Nuclear Science
2024, Vol. 9, No. 4, pp. 71-81
https://doi.org/10.11648/j.ns.20240904.11

Review Article

Prospects of Nuclear Energy for Clean and Sustainable Energy Development in Rwanda

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Abstract

Rwanda, just like many other developing countries, still faces challenges in the energy sector. The country is still not able to supply reliable and affordable electricity to meet the current and future energy needs, as a result of rapid economic growth, increasing population and urbanization. Rwanda currently has limited generation resources, particularly during the dry season, when several hydropower stations are experiencing water shortages. Sometimes, leased diesel generation is needed to meet peak demand, which comes at a hefty cost. Efforts are being made to determine the true number of existing resources in the country for energy generation. Diversifying sources of energy inevitably becomes a strategic option. Rwanda has decided to embark on an ambitious programme for nuclear development as one of the alternatives to tackle energy challenges. This paper briefly presents plans featuring in the nuclear science and technology programme with the ultimate goal to leverage nuclear applications for sustainable social-economic development. A review of the country's energy sector status is presented with focus on prospects of the nuclear programme as the solution to the country's high energy demand and applications in different socio-economic sectors. In efforts to join the rest of world in the "net zero" greenhouse gas emission by 2050, Rwanda embraces the perspective under which nuclear energy is foreseen as a source of energy that most supports the efforts.

Keywords

Nuclear Energy, Sustainable Energy, Safety, Nuclear Reactor, Rwanda

1. Introduction

Rwanda is a landlocked country with a population of about 13.2 million people with an annual population growth rate of 2.3% as of 2022 on an area of 26,338 km^2 [1]. It is located in the Great Rift Valley of the Central Africa and borders with Uganda (North), Tanzania (East), Burundi (South) and the Democratic Republic of Congo (West) [2].

With rapid economic development, population growth and urbanization, Rwanda faces a great challenge to meet its increasing energy demand. Currently, Rwanda's energy supply is dominated by hydropower and thermal energy, while the supply of oil, natural gas and renewable energies is relatively short [3]. Meanwhile, biomass still dominates the primary energy consumption in the country, with more than 85% of the population still relying on biomass for energy [4]. Of the remaining 15% of the primary energy consumption, petroleum products occupy 11% and are mostly used for trans-

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Received: 9 October 2024; **Accepted:** 30 October 2024; **Published:** 26 November 2024

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portation, while electricity only accounts for 4%.

The electricity supply in Rwanda is made of domestic generation and foreign imports from the neighboring countries. As of January 2024, the total installed capacity is 332.6 MW which, by technology mix comes from thermal sources (51 %), hydro sources (43.9%) and solar sources (4.2%) [3, 5, 6]. The country is targeting a generation capacity of 556MW and 100% electricity access by 2024 with 52% on-grid and 48% off-grid [7].

In the long run, Rwanda's energy resources are insufficient to meet the country's constantly increasing demand. The combined energy sources' capacity is estimated to be between 650 and 700 MW, and the Vision 2050 goals can only be met if installed capacity increases by up to 2.5 to 4.5 GW, depending on projected scenarios [8].

The switch from biofuels and the overall dominance of electricity use in the nation's final energy mix are the main causes of Rwanda's rapidly increasing power demand. The country's carbon footprint will drop dramatically as a result of this shift, which will also help the environment. It is clear that local resources alone cannot support the projected demand growth of 40-50 times relative to the current level, which is necessary to achieve this transition and is in line with Vision 2050 goals [8]. To achieve these goals, the country needs to put more efforts into diversifying its energy mix to increase generation capacity and electricity supply.

The energy sector development potential remains high. The key drivers of growth remain the connection of households to the national grid, the development of economic sectors, the commissioning of large industrial and commercial consumers, population growth. The growth rate is influenced by many factors, including the commissioning of generating capacities, the development of the power grid infrastructure and distribution networks, the financial and economic conditions at the national and global level, etc [1, 2].

As Rwanda aspires to achieve an upper-middle income status by 2035 and high-income status by 2050, the role to be played by a stable and clean energy is imperative to provide reliable and affordable energy supply [7]. One of the sources fitting into the above description is nuclear energy. The latter is expected to not only play a key role in the socio-economic transformation of the country, but also be part of the country’s efforts to meet the 7th goal of the United Nations Sustainable Development Goals (SDG 7) which calls for access to affordable, reliable, sustainable and modern energy for all [10]. Nuclear energy is a sustainable energy source: it is a clean energy without greenhouse gases emissions and its impact will affect positively the future generations. Currently, the country has embarked on a mission to include the nuclear in the energy mix as well as its applications in line with its national strategy for transformation and vision [11, 12].

This expresses the importance of investigating further the challenges and opportunities associated with the development of nuclear energy. Therefore, the main objectives of this paper are to review different types of nuclear energy production technologies and to explore the prospects of nuclear energy development in the Rwandan perspective for a sustainable socio-economic development of the country. The paper fills the knowledge gap by being the first paper attempting to understand the prospects and opportunities of nuclear energy development in Rwanda. The remaining part of the paper is subdivided as follows: section 2 describes the demand and challenges in Rwanda’s electricity production; section 3 describes the status, safety and technologies of nuclear energy as clean and sustainable energy; while section 4 involves the prospects of nuclear energy in Rwanda and section 5 provides the conclusions and recommendations.

2. Demand and Challenges in Electricity Production

One of the biggest problems the world is currently dealing with is the scarcity of energy. The rise in global population and economic development necessitates a reliable energy source to meet the growing demand for energy. Rwanda like many other countries in the world, faces significant challenges in addressing the growing demand for electricity in all sectors. With the country’s demand for electricity increasing at a rate of 10% (growth base case scenario) per year [13, 14], there is a need to plan for new electricity generation capacity to meet the demand. Since the last decade, Rwanda has made significant changes in terms of structural reforms in the energy sector to respond to the demand in energy due to its socio-economic reform programs [3]. However, plans to increase access to electricity present a number of challenges including:

1. High cost of electricity: compared to other nations in the region, Rwanda has a comparatively high cost of electricity, but its average usage is also incredibly low. The Rwandan electricity tariff of 0.25 USD/kWh is the second highest in Africa and the highest in East African region (EAC), more expensive than the average tariff of about 0.16 USD/kWh in EAC [4]. This issue can be resolved by implementing improved investment coordination and integrated planning, achieving 70% electrification and energy access, and giving priority to large electrical users. The tariff will rise if demand cannot keep up with the increasing generation capacity. By diversifying resources and raising the proportion of clean power generation in the overall generation mix, the cost of generation and losses should be controlled in order to address this problem [5].
2. Inadequate reserve margin: reserve margins are insufficient to uphold criteria for supply quality. Starting with an estimate of the real peak demand for power consumption and establishing a reserve margin of 15% in accordance with international best practice would be one way to approach this problem. For instance, the supply should be 563 MW if the entire demand is 473

MW [15].

3. High system losses: Electricity networks naturally experience energy losses between generation and consumption. In Rwanda, network distribution losses currently stand at 23%, which is far higher than the international benchmark of 6-8% and is a severe problem that needs more attention [5]. Even if these losses cannot be totally eliminated, they can still be significantly and cost-effectively decreased by better network planning and upkeep.
4. Dependency on hydroelectric power: The majority of Rwanda's electricity comes from hydropower source (43.9% as of 2024 [3, 6]), which is susceptible to changes in weather and water levels. Changes in precipitation patterns always affect hydropower production by increasing or declining water levels, hence causing water scarcity or flooding [16]. This results in frequent disruptions of electricity supply. As such, tapping more into other energy resources in the country is seen as one of the ways to mitigate the risks associated with frequent disruptions of hydroelectric power [5].
5. Limited infrastructure: Access to power is still a problem in Rwanda's rural areas, where there is a lack of electricity infrastructure. Additionally, the nation faces difficulties in developing and modernizing its transmission and distribution networks [5].

Overall, large investments in infrastructure, a diverse energy mix, increased access to power, and increased production and distribution of electricity is needed to meet Rwanda's rising demand for electricity and to ensure reliable and affordable energy supply to the country's population.

In terms of the amount of electricity per capita, Rwanda has one of the lowest indices worldwide. The current indicator is estimated at 75 kWh/person [17]; however, this metric reaches 1,600-2,500 kWh/person in nations with a middle-income status. The Vision 2050 target is to reach 1,026 kWh/person by 2035 and 3,080 kWh/person by 2050 [18].

3. Nuclear Energy as Clean and Sustainable Energy

3.1. How Nuclear Energy Is Produced

Nuclear energy is the energy found in the nucleus or core of an atom. Everything in the universe is made up of atoms and the nucleus is held together by energy. The compact nucleus of an atom has a huge amount of energy that can be released after atoms split through the process of fission reaction [3]. This process produces nuclear energy which is then used for different applications such as electricity whereby the produced energy (heat) produces steam (vapor) used by the turbine to generate electricity. In a conventional Nuclear Power Plant (NPP), the fission reaction is triggered and heats water to produce steam. The steam energy is then converted into electrical energy that is passed to national grid for consumption by the population.

Nuclear energy is increasingly and widely acknowledged to play a role in the future global energy mix and to contribute to sustainable development. Numerous factors affect the development of nuclear energy and its role in the global energy transition. Some of these factors, like the rate of innovation in nuclear technologies and the design of policies on nuclear waste management, are largely influenced by sector-specific actions, while others, like energy policies, market design, and financing structures, are shaped and influenced by other stakeholders [4].

Due to its high energy density and internalization of the costs associated with health and the environment, nuclear energy has a strong competitive position from the standpoint of sustainable development [5]. Utilizing nuclear energy has numerous sustainability benefits over competing options, which explains its growing involvement in practically all significant studies outlining realistic approaches toward sustainable energy provision [6].

3.2. Safety of Nuclear Energy

Safety of nuclear energy has long been a serious concern that all nations are still working hard to address. Discussions on the safety of nuclear energy increased following major accidents at nuclear installations, the most recent being at the Fukushima Daiichi Nuclear Power Station that occurred after the Tohoku earthquake and the enormous tsunami on 11th March 2011 [7].

For every nuclear energy program to be implemented successfully, public acceptability of nuclear energy is essential. Thanks to technology advancements in terms of safety, the public perception on the use of nuclear energy for peaceful purposes has improved and countries are putting in place new nuclear energy projects for their sustainable socio-economic development.

According to International Atomic Energy Agency (IAEA), nuclear safety is the achievement of adequate operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from radiation hazards [8, 9].

Security must always be ensured in addition to the safe operation of nuclear installations, the safe handling of radioactive material, and the safe transit of that material. IAEA defines 'Nuclear security' as the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities. 'Nuclear security' is often abbreviated to 'security' in IAEA publications on nuclear security [10].

The technology of nuclear installations is mainly based on safety functions, and the main safety principle for all nuclear installations is the defense-in-depth principle. The defense-in-depth involves a hierarchal deployment of different levels of equipment and procedures to maintain the effectiveness of physical barriers placed between radioactive materials and the workers, the public, and the environment, during normal operation, anticipated operational occurrences, and, in the case of some barriers, accidents at nuclear installations [11].

The levels of defense-in-depth are shown in Figure 1 and described as follows:

1. Level 1 - preventing abnormal operation and system failures.
2. Level 2 - detecting failures and comprehensive management of operating malfunctions. This is performed with systems for control, protection, monitoring and review, to maintain the nuclear installation within its normal operating condition and prevention of failures.
3. Level 3 - comprehensive accident management by controlling accidents within the design basis.
4. Level 4 - comprehensive management of severe nuclear installation accidents, by preventing progression of accidents, and mitigation of consequences of severe accidents (beyond design basis accidents).
5. Level 5 - limiting radiological consequences in the event of release of important radioactive hazards (beyond design basis accidents). This involves off-site emergency response.

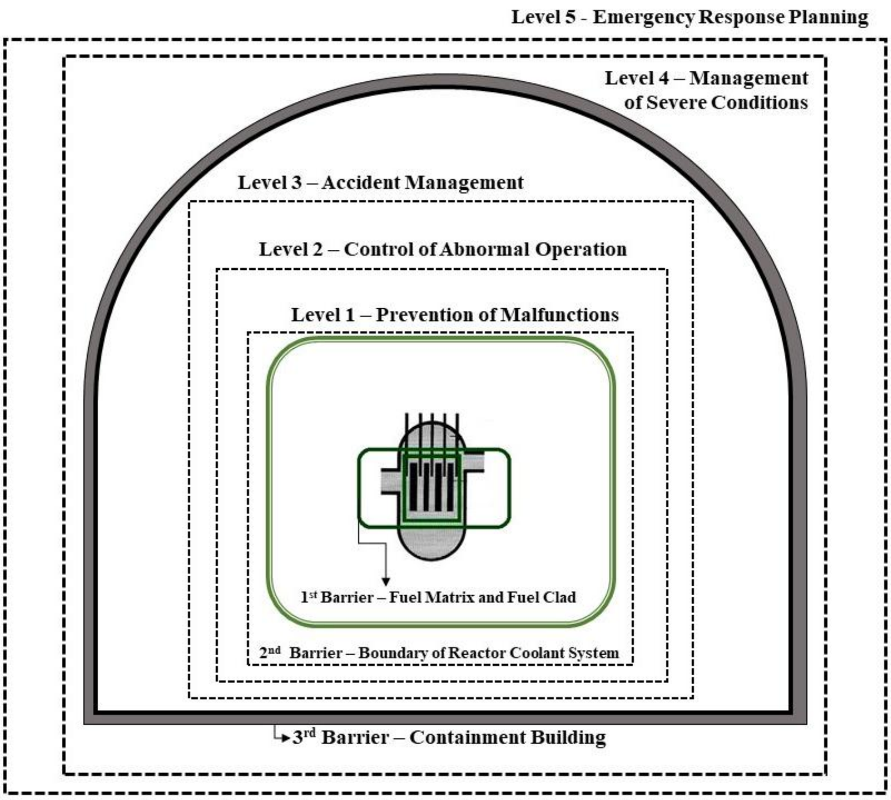

Figure 1. *Defense-in-depth: five successive levels of protection. Adapted from [11].*

3.3. Nuclear Reactor Technologies by Generation

A nuclear reactor, which is the main part of the NPP, is a device that initiates and controls a self-sustained nuclear chain reaction. Typically, nuclear reactor designs are categorized into "generations", referred to as Generation I, II, III, III+, and IV as shown in the Figure 2 [12]. The fundamental distinctions between the successive generations of reactors derive from the defining major characteristics of the design and deployment of nuclear power reactors. Some of the characteristics include the cost effectiveness, safety, security and non-proliferation, connectivity to the grid and the fuel cycle. The reactor fuel cycle is the defining factor for the reactor’s safety and security significancy.

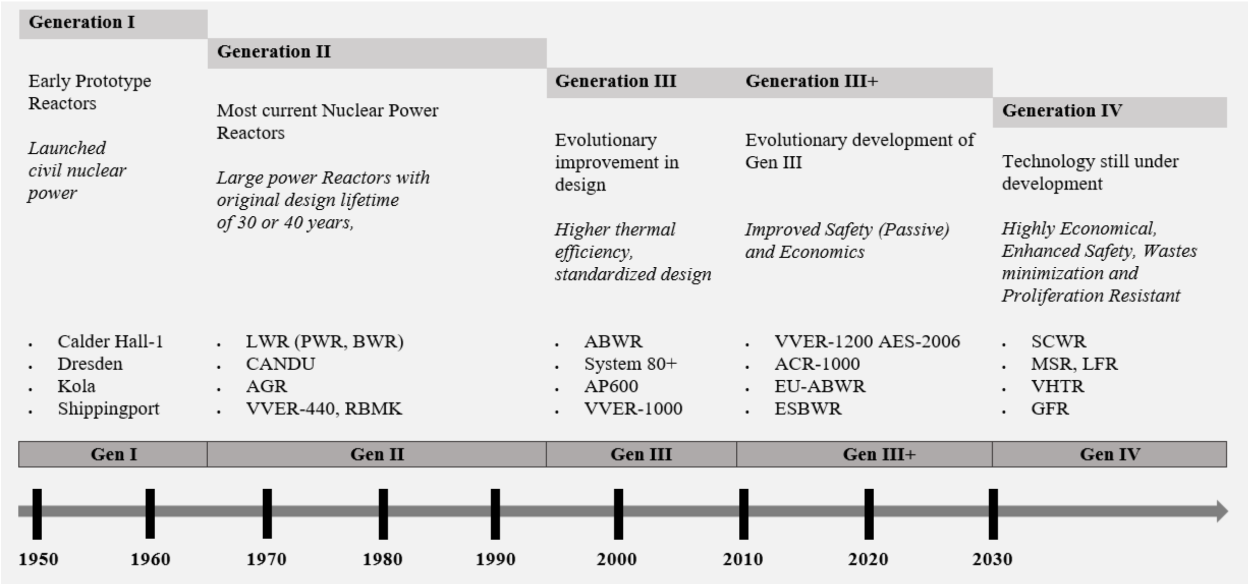

Figure 2. *Evolution of Nuclear power (US Department of Energy). Adapted from [12].*

Currently, three generations of nuclear reactors that were originally created for naval use starting in the late 1940s are in use worldwide [28].

There is a new generation of nuclear reactors that are referred to as Generation five (Gen-V). They are theoretically viable designs that are currently not under active examination or research. One of the conceptual designs of the Gen-V reactor is the Dual Fluid Reactor (DFR) design, which combines the concepts of the Liquid-metal cooled Fast Reactor (LFR) and a Molten Salt Reactor (MSR). The molten fuel salt of the DFR is cooled using a separate liquid lead loop in contrast to the molten salt reactor concept of Gen-IV, which theoretically enables higher power densities and better breeding performance [29]. With the DFR design, a very high-power density, an operating temperature of 1000 ℃ for effective electricity generation, and a higher neutron economy for breeding or transmutation are all achievable [30].

In September 2023, the Dual Fluid Energy Inc., a Canadian-German nuclear technology company and the Government of Rwanda, represented by the Rwanda Atomic Energy Board (RAEB), signed a cooperation agreement to work together on three building of a demonstration Dual Fluid nuclear reactor in Rwanda. The goal of the experiment referred to as "Critical Demonstration Experiment (CDE)" is to study in detail the behavior of a low-power Dual Fluid core in an experimental setup. The experiment will run for at most 2 years, and is expected to start in 2026 and be completed by 2028 [31, 32].

3.4. Status of Nuclear Energy in the World and Prospects

Since the 1950s, the first nuclear power plants went online for commercial use. With the power reactors, nuclear energy presently generates about 10% of the world's electricity [33]. With around 25% of the total in 2023, nuclear power is the second-largest source of low-carbon energy worldwide, after hydropower [34]. There are around 220 research reactors that use nuclear energy in more than 50 countries. These reactors are used not just for research but also for teaching and the manufacture of industrial and medicinal isotopes [35].

As of December, 2023, 413 reactors in 31 countries provided a total of over 371.5 GW(e) of operating nuclear power capacity. United States of America, China and France are respectively the top three producers of nuclear electricity [33].

From December 2023, 17 countries are constructing 59 reactors with the capacity of 61.1 GW(e) to be added to their grid. Over the previous 10 years, nuclear power capacity has stayed steady, with an extra 69.8 GW(e) of nuclear capacity added to the grid since the start of 2013. Asia accounted for more than 79% of this capacity expansion, with 55.4 GW(e) of total capacity (from 54 reactors) installed to the grid during the same time period. With 40.02 GW(e) of additional capacity added to the grid since the start of 2013, China is leading the expansion in the area [33].

South Africa is the only country on the African continent with commercial nuclear reactors, with a combined net capacity of 1.9 GW(e). Other countries like Egypt are in advanced stages of construction of nuclear power plants for electricity generation, which are expected to be operable by 2030 [34].

The shares of world's electricity production by source are shown in Figure 3. Currently, fossil fuels continue to be the dominant source of electricity production. Coal itself accounted for about 35.51% of the world's energy mix in 2023, with natural gas coming in second with about 22.46% [36]. Despite the usage of fossil fuels, governments' efforts to prevent global warming have intensified, and levelized costs have fallen, leading to a more dramatic year-over-year expansion in the share of renewable energy sources in the world's electricity in recent years.

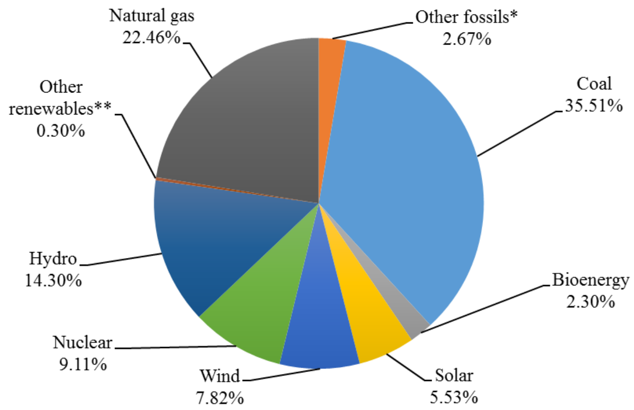

Figure 3. *Electricity generation by energy source, 2023 [13].*

* Includes oil and petroleum products, and manufactured gases
** Includes geothermal, tidal, and wave power

Globally, there is a need for new generating capacity to meet rising global energy demand as well as to replace outdated fossil fuel units, particularly coal-fired ones that produce large amounts of CO2 emissions. According to predictions, fossil fuels will no longer be the primary source of energy by the year 2040 [35]. As of 2020, the nuclear electrical generating capacity was estimated at 5% of the world total. According to the IAEA's best-case projected scenario, the installed nuclear power capacity worldwide will rise by 20% in 2030, and 60% in 2040, while it will more than double in 2050 compared to 2020 levels. Meanwhile, the worst-case scenario predicts a 7% decline in capacity in 2030, a 4% decline in 2040, and a recovery to the 2020 levels by 2050 [36].

Figure 4 shows the projected generation capacity of nuclear under both the best-case and worst-case scenarios.

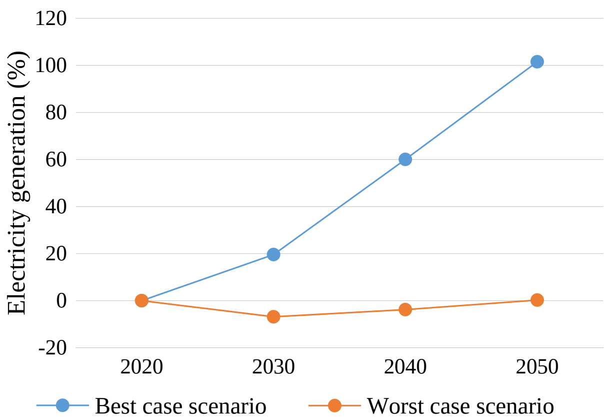

Figure 4. *World nuclear electrical generating capacity projections [37].*

4. Prospects of Nuclear Energy in Rwanda

4.1. Opportunities for Rwanda's Nuclear Energy Development

Rwanda's economy is expected to depend more and more on the industrial sector to achieve its development goals. However, if manufacturing doesn't improve quickly, the country will not be able to achieve its next objectives, which is to reach the upper middle-class status by 2035 and high-income level by 2050 [7]. There is still a need for a strong energy foundation for advanced industrialization, and hence nuclear energy can be for Rwanda an efficient way to compete on the international market [38].

In terms of nuclear energy development, Rwanda is expected to benefit from a number of opportunities:

1. Meeting energy demand: at the moment, hydroelectric power is Rwanda's main source of energy, while access to other energy sources is limited [5]. Generating nuclear energy could help the nation's energy mix become more diverse and fulfill the rising energy demand.
2. Economic development: nuclear energy has the potential to produce new markets and but also it can encourage economic expansion and draw in international investment [39]. At the same time, NPP would impact the social well-being of Rwandan population by generating long-term jobs.
3. Energy security: nuclear energy can offer a dependable energy supply that is unaffected by the elements or other outside variables [40]. By doing so, the country can increase energy security and decrease reliance on imports.
4. Climate change mitigation: nuclear energy is a low-carbon energy source that can aid in lowering greenhouse gas emissions and reducing the effects of climate change [39].

When used efficiently, nuclear technology can have a wide range of applications in significant economic sectors. In agriculture, nuclear technology has a huge impact on the decline of poverty by increasing output and lowering post-harvest losses, while it can contribute to improved health in disease diagnosis and treatment.

The following sections (4.2 and 4.3) discuss major projects Rwanda is working on to benefit from nuclear energy for peaceful purpose.

4.2. The Center for Nuclear Science and Technology

As per requirements of the IAEA, all member states that desire to develop nuclear energy need to have a body in charge of the use of nuclear energy for peaceful purposes. In 2020, Rwanda established the Rwanda Atomic Energy Board

(RAEB) with the primary objective of promoting the peaceful use of atomic energy for long-term socio-economic development [41-43].

The country plans to establish the Center for Nuclear Science and Technology (CNST) to further its ambitious sustainable development initiatives. The CNST will offer advantages that are expected to significantly benefit various industries including securing and supplying isotopes for medical and industrial manufacturing purposes, advancing knowledge in material science and engineering, reducing mortality rate from cancer and related diseases, improving life quality and expectancy, developing human resource for nuclear energy and science sectors, increasing crop yield and shelf-life with irradiation treatment, and enhancing the effectiveness of the nation [38]. The establishment of the CNST is therefore a significant first step for a newcomer country, which wants to take advantages of nuclear technologies and set itself up for more nuclear projects. The CNST creates the practical framework for the growth of the country's nuclear program, offers a wide range of applications that directly impact each citizen's quality of life and win their trust by removing their concerns about the "nuclearization" of the nation, ensures ongoing capacity building, and establishes a strong safety culture [44].

The CNST will develop into a cutting-edge platform for conducting a wide spectrum of scientific research and using radiation and nuclear technology in real-world applications. It will make possible the production of radioisotopes for widespread usage in industry, agriculture, healthcare, and other sectors, addressing also the problem of the absence of effective cancer treatments. The center will also make it easier to analyze the elemental makeup of ores, minerals, and environmental samples, train highly skilled local workers for the nuclear industry, support research into digital technologies, and do a lot more. The CNST will subsequently pave way for the establishment of the nuclear power plant based on the Small Modular Reactor (SMR) technology. In order to speed up knowledge and technology transfer as well as talent development, the country is working on public-private partnerships during the ongoing SMR technology development process [45].

4.3. Nuclear Power Plant Based on SMR Technology

SMRs are modern Nuclear Power Plants (NPP) with power capacity of up to 300 MW(e) per unit, or around one-third of that of conventional NPP. Small refers to the physicality, which is much smaller than a typical nuclear power reactor. Modular, which is an advantage provided by this technology, refers to the aspect that enables systems and components to be pre-assembled in a factory before being shipped as a whole to a place for installation. SMRs are equipped with advanced engineering characteristics and can be deployed as a single or multi-module plant [46, 47].

Since 2022, at least 20 Member States have ongoing national programs for the design and development of SMR technology, with the goal of deploying it by 2035. The majority of these programs involved international cooperation. As of 2023, more than 80 SMR concepts and designs exist worldwide. While some of them are said to be deployable in the near future, the majority are still in various phases of development [46].

With the current energy system and energy forecasts, reactors with installed capacities ranging from 30 to 100 MWe are foreseeable as the best option for integration into the Rwandan electricity infrastructure.

In order to meet Vision-2050's requirements for the growth path of installed capacity, Rwanda identified the need to construct a nuclear power plant based on SMR technology as soon as possible [47]. From the literature available, the most promising SMRs among the 30-100 MW existing SMR technologies are those that are in the latter stages of development. These include CAREM (from Argentina with planned operation in 2023) and RITM-200N (from Russia with planned operation in 2028) among others [46].

RAEB, acting as the country's Nuclear Energy Program Implementing Organization (NEPIO) completed the pre-feasibility study for SMR project that identified candidate sites for the construction of the first ever Nuclear Power Plant based on SMR technology in Rwanda [48]. The necessary resources are being provided to the national nuclear authority to enable it to oversee and control the process. This strategy chosen by the country will accelerate the transfer of knowledge and technology as well as the development of skills, which will enable the country's nuclear energy projects to be implemented quickly [49].

While Rwanda as an embarking country in the nuclear energy program is developing its infrastructures to accommodate the nuclear power, it remains a critical issue to establish the nuclear fuel supply chain. The country that currently does neither have significant domestic uranium reserves nor technical know-how, can count on mechanisms to secure reliable nuclear fuel (uranium) such as the international market, regional cooperation and contracts with internationally recognized suppliers [4]. The specific mechanism to adopt in the management of the nuclear fuel supply depends on various factors such as the country's development stage of its nuclear power program, the technology to be used and the comprehensive energy strategy of the country. Rwanda, that is exploring the SMR technology for nuclear power program can leverage the new collaborative effort between stakeholders in the nuclear industry, with focus on SMR to accelerate its deployment [29]. European countries under "European Industrial Alliance on SMRs" offer a variety of expertise in the acceleration, development, demonstration and deployment of SMR projects.

The SMR is a basic deployable electricity generation technology that guarantees the energy system's stability and reliability. It also guarantees the supply of electricity in compliance with all standards for the quality of electric power, all of which are vital for the growth of the service and energy-intensive industries [46].

4.4. Regulatory Framework

Despite the enormous advantages of using nuclear technology, its usage needs to be properly coordinated and regulated for the country to get the most out of the technology while adhering to international nuclear safety, security, and safeguards regulations [50]. The IAEA oversees and regulates the use of nuclear technology globally due to the inherent threats it poses to public health and the environment in case of misuse. Rwanda Utilities Regulatory Authority (RURA) is the national regulator and provides a variety of regulatory services for nuclear and radiation safety and security, including authorization and licensing, inspections, radiation monitoring (environmental), accreditation, radiation source registration, and other services related to the nuclear field.

The IAEA recommends that if a country is considering to adopt a specific reactor design, it has to model most of its laws and regulations after a country with prior experience with that specific design. The regulatory body in the buying country may be able to complete its regulations more swiftly if this strategy is used, and the vendor country will already be acquainted with the requirements [52, 53].

4.5. Key Economic Aspects of SMR Technology

While many SMR designs are still under development, there are many economic factors expected to drive the successful deployment of nuclear power plants based on SMR technology. Some of these key drivers include but not limited to: economies of scale and standardization that bring up the modularity and mass production aspects to make them cost-effective; the flexibility and scalability to match the demand while decentralizing the energy and taking into consideration applications beyond electricity production such as hydrogen production, heat for industries among others [53].

However, though SMRs present economic benefits, they also present challenges especially for the first-of-a-kind nature of many designs that face the challenges of higher costs at initial stages [53, 54].

Designers of SMRs argue that the overnight cost per kilowatt (kW) of SMRs could be less than that of advanced light-water reactors, despite the fact that the economics of SMRs, capital costs, operation and maintenance costs, and fuel costs are yet to be established [55].

A study by the US Energy Impact Center (EIC) indicates that a traditional pressurized water reactor (PWR) unit of 1,144 MWe costs $4,764 per kW of power generated, while a 114-MWe SMR unit would cost $2,653. The same study indicates that the conventional plant's Levelized Cost Of Electricity (LCOE) would be $92/MWh, while the SMR's would be $36/MWh [56].

The LCOE serves as the fundamental economic metric for each generating power station. Cost per MWh is normally calculated as the sum of the lifetime construction and operation costs of a power plant divided by the total amount of electricity distributed from the plant during that time. This study focused only on prospects of nuclear development in Rwanda, future studies could conduct a techno-economic assessment of SMR technology in the Rwandan context.

5. Conclusions and Recommendations

This paper is motivated by the recent interest of Rwanda to drive its nuclear ambitions for sustainable social economic development. The high costs and scarcity of energy in the country affect a variety of sectors that largely depend on energy for operations, hence rising the production cost. To curb negative ramifications thereof such as decrease of aggregate supply, cost-push inflation passed onto consumers etc., it is imperative for the government of Rwanda to lower the energy cost, demand of which is rising with other developments in various sectors. Realizing this will be one of the topmost drivers towards achieving the status of a middle-income economy by 2035 and a high-income economy by 2050. Meanwhile, the ambitious plans, which the government of Rwanda is eyeing in its long-run strategies, will necessitate nuclear energy applications to be achieved. These include food security, developing quality manufacturing and industrial processing, material science's research and development, academic areas, a regional health hub and a medical tourism center. Given the advancements in nuclear science and technology since its inception in the 1950s, using such a clean and safe technology will be vital for the country to realize its socio-economic transformation goals as outlined in its vision 2050. Should Rwanda's clean energy future include nuclear energy, it is high probable that this SMR technology will play a significant role.

For a successful development of nuclear program in Rwanda, the following recommendations are provided:

1. *Improve public opinion on benefits of nuclear energy*: it is open knowledge worldwide that, nuclear energy is always met by less positive attitude and misconception from the public, mostly due to concerns about its safety, previous accidents of nuclear installations and subsequent health effects, as well as proliferation of nuclear weapons. To alleviate these unfavorable attitudes, safety aspects must be fully addressed to the public by better communicating them about the risks and educating them about the current and past improvements of nuclear technology.
2. *Capacity building in nuclear energy program*: in order for a nuclear program to be successful in Rwanda, there is a need to develop qualified personnel for operation, maintenance, safety research and better inspection of nuclear installations at all levels.
3. *Increase research and development activities in nuclear*

energy: it is imperative to develop curricula and consolidate education programs for designing, constructing and operating nuclear installations. Research and development of new and updated technologies should also be intensified in an effort to control the cost and duration of nuclear projects.

4. *Strengthen the institutional management*: efforts should be made to build strong institutional capacity in order to increase coordination among stakeholders, effectiveness and accountability in implementing nuclear energy projects.

Abbreviations

ABWR	Advanced Boiling Water Reactor
AES	Advanced Engineering Solution
AGR	Advanced Gas-cooled Reactor
BWR	Boiling Water Reactor
CANDU	Canada Deuterium Uranium
CAREM	Central Argentina de Elementos Modulares (spanish, Argentina SMR design)
CDE	Critical Demonstration Experiment
CNST	Center for Nuclear Science and Technology
DFR	Dual Fluid Reactor
EAC	East African Community
EIC	Energy Impact Center
ESBWR	Economic Simplified Boiling Water Reactor
EU-ABWR	European Advanced Boiling Water Reactor
GFR	Gas-cooled Fast Reactor
IAEA	International Atomic Energy Agency
LCOE	Levelized Cost Of Electricity
LFR	Lead-cooled Fast Reactor
LWR	Light Water Reactor
MSR	Molten Salt Reactor
NEPIO	Nuclear Energy Program Implementing Organization
NPP	Nuclear Power Plant
PWR	Pressurized Water Reactor
RAEB	Rwanda Atomic Energy Board
RITM-200N	Russian land based SMR design
RURA	Rwanda Utilities Regulatory Authority
SCWR	Super Critical Water Reactor
SDG	Sustainable Development Goals
SMR	Small Modular Reactor
VHTR	Very High Temperature Reactor
VVER	Water Water Energetic Reactor (Russian type of the Pressurized Water Reactor)

Acknowledgments

The authors are thankful to Rwanda Atomic Energy Board, Rwanda Energy Group, International Atomic Energy Agency and the Ministry of Infrastructure of Rwanda for providing useful information.

Conflicts of Interest

The authors declare no conflicts of interest.

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