53(2):155-162.
18. Hultman N, Koomey J. (2013) Three Mile Island: The driver of US nuclear power's decline? Bull At Sci. 69(3):63-70.
19. Litmanen T, Solomon BD, Kari M (2014) The utmost ends of the nuclear fuel cycle: Finnish perceptions of the risks of uranium mining and nuclear waste management. J Risk Res 17(8): 1037-59.
20. Ramana MV (2018) Technical and social problems of nuclear waste. Wiley Interdiscip Rev Energy Environ 7(4):e289.
21. Schaffer MB (2011) Toward a viable nuclear waste disposal program. Energy policy 39(3):1382-1388.
22. Miller SE, Sagan SD (2009) Nuclear power without nuclear proliferation? Daedalus 138(4):7-18.
23. Grape S, Svärd SJ, Hellesen C, Jansson P, Lindell MÅ (2014) New perspectives on nuclear power—Generation IV nuclear

energy systems to strengthen nuclear non-proliferation and support nuclear disarmament. Energy Policy 73:815-819.

24. Vujić J, Bergmann RM, Škoda R, Miletić M (2012) Small modular reactors: Simpler, safer, cheaper? Energy 45(1): 288-295.
25. Drace Z, Ojovan MI, Samanta SK (2022) Challenges in planning of integrated nuclear waste management. Sustainability 14(21): 14204.
26. Michalski M (2019) Development of nuclear power as an alternative to fossil fuels. Acta Innovations 30:38-47.
27. Nakagawa N, Kosai S, Yamasue E (2022) Life cycle resource use of nuclear power generation considering total material requirement. J Clean Prod 363:132530.
28. Paltsev S (2016) The complicated geopolitics of renewable energy. Bull At Sci 72(6):390-395.
29. Wibisono AF, Shwageraus E (2016) Thermodynamic performance of Pressurized Water Reactor power conversion cycle combined with fossil-fuel super heater. Energy 117:190-197.
30. March-Leuba J, Cacuci DG, Perez RB (1986) Nonlinear dynamics and stability of boiling water reactors: part 1—qualitative analysis. Nucl Sci Eng 93(2):111-123.
31. Park S, Kim J, Han S, Jee K (2018) Distribution characteristics of 14 C and 3 H in spent resins from the Canada deuterium uranium-pressurized heavy water reactors (CANDU-PHWRs) of Korea. J Radioanal Nucl Chem 277(3):503-511.
32. Serp J, Allibert M, Beneš O, Delpech S, Feynberg O, et al.(2014) The molten salt reactor in generation IV: Overview and perspectives. Prog Nucl Energy 77:308-319.
33. Locatelli G, Bingham C, Mancini M (2014) Small modular reactors: A comprehensive overview of their economics and strategic aspects. Prog Nucl Energy 73:75-85.
34. Locatelli G, Mancini M, Todeschini N (2013) Generation IV nuclear reactors: Current status and future prospects. Energy Policy 61:1503-1520.
35. Glasstone S, Sesonske A (2012) Nuclear reactor engineering: Reactor systems engineering. Springer Science & Business Media.
36. de Bakker PM, Slugen V, de Grave E, van Walle E, Fabry A (1997) Differences between eastern and western-type nuclear reactor pressure vessel steels as probed by Mössbauer spectroscopy. Hyperfine Interact. 110:11-116.
37. Mustafa MQ (2011) Nuclear Energy. Strateg Stud. 31(1/2): 171-194.
38. Adamantiades A, Kessides I (2009). Nuclear power for sustainable development: Current status and future prospects. Energy Policy. 37(12):5149-5166.
39. Hatra G (2018) Radioactive pollution: An overview. Holistic Approach Environ. 8(2):48-65.
40. Farjana SH, Huda N, Mahmud MP, Lang C (2018) Comparative life-cycle assessment of uranium extraction processes. J Clean Prod 202:666-683.
41. Boryło A, Skwarzec B (2014) Activity disequilibrium between 234 U and 238 U isotopes in natural environment. J Radioanal Nucl Chem 300:719-727.
42. Wu J, Chen J, Zou C, Yu C, Cai X, et al. (2022) Transition to thorium fuel cycle on a heavy water moderated molten salt reactor by using low enrichment uranium. Ann Nucl Energy 165:108638.
43. Younas T, Hameed S, Sattar S, Quadri SA, Saeed U, et al. (2018) Enrichment of Uranium. In2018 IEEE 5th International Conference on Engineering Technologies and Applied Sciences (ICETAS). IEEE pp. 1-4.
44. Kessler G (2012) sustainable and safe nuclear fission energy: Technology and safety of fast and thermal nuclear reactors. Springer Science & Business Media pp. 59-71.
45. Humphrey UE, Khandaker MU (2018) Viability of thorium-based nuclear fuel cycle for the next generation nuclear reactor: Issues and prospects. Renew Sustain Energy Rev. 97:259-275.
46. Chilvers J, Burgess J (2008) Power relations: the politics of risk and procedure in nuclear waste governance. Environ Planning A 40(8):1881-900.
47. Darda SA, Gabbar HA, Damideh V, Aboughaly M, Hassen I (2021) A comprehensive review on radioactive waste cycle from generation to disposal. J Radioanal Nucl Chem 329(1):15-31.
48. Ojovan MI, Steinmetz HJ (2022) Approaches to Disposal of Nuclear Waste. Energies. 15(20):7804.
49. Khelurkar N, Shah S, Jeswani H (2015) A review of radioactive waste management. In2015 International Conference on Technologies for Sustainable Development (ICTSD). IEEE pp. 1-6. IEEE.
50. Hosan MI (2017) Radioactive waste classification, management and environment. Eng Int 5(2):53-62.
51. Jasanoff S, Kim SH (2009) Containing the atom: Sociotechnical imaginaries and nuclear power in the United States and South Korea. Minerva 47:119-146.
52. Srinivasan TN, Rethinaraj TG (2013) Fukushima and thereafter: Reassessment of risks of nuclear power. Energy Policy 52:726-736.
53. Kettunen J, Reiman T, Wahlström B (2007) Safety management challenges and tensions in the European nuclear power industry. Scand J Manag 23(4):424-444.
54. Kurniawan TA, Othman MH, Singh D, Avtar R, Hwang GH, et al. (2022) Technological solutions for long-term storage of partially used nuclear waste: A critical review. Ann Nucl Energy 166:108736.
55. Alwaeli M, Mannheim V (2022) Investigation into the current state of nuclear energy and nuclear waste management-A state-of-the-art review. Energies 15(12):4275.
56. Islam MS, Faisal SI, Khan S (2021) Development and strengthening of the nuclear and radiation safety infrastructure for nuclear power program of Bangladesh. Nucl Eng Technol 53(5):1705-1716.
57. Wahlström B (2001) Assessing the influence of organizational factors on nuclear safety. InSafety culture in nuclear power operations. CRC Press pp. 200-212.
58. Ewing RC, von Hippel FN (2009) Nuclear waste management in the United States—Starting over. Science 325(5937):151-152.
59. Kessides IN (2010) Nuclear power: Understanding the economic risks and uncertainties. Energy Policy 38(8):3849-3864.
60. Torp O, Klakegg OJ (2016) Challenges in cost estimation under uncertainty: A case study of the decommissioning of Barsebäck Nuclear Power Plant. Adm Sci. 6(4):14.
61. Laraia M (2012) Nuclear decommissioning. Lect Notes Energy pp. 66-65.

62. Michal V, Ljubenov V (2016) IAEA perspectives on preparation for decommissioning.
63. Lenzen M (2008) Life cycle energy and greenhouse gas emissions of nuclear energy: A review. Energy Convers Manag 49(8):2178-2199.
64. Ozcan B, Ulucak R (2021) An empirical investigation of nuclear energy consumption and carbon dioxide (CO2) emission in India: Bridging IPAT and EKC hypotheses. Nucl Eng Technol 53(6):2056-65.
65. Li H, Jenkins-Smith HC, Silva CL, Berrens RP, Herron KG (2009) Public support for reducing US reliance on fossil fuels: Investigating household willingness-to-pay for energy research and development. Ecol Econ 68(3):731-742.
66. Rosen MA (2020) Nuclear energy: Non-electric applications. Eur J Sustain Dev Res 5(1):em0147.
67. Kim JH, Alameri SA (2020) Harmonizing nuclear and renewable energy: Case studies. Int J Energy Res 44(10):8053-8061.
68. Graves C, Ebbesen SD, Mogensen M, Lackner KS (2011) Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy. Renew Sustain Energy Rev 15(1): 1-23.
69. Whitfield SC, Rosa EA, Dan A, Dietz T (2009) The future of nuclear power: Value orientations and risk perception. Risk Anal 29(3):425-437.
70. Wang S, Wang J, Lin S, Li J (2019) Public perceptions and acceptance of nuclear energy in China: The role of public knowledge, perceived benefit, perceived risk and public engagement. Energy Policy. 126:352-360.
71. Edwards MW, Schweitzer RD, Shakespeare-Finch J, Byrne A, Gordon-King K (2019) Living with nuclear energy: A systematic review of the psychological consequences of nuclear power. Energy Res Soc Sci 47:1-5.
72. Sun C, Zhu X, Meng X (2016) Post-Fukushima public acceptance on resuming the nuclear power program in China. Renew Sustain Energy Rev 62:685-694.
73. Renn O (1990) Public responses to the Chernobyl accident. J Environ Psychol 10(2):151-167.
74. Baron J, Herzog S (2020) Public opinion on nuclear energy and nuclear weapons: The attitudinal nexus in the United States. Energy Res Soc Sci 68:101567.
75. Dawson JI, Darst RG (2006) Meeting the challenge of permanent nuclear waste disposal in an expanding Europe: Transparency, trust and democracy. Env Polit 15(4):610-627.
76. Nguyen VP, Yim MS (2018) Examination of different socioeconomic factors that contribute to the public acceptance of nuclear energy. Nucl Eng Technol 50(5):767-772.
77. Wealer B, Bauer S, Hirschhausen CV, Kemfert C, Göke L (2021) Investing into third generation nuclear power plants-Review of recent trends and analysis of future investments using Monte Carlo Simulation. Renew Sustain Energy Rev 143:110836.
78. Barkatullah N, Ahmad A (2017) Current status and emerging trends in financing nuclear power projects. Energy Strategy Rev 18:127-140.
79. Gross R, Blyth W, Heptonstall P (2010) Risks, revenues and investment in electricity generation: Why policy needs to look beyond costs. Energy Econ 32(4):796-804.
80. Bahgat G (2006) Europe's energy security: challenges and opportunities. Int Aff 82(5):961-975.
81. Buongiorno J, Corradini M, Parsons J, Petti D (2019) Nuclear energy in a carbon-constrained world: Big challenges and big opportunities. IEEE Power Electron Mag 17(2):69-77.
82. Gburčik P, Gburčik V, Gavrilov M, Srdanović V, Mastilović S (2006) Complementary regimes of solar and wind energy in Serbia. Geogr Pannonica. 10:22-25.
83. Marcus GH (2000) Considering the next generation of nuclear power plants. Prog Nucl Energ 37(1-4):5-10.
84. Clack CT, Qvist SA, Apt J, Bazilian M, Brandt AR, et al. (2017) Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. Proc Natl Acad Sci 114(26): 6722-6727.
85. Bersano A, Segantin S, Falcone N, Panella B, Testoni R (2020) Evaluation of a potential reintroduction of nuclear energy in Italy to accelerate the energy transition. Electr J. 33(7):106813.
86. Walker JS (2001) Nuclear power and nonproliferation: The controversy over nuclear exports, 1974–1980. Dipl Hist 25(2): 215-249.
87. Carless TS, Redus K, Dryden R (2021) Estimating nuclear proliferation and security risks in emerging markets using Bayesian Belief Networks. Energy Policy 159:112549.
88. Ogilvie-White T (1996) Is there a theory of nuclear proliferation? An analysis of the contemporary debate. Nonproliferation Rev 4(1):43-60.
89. Gottemoeller R (2015) The nuclear non-proliferation treaty at 45. N Z Int Rev 40(5):6-8.
90. Ramana MV (2009) Nuclear power: Economic, safety, health, and environmental issues of near-term technologies. Annu Rev Environ Resour 34:127-152.
91. Sovacool BK (2008) Valuing the greenhouse gas emissions from nuclear power: A critical survey. Energy Policy 36(8): 2950-2963.
92. Abdelouas A (2006) Uranium mill tailings: geochemistry, mineralogy, and environmental impact. Elements 2(6):335-341.
93. Arent D, Pless J, Mai T, Wiser R, Hand M, et al. (2014) Implications of high renewable electricity penetration in the US for water use, greenhouse gas emissions, land-use, and materials supply. Appl Energy 123:368-377.
94. Vearrier D, Curtis JA, Greenberg MI (2009) Technologically enhanced naturally occurring radioactive materials. Clin Toxicol 47(5):393-406.
95. Liu B, Peng T, Sun H, Yue H (2017) Release behavior of uranium in uranium mill tailings under environmental conditions. J Environ Radioact 171:160-168.
96. Lerch RE, Norman RE (1984) Nuclear fuel conversion and fabrication chemistry. Radiochim Acta. 36(1-2):75-88.
97. Herbst RS, Baron P, Nilsson M (2011) Standard and advanced separation: PUREX processes for nuclear fuel reprocessing. Woodhead Publ pp. 141-175.
98. Settle FA (2009) Uranium to electricity: The chemistry of the nuclear fuel cycle. J Chem Educ 86(3):316. [Crossref] [Google Scholar]
99. Sharrad CA, Harwood LM, Livens FR (2011) Nuclear fuel cycles: Interfaces with the Environment. Nucl Energy 32:40-56.
100. Kyne D, Bolin B (2016) Emerging environmental justice issues in nuclear power and radioactive contamination. Int J Environ Res Public Health 13(7):700.

101. Deng D, Zhang L, Dong M, Samuel RE, Ofori-Boadu A, et al. (2020) Radioactive waste: A review. Water Environ Res (10): 1818-25.
102. Hall DS, Keech PG (2017) An overview of the Canadian corrosion program for the long-term management of nuclear waste. Corros Eng Sci 52(sup1):2-5.
103. Kraft ME (2000) Policy design and the acceptability of environmental risks: Nuclear waste disposal in Canada and the United States. Policy Stud J 28(1):206-218.
104. Kopytko N, Perkins J (2011) Climate change, nuclear power, and the adaptation–mitigation dilemma. Energy Policy 39(1): 318-333.
105. Miller S, Shemer H, Semiat R (2015) Energy and environmental issues in desalination. Desalination. 366:2-8.
106. Iqbal J, Howari FM, Mohamed AM, Paleologos EK (2021) Assessment of radiation pollution from nuclear power plants. J Sustain Sci Manag pp. 1027-1053.
107. Hesse-Honegger C, Wallimann P (2008) Malformation of true bug (Heteroptera): A phenotype field study on the possible influence of artificial low-level radioactivity. Chem Biodivers 5(4):499-539.
108. Lake JA (2002) The fourth generation of nuclear power. Prog Nucl Energy 40(3-4):301-307.
109. Corwin WR, Burchell TD, Katoh Y, McGreevy TE, Nanstad RK, et al. (2008) Generation IV Reactors Integrated Materials Technology Program Plan: Focus on Very High Temperature Reactor Materials. ORNL/TM-2008/129 pp. 20-21.
110. Arostegui DA, Holt M (2019) Advanced Nuclear Reactors: Technology Overview and Current Issues. Congressional Research Service.
111. Scarlat RO, Laufer MR, Blandford ED, Zweibaum N, Krumwiede DL, et al. (2014) Design and licensing strategies for the fluoride-salt-cooled, high-temperature reactor (FHR) technology. Prog Nucl Energy 77:406-420.
112. Ross M, Bindra H (2021) Estimating energy storage size for Nuclear-Renewable hybrid energy systems using data-driven stochastic emulators. J Energy Storage 40:102787.
113. Stephens J, van der Zwaan B, Kennedy JF (2005) CO2 Capture and Storage (CCS): Exploring the research, development, demonstration, and deployment continuum. Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University.
114. Yildiz B, Kazimi MS (2006) Efficiency of hydrogen production systems using alternative nuclear energy technologies. Int J Hydrog Energy 31(1):77-92.
115. Stoots CM, O'Brien JE, Condie KG, Hartvigsen JJ (2010) High-temperature electrolysis for large-scale hydrogen production from nuclear energy–experimental investigations. Int J Hydrog Energy 35(10):4861-70.
116. Naterer GF, Fowler M, Cotton J, Gabriel K (2008) Synergistic roles of off-peak electrolysis and thermochemical production of hydrogen from nuclear energy in Canada. Int J Hydrog Energy 33(23):6849-6857.
117. Ball M, Wietschel M (2009) The future of hydrogen–opportunities and challenges. Int J Hydrog Energy 34(2): 615-627.