Review

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Review

Peaceful Uses of Nuclear Energy in Less Industrialized Countries: Challenges, Opportunities, and Acceptance

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Abstract: This paper introduces a holistic framework to assist less industrialized countries in adopting nuclear energy (NE) for peaceful purposes, amid the challenges and opportunities this entails. It underscores the pressing need for sustainable and secure energy solutions, proposing NE as a viable option. The study aims to delve into the technical, social, economic, regulatory, and policy aspects of NE's development and its broader applications beyond conventional power generation, such as in industrial processes, medical applications, agricultural advancements, and mining activities, specifically targeting less industrialized regions. Employing a systematic review of existing practices, the paper identifies and examines barriers to NE adoption, alongside strategies to mitigate these issues. Findings suggest that NE can play a pivotal role in fostering economic growth and scientific progress, potentially sparking the emergence of new industries within these countries. However, significant obstacles—namely governance, public acceptance, safety, security, development of expertise, and securing financing—pose considerable challenges. The paper concludes that a strategic and well-coordinated deployment of NE is essential for driving socio-economic growth and environmental sustainability in less industrialized countries. It emphasizes the necessity for comprehensive planning and international collaboration to fully unlock NE's potential, advocating for a multi-faceted approach to overcome the identified hurdles.

Keywords: energy transition and climate change; nuclear energy and development; peaceful uses of nuclear energy; energy policy; energy and less industrialized countries; energy security

1. Introduction

In less industrialized countries, nuclear energy (NE) has long been entangled with concerns of weaponry or adverse incidents since the late 1970s. However, it's imperative to recognize the substantial benefits nuclear energy has brought to society when harnessed for peaceful purposes. There's a growing acknowledgment of the significant potential for NE to play an expanded role in providing clean and abundant electricity.

Globally, nuclear power can substantially contribute to clean electricity generation, with over 430 nuclear reactors producing nearly 400 GW of electricity (about 10% of the demand) and additional reactors under construction and planned. The role of nuclear power is deemed crucial to achieve deep decarbonization and limit the rise in global temperature. According to the International Energy Agency (IEA), meeting the necessary pace of CO2 emissions reductions outlined in the Paris Agreement poses a significant challenge [1]. Achieving these goals requires efficiency improvements, increased investment in renewable energy, and expanded utilization of nuclear power.

Notably, nuclear power plants emit CO2-equivalent emissions per unit of electricity comparable to wind over their life cycle and emit just about one-third of the emissions compared to solar power. Unlike renewables, nuclear power plants maintain continuous electricity generation, providing a stable source distinct from the intermittent nature of standalone wind and PV solar. Additionally,

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small modular reactors (SMRs) offer technological and financial attributes that can broaden global access to the advantages of NE.

Beyond electricity generation, the peaceful use of nuclear energy significantly enhances human life across health, agriculture, food preservation, industry, and scientific exploration. Nuclear technology is instrumental in cancer diagnosis and treatment, radiography, blood irradiation, and the sterilization of biological tissues. It also contributes to the scientific understanding of environmental issues like climate change.

Moreover, nuclear technology extends its benefits to agriculture, countering food diseases, and has diverse applications in industries vital to mining, flow measurement, and leak detection. Even space exploration benefits from nuclear technology, highlighting its multifaceted utility and potential contributions to skilled workforces and innovative ecosystems.

While recognizing the myriad advantages, expanding nuclear energy deployment demands careful management due to associated risks. Social acceptance and waste management are critical considerations. While technological innovations make nuclear energy safer, public attitudes toward it have become more supportive, partly due to concerns about climate change and geopolitical events.

This study aims to uncover the prospects and obstacles less industrialized countries face in developing strategies and capabilities to harness nuclear energy for peaceful purposes. The paper's primary contribution lies in providing a holistic framework for these countries, encompassing applications, economic advantages, spillover effects, governance, social acceptance, safety, security, technological capabilities, human resource development, finance, infrastructure, and local industry participation.

2. The State of NE Industry in the World

Since the 1950s, the utilization of nuclear energy for power generation and various peaceful applications has experienced substantial growth. As of January 2024, the global landscape includes 436 operational power reactors, collectively boasting a capacity of 392 GW. In 2022, these reactors generated 2,545 TWh of electricity, constituting 10% of the world's electricity production. The reliability of nuclear power is underscored by its impressive worldwide capacity factor of 80%, ensuring a consistent and dependable supply of electricity 24/7 [2].

The United States leads the world in Nuclear Power Plants (NPP) with 93 facilities, contributing 24.2% to the global nuclear electricity capacity. Next France with 56 plants (15.6%), China with 55 plants (13.5%), and Russia with 36 plants (6.9%). There's a notable ongoing expansion, with 62 reactors under construction and an additional 114 in the planning stages, representing capacities of 69.3 GW and 112.3 GW, respectively—furthermore, proposals for an additional 326 reactors exist [3]. Among the reactors under construction, Asia dominates with 46 units, constituting 74% of the total MWe under construction, with China alone accounting for 43%.

In addition to commercial Nuclear Power Plants, the International Atomic Energy Agency (IAEA) research reactor database, as of January 2024, reports 225 operational research reactors in 54 countries, 20 under construction, and 13 in the planning phase [4]. Looking at the historical perspective, the World Nuclear Association notes that approximately 200 commercial, experimental, or prototype reactors, along with over 500 research reactors and several fuel cycle facilities, have been decommissioned, with some undergoing complete dismantling [5]. This comprehensive overview paints a vivid picture of the dynamic and evolving state of the global nuclear energy industry.

3. Unlocking the Potential of Peaceful Nuclear Applications

As noted, with the breadth of applications for nuclear energy, including in providing clean electricity generation [6], there is a growing need for all countries with nuclear technology to increase their existing nuclear industry and for countries that are less industrialized in nuclear technology to foster the utilization of nuclear energy for peaceful purposes. The parts in this section summarize some of the main applications of nuclear energy in different sectors, which have positively impacted our life quality and productivity and search for a fundamental understanding of our world.

For new commers, technological transfer involves discussing cooperative frameworks between nations and international bodies like the IAEA, which support knowledge exchange and capacity building. Highlighting the establishment of Centers of Excellence and the significance of international partnerships and academic exchanges in building local expertise emphasizes the critical role of technology transfer in sustainable nuclear program development. This approach not only ensures operational and safety standards but also fosters innovation and research within less industrialized countries, contributing to global nuclear safety and efficiency advancements.

3.1. Power Generation

Nuclear power stands as a significant contributor to expanding the clean energy supply and plays a crucial role in achieving the deep decarbonization imperative for limiting global temperature rise to 1.5 °C. Without an augmented role for nuclear power, effectively addressing climate change becomes considerably more challenging [1,7].

As the second most substantial source of low-carbon power, nuclear energy surpasses solar and wind, particularly in regions like Asia, where grid connections and new construction projects are burgeoning. Strategies for NPPs are expanding globally, with a focus on ~1,200 MW Pressurized Water Reactors—however, diverse grids worldwide present opportunities for leveraging SMRs[1] or micro-reactors.

Despite ongoing reactor shutdowns in the UK and the U.S., active initiatives in the U.S. aim to enhance nuclear power's competitiveness. These efforts target extending NPP lifetimes and reducing the cost of nuclear generation [8–11]. SMRs and micro-reactors offer advantages such as lower initial capital investment, greater sitting flexibility for unconventional locations, and increased scalability [12].

Microreactors, designed to produce 1-20 megawatts of thermal energy, present a clean and reliable energy source applicable to various commercial uses. Beyond electricity generation, non-electric applications include district heating, water desalination, and hydrogen fuel production [13]. Microreactors are crucial in emergency responses, catering to energy needs in areas like the mining industry and less industrialized countries lacking large grid capacities [14].

Three notable features define Microreactors: they are factory-fabricated, transportable, and self-adjusting for power needs. Their compact, portable nature allows easy deployment in remote areas. With fail-safe and self-adjusting mechanisms, microreactors feature fewer components, reduced maintenance requirements, and decreased operator dependence. Rapid on-site installation enables power connection within a few months and, in some cases, within weeks.

Some other benefits of micro-reactors are [15]:

- Effortless integration with renewables in microgrids.
- Deployment for emergency response, aiding power restoration in disaster-stricken areas.
- Extended core life, operating continuously for 10 - 20 years without refueling.
- Characteristics facilitating rapid installation and removal.
- Flexibility to be "right sized" for specific locations and certainly scalable.

For less industrialized countries or areas hard to reach by nearshoring power plants, where grid connections are much more complex, Micro or SMRs can provide a cost-effective and reliable solution for energy needs. In addition, for emergency power, energy for remote areas like mining sectors, and even the ultimate production of hydrogen, using micro-reactors can be a great advantage for their power reliability.

The SMRs and Microreactors are often going to upgrade fuel designs. They use higher enrichment, called High-Assay, Low-Enriched Uranium (HALEU), which is over 5% but less than 20% [16].

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[1] Small modular reactors (SMRs) are next-generation nuclear reactors with a power capacity of up to 300 MWe per unit, representing approximately one-third or less of the generating capacity of conventional nuclear power reactors.

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Over the next decade, several microreactor designs are being developed and may soon be ready for deployment. These compact reactors can be small enough to be transported in a truck and have the potential to address energy challenges in various regions with diverse energy and power requirements [17].

3.2. Spillover Effects[2]

Beyond their primary role in electricity generation, nuclear reactors are versatile tools with applications in diverse sectors. Specifically, engineered reactors can supply process heat for hydrogen generators, cater to industrial processes, produce medical isotopes, and catalyze innovation in nuclear and related fields. The pursuit of nuclear energy, encompassing the supply chain, workforce development, and regulatory frameworks, yields derivative benefits in three interconnected ways:

- **Innovative Ecosystem Creation:** The construction and operation of nuclear reactors serve as catalysts for an innovative ecosystem. This ecosystem propels technologies, including nuclear energy, through development cycles and into the marketplace.
- **Technology Transfer and Startup Drive:** Technologies developed within the nuclear ecosystem find applications beyond nuclear activities, driving startups that support the broader nuclear enterprise. This cross-pollination contributes to technological advancements in various sectors.
- **Inspiration for Innovations:** Products derived from nuclear reactors, such as electricity, heat processes, or medical isotopes, inspire innovative uses in different fields. This sparks entrepreneurship and advancements in unrelated areas.

In 2022, the IEA underscored the crucial role of innovation in achieving climate goals [18]. It recognizes that a significant portion of emissions reductions for net-zero targets by 2050 relies on technologies not yet available in the market. This includes emerging technologies like small modular reactors and micro-reactors. Innovations are imperative in transportation, heavy industry, and nuclear technology, and nuclear energy stands out as an enabler for achieving these climate goals.

One notable application is nuclear power electrolysis, which produces emissions-free hydrogen ("pink" hydrogen). While the cost of nuclear hydrogen generation is currently higher than alternative "green" options, the economic advantages arise as nuclear reactors can operate steadily, utilizing excess electricity to produce and store hydrogen. This stored energy can then be utilized across various applications.

Furthermore, nuclear reactors are pivotal in providing heat for industrial processes. While present designs generate substantial low- to medium-temperature heat, fulfilling high-temperature heat requirements (above 400 °C) necessitates advanced reactors like high-temperature gas reactors. These capabilities position nuclear energy as a vital contributor to reducing emissions in industries requiring diverse heat levels.

3.3. Industry

Nuclear techniques, particularly radioisotopes, play a pivotal role in various industrial applications. They are instrumental in determining material properties, assessing contamination levels, sterilizing components, monitoring industrial processes, and altering properties for innovative material development. These techniques, categorized into measurements with radioisotopes, industrial radiography, ionization applications, radioactive indicators, massive irradiation, and miscellaneous applications, have been extensively documented [19,20].

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[2] Spillovers refer to the unintended consequences of research, innovation, and technology development that have broader economic, social, and environmental impacts beyond their original objectives. While often beneficial, enhancing productivity, fostering new industries, and promoting societal advancements, spillovers can also present challenges, such as market disruptions and workforce displacements. Recognizing and managing these spillover effects are crucial for policymakers and businesses aiming to harness the full potential of innovation for economic growth and societal well-being.

Beyond electricity generation, nuclear energy offers a low-carbon alternative for producing heat and steam crucial in industrial processes. Nuclear power plants have proven effective in providing low-temperature heat (<200 °C) for district heating and desalination. Additionally, advanced reactors, like high-temperature gas reactors, can supply heat to replace fossil-generated heat in materials processing or contribute to hydrogen production.

SMRs and medium-sized reactors are particularly well-suited for cogeneration, finding applications in industrial settings to meet diverse demands in hubs like petrochemical, mining, and agriculture complexes [21].

The IEA emphasizes that for nuclear-generated heat to compete with fossil fuels, plant investment costs must stay below USD 3,000/kWe [18]. Achieving this cost competitiveness requires more innovation and a robust supply chain. It's crucial to note that advanced nuclear reactors, such as high-temperature gas reactors, pose distinct risks, sometimes greater than those associated with light water reactors. Integrating nuclear into industrial plants introduces complexities, compounding the already intricate operations found in facilities like chemical plants [22]. This highlights the need for careful consideration and planning when incorporating nuclear technologies into industrial processes.

3.4. Health

Over the past six decades, the expansion of nuclear technology to support health, particularly in producing radioisotopes for medical applications, has shown remarkable promise and growth. Notable advancements include the historical production of Mo-99, increased fission fragment production, and a growing application of alpha and beta isotopes for therapy. The evolution of medical applications for radioisotopes has been a prominent trend.

The roots of radioisotope development trace back to the late 1930s and early 1940s, with Oak Ridge National Laboratory (ORNL) marking a significant milestone by initiating the production of Iodine-131 in 1946. The 1960s and 1970s witnessed the ascendancy of Tc-99M as the most widely used isotope for medical purposes. The annual performance of over 40 million nuclear medicine procedures indicates a ~5% annual projected growth.

The global nuclear radioisotope market, valued at $9.6 billion in 2016, has not only sustained this growth but exceeded expectations, reaching $17.1 billion in 2020. Projections indicate that the market could further escalate to $36.9 billion by 2027 [23]. To meet this burgeoning demand, substantial investments have been directed towards nuclear radioisotope production, employing both reactors and accelerators in the U.S. and globally. While accelerator production shows promise, nuclear reactors are expected to continue playing a pivotal role in meeting the expanding global demand for radioisotopes. The successful operation of reactors and accelerators necessitates establishing a workforce and a regulatory environment adept at managing nuclear and radiological hazards.

3.5. Agriculture

Nuclear science and technology are crucial in ensuring global access to a safe, secure, and high-quality food supply [24]. Collaborations between scientists and farmers drive innovation in agricultural practices, exemplified by applying nuclear technologies. One notable method involves exposing seeds to radiation, a process that facilitates the development of more robust plant varieties. By carefully selecting radiation-induced mutations, these varieties exhibit enhanced resilience to drought and offer increased nutritional value, ultimately contributing to improved crop yields and livestock health. Importantly, these plants are scientifically verified to be safe and free from lingering radiation.

Furthermore, nuclear techniques are instrumental in mitigating the growth and impact of harmful organisms. The Sterile Insect Technique, which employs radiation, has proven effective in reducing populations of pests that pose threats to crops and livestock. This technique stands as a testament to the constructive role nuclear science can play in sustainable and efficient agricultural practices.

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3.6. Mining

Nuclear techniques have significantly boosted the efficiency of mineral exploration, mining, and processing [25]. They are invaluable tools in optimizing the entire spectrum of activities related to the exploration, extraction, and processing of raw materials, resulting in substantial energy and material savings.

In geological research, nuclear techniques play a pivotal role by facilitating age determination and providing crucial insights into the elemental distribution within different rock types. These techniques are deployed for geochemical exploration to analyze sediments and water, offering detailed information on their elemental composition to trace valuable mineralization.

In mining operations, nuclear techniques are critical in enhancing ore recovery, conducting geophysical exploration for uranium, utilizing borehole logging in oil, and assessing the feasibility of exploiting ore deposits through mineral exploration. A direct-use technique involves logging natural radioactivity (gross or gamma spectrometric), yielding valuable information about uranium, thorium, and potassium content, and providing indirect insights into the mineral composition.

These nuclear techniques have several advantages, including their rapid and straightforward implementation, even in locations where other methods may not be viable. Moreover, the ability to sample most or all of a process stream ensures more representative results than analyses based on individual samples. Additionally, the near real-time availability of results enables the application of these measurements for online process control applications.

3.7. Economic Benefits

In pursuing carbon neutrality by 2050, nuclear energy stands alongside renewables such as solar, wind, and hydroelectric as a crucial component. The IEA projects that nuclear' s share in the generation mix will remain at approximately 10% in various scenarios, with more ambitious projections suggesting a sharp increase in its contribution to reach 50% of total energy consumption in the IEA Net Zero Emissions (NZE) scenario [26]. The recent energy crisis has prompted economies to reconsider nuclear energy, with growing interest in small modular reactors and micro-reactors for emissions reduction and power system reliability [27]. Lifetime extensions for existing reactors, revival of suspended operations, and new constructions are evident, with the most extensive nuclear reactor construction programs currently in China and India [13,28].

Nuclear energy is recognized as a potent economic stimulant, offering significant advantages such as job creation, business opportunities, human resource development, scientific advancements, environmental sustainability, and enhanced energy security. The construction and operation of nuclear power plants provide employment opportunities and business prospects for local communities and firms. Economic benefits from a nuclear development program depend on the country's characteristics, with smaller nations potentially experiencing more substantial relative benefits.

In the U.S., the siting of nuclear facilities has primarily led to positive effects locally, including increased property values, economic expansion, more significant tax revenue, improved public services, community growth, additional jobs and employment, and school investments [29].

Studies suggest that a nuclear power plant typically creates between 400 to 1,000 direct jobs per gigawatt electric (GWe) capacity, paying approximately 30% more than other local jobs [30,31]. The IAEA surveyed in 2021 across ten countries, assessing the economic impact of nuclear power on GDP and employment. Results indicated potential GDP growth of 0.2% to 3%, leading to billions in assets, with 10% to 70% of investments made in-country [32].

The global nuclear energy services market associated with Nuclear Power Plants (NPPs was valued at US$7.068 billion in 2019 and is expected to reach US$9.136 billion by 2026 [23,33]. Nuclear energy provides environmental protection, emitting only 12 grams of CO2 equivalent per kilowatt-hour, placing it among the lowest-emission energy sources. It complements renewables by offering a reliable source during their production downturns, reducing vulnerability to fossil fuel price volatility, and supporting various industries, including health services and mining.

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Nuclear reactors generate electricity and produce heat, enabling the supply of energy products beyond electricity, such as district and process heat, desalination, and potentially pink hydrogen production. Moreover, nuclear energy is vital in scaling up a country's scientific, research, and industrial capacities, driving innovation, and fostering economic growth.

In summary, nuclear energy offers diverse economic advantages, including environmental sustainability [5], energy diversification, industry support, access to essential services, and the expansion of scientific and industrial capabilities.

4. Challenges in Implementing Nuclear Energy Programs for Peaceful Purposes

Implementing a NE program requires long-term commitment of local authorities and citizenry support. A clear plan and stages should be prepared and defined well in advance to close the gaps, always putting safety and security upfront and creating a proper business environment to enable the needed investments [34,35].

4.1. The Role of Governance and the State in Promoting NE Programs for Peaceful Purposes

In orchestrating a nuclear program, the State assumes one of three key roles: champion, regulator, or owner/operator. Depending on the specific country and its phase in the development cycle, all three roles might be necessary, even critical, for the success of nuclear energy deployment. However, implementing these roles concurrently raises potential inherent conflicts of interest that must be carefully considered.

Introducing nuclear energy into a developing country involves addressing many infrastructure issues. The IAEA's Milestones report outlines the challenges for countries aspiring to pursue nuclear power, identifying 19 national infrastructural needs, and providing a roadmap to assess readiness for implementing nuclear energy [36]. Many of these areas involve the government and the established regulatory framework. The country is responsible for implementing a nuclear power program, necessitating a clearly defined and steadfast government role, vision, and long-term commitment.

Experts emphasize that achieving global net-zero emissions will be challenging without incorporating nuclear energy. However, establishing a nuclear energy ecosystem and attracting private-sector financing poses significant challenges without substantial government involvement to manage and mitigate associated risks. Large nuclear projects historically rely on state ownership or regulated monopoly structures to guarantee revenues and reduce investor risk [18].

The role of regulatory bodies and oversight in the governance of nuclear energy, including its supply chain, is of paramount importance and falls within the purview of the State. Due to the specialized nature and unique risks associated with nuclear energy, regulatory agencies, and governance structures require individuals with highly specialized knowledge and experience. Conflicts of interest between the three roles necessitate thorough understanding and effective management.

Drawing from the lessons of the early days of the nuclear era in the United States, conflicts of interest emerged in the Atomic Energy Commission's (AEC) dual roles of promoting nuclear energy and ensuring reactor safety [37]. Separation of enabling and regulatory aspects was deemed necessary for safety and credibility in the nuclear energy enterprise. In the U.S., the AEC was split into the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE), each focusing on distinct aspects of nuclear energy.

Separating functions allows the regulatory body to support future nuclear energy deployment through communication, public engagement, and cooperation with the organization promoting nuclear energy. However, the government must be capable of supporting nuclear energy if it aligns with the country's goals while also objectively regulating its use after implementation. This dual role requires careful navigation to avoid conflicts of interest, especially in the early stages of program initiation, where expertise may be limited.

Developing robust policy and regulatory frameworks entails examining best practices from countries that have successfully updated their nuclear regulatory environments. This includes the establishment of independent regulatory authorities, adherence to international safety and security standards, and the integration of nuclear policies within broader national energy and climate strategies.

4.2. Social Acceptance and Communication with the Public

The oil crises of the 1970s and 1980s significantly propelled nuclear power; however, incidents at Three Mile Island in the U.S. (1979), Chernobyl in Ukraine (1986), and the Fukushima meltdown in Japan (2011) triggered anti-nuclear sentiments, impeding the growth of nuclear power. Consequently, and coupled with reactors reaching the end of their useful lifespan in the 1990s-2020s, many reactors were decommissioned, leading to a decrease in nuclear power's contribution to total electricity production from 17% in 1996 to 10% today.

Global attitudes toward nuclear energy vary, ranging from strong support in some countries to outright bans in others. With a regression analysis of survey data spanning 59 countries over 27 years, Nguyen, V. and Yim, M. (2018) [38] finds that public acceptance of nuclear power is positively influenced by education level and site geological suitability, while improved living standards and more democratic government are associated with declining acceptance. Targeted communication/education and weighing social and geographic factors stand out as key recommendations for policymakers considering nuclear energy. Recently, amid escalating concerns about climate change and energy security, particularly underscored by the Russian invasion of Ukraine, governments and societal acceptance of nuclear energy are on the rise, as indicated by 2022 surveys.

In a January 2022 Pew Research Center survey, 35% of adults in the U.S. believed that the federal government should encourage nuclear power production, 26% thought it should discourage it, and 37% believed it should neither promote nor prevent it [39]. In contrast, a survey by the American Nuclear Society (ANS) conducted by Bisconti Research from 1983-2022 concluded that in 2022, 77% of surveyed people in the U.S. favored nuclear energy [40,41],[3] demonstrating a positive trend despite past accidents [40]. This support in the U.S. surpasses that in Finland (60%) and Japan (53% in March 2022) [42,43]. A 2021 UK survey found that 39% of respondents supported or strongly supported nuclear energy, while only 17% opposed or strongly opposed its implementation in the country [44,45].

Nuclear energy is experiencing a renewed opportunity to become a prominent part of the global energy grid. However, any nuclear accident has far-reaching effects, impacting the entire industry. Solid international cooperation and adherence to gold safety and security standards are critical. Social acceptance hinges on prioritizing safety and security in successfully deploying nuclear energy and managing spent nuclear fuel.

To enhance the likelihood of social acceptance for an expanded nuclear energy program, governments should transparently communicate their objectives, including clear targets, policies, decision-making processes, and surveillance, as outlined by the Economic Research Institute for ASEAN and East Asia (ERIA) in 2018 [46,47]. Recognizing the complexity and potential concerns surrounding nuclear technology, effective communication guided by a comprehensive plan can provide the public with information on benefits and risks, forming a basis for informed decision-making aligned with the government's goals for the country.

If there is a decision to embrace NE, the government's communication plan for the NE program must be meticulously structured to engage civil society effectively. Here's a synthesized breakdown:

- ◎Audience:
    - Focus messages on national and local communities, detailing the importance of NE, the plan's steps and timeframe, benefits, and risks, with a particular emphasis on how these will be managed.

[3] The question was: "Overall, do you strongly favor, somewhat favor, somewhat oppose, or strongly oppose the use of nuclear energy as one of the ways to provide electricity in the United States?".

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- Engage local stakeholders who understand local issues, cultures, and attitudes, especially those employed in areas where facilities will be located.

- ◎Message:
  - Emphasize the demand for nuclear power, illustrating how each citizen can benefit, moving beyond the technology itself.
  - Clearly explain risks and detail how they will be mitigated and managed in case of adverse events.
  - Communicate strong government leadership, positioning the State, national, and local authorities at the forefront and entirely in command, elucidating their roles, benefits, and risks, along with a comprehensive plan regularly reviewed and communicated, featuring key milestones.
- ◎Context:
  - Recognize the importance of local content and the development of local businesses in enhancing the understanding and participation of local stakeholders in the nuclear industry.
  - Highlight economic benefits and work opportunities to bridge communication gaps with local communities, schools, colleges, and universities.
- ◎Media and Methods:
  - Choose appropriate communication channels and messages to shape informed public opinion on the NE program's costs, benefits, risks, and opportunities.
  - Leverage various media, including social media, for effective communication and citizenry awareness of nuclear power.
  - Share personal stories and experiences related to NE, emphasizing both the positive outcomes and any challenges or issues, fostering a relatable narrative.
  - Encourage collaboration between industry, academia, and government to develop a shared understanding of the costs and benefits of NE, engaging in open communication with civil society.
- ◎Outcomes:
  - Build trust by addressing a broad range of issues, including technical aspects, integrity, competence, surveillance, safeguards, safety and security, NE waste management, risks, benefits, and goodwill.

4.3. NE Safety, Security, and Safeguards

Applying advanced nuclear technology globally requires a dedicated focus on maintaining nuclear safety and security. Throughout the history of nuclear technology, substantial progress has been made in enhancing nuclear safety and security measures. The significance of safety arises from the potent energy release inherent in nuclear fission, making it crucial to prevent accidents or misuse, underscoring the need for robust safety and security protocols. With seven decades of experience since the inception of the first nuclear power reactor, the collective knowledge gained must be retained and applied on a global scale.

The safety aspect has been enriched by lessons learned from pivotal incidents at Three Mile Island, Chernobyl, and Fukushima. Improved technical design, construction practices, and organizational structures have been pivotal in enhancing safety protocols [48].

Regarding security considerations, the nuclear energy industry must implement stringent measures to prevent unauthorized access to critical equipment and materials and safeguard facilities against potential harm. Security measures include physical barriers, electronic surveillance, background checks, and well-armed security personnel [49].

The IAEA sets forth Nuclear Safeguards, which are technical requirements for nuclear facilities and materials. The IAEA's objective is to independently verify a state's commitment to ensuring peaceful nuclear applications and preventing material diversion. States accept these requirements through safeguards agreements [50]. The European Union (EU) also manages a nuclear safeguard

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system under the Euratom Treaty, ensuring that nuclear material in Europe is used for its intended purposes and upholding non-proliferation treaty commitments [51].

In the context of safety and security for nuclear technology, specific considerations arise with the growing development and application of SMRs and Micro Reactors. These innovations promise to reduce carbon emissions in less industrialized countries, support emergency energy needs, and power remote sectors such as mining and transportation.

A notable microreactor company focusing on less industrialized countries and sectors like mining and emergency energy needs has designed a fully solid core utilizing advanced materials for enhanced safety and efficiency [17]. The micro-reactor employs UO2 fuel and operates in the fast spectrum, eliminating the need for a moderator. Heat is conducted from the fuel pins to the solid core via thermal conduction, with liquid metal, likely bismuth eutectic, enhancing heat transport. Helium gas recirculation removes heat from the core, driving a gas turbine for electricity production.

The second major component of SMRs and micro-reactors is the fuel update to HALEU. With historical fuel enrichment at less than 5%, HALEU advancements to nearly 20% contribute to prolonged fuel applications, increasing safety. The US NRC has updated security requirements for HALEU fuel, emphasizing the Category II requirements for advanced reactors (US NRC, Title 10 of the USA Code of Federal Regulations (CFR), Part 73.67) [52].

In conclusion, the evolution of nuclear safety and security, coupled with innovations like SMRs and Micro Reactors, underscores the ongoing commitment to harnessing nuclear technology responsibly and sustainably.

4.4. Nuclear Waste Management and Disposal

Nuclear technologies benefit many areas of people's lives, such as sterilizing food and medical instruments, developing more resistant crops to pests and different environmental conditions, diagnosing, and treating patients, and producing electricity and heat. Research nuclear reactors are being used in 53 countries in science and to produce radioisotopes for medical and industrial use, and 30 countries use nuclear energy for electricity production. Like numerous other processes, several uses of nuclear technologies generate waste materials. All countries employing nuclear technologies are responsible for managing radioactive waste safely, aiming to minimize the risk it poses to people and the environment, both presently and in the future.

Depending on the material, nuclear waste can be toxic for extended periods, which requires selecting and constructing suitable sites for its storage and disposal. Some radioactive waste lasts only a few days, while others can last thousands of years. The IAEA standards have six classes for radioactive waste: high, intermediate, low, very low, very short, and waste exempt level. Each has different management and disposal requirements, with some, like very low-level and short-lived waste, requiring a few days of safe and secure storage, and high-ionizing and long-lived waste, requiring extended, safe, and secure facilities for their storage.

An essential part of the strategy that a country designs for the peaceful uses of NE is the design and implementation of a radioactive waste management system that, with the highest safety and security standards and safeguard obligations [53], considers the safe selection, treatment and/or reprocessing, storage, and disposal of liquid, solid and gaseous discharges from the operations of the nuclear industry, to protect over long periods the people and the environment.

The IAEA helps its Member States establish an appropriate safety framework for managing radioactive waste and spent fuel, including assistance in developing safety standards for pre-disposal and waste management and supports Member States in their application of these standards [54,55].

Today, and for the more complex high-level and long-lived radioactive waste, most countries have developed or plan to establish a centralized waste processing and storage facility [56], where the waste of the nuclear fuel cycle can be placed in a deep geological repository [57,58]. Geological disposal has gained international recognition as the most effective method for ensuring the long-term, secure disposal of used nuclear fuels and radioactive waste materials originating from nuclear power generation, nuclear weapons programs, medical treatments, and industrial application [59].

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However, depending on the contracts associated with the nuclear facility, size, and operation cycle, waste and spent fuel can be sent abroad for treatment, disposal, and storage [60].

4.5. Areas of expertise

A path to access nuclear power technology for a newcomer for its implementation is through an integrated plant supplier.

However, several steps are required to reach the status of an integrated signed contract. Among them stand out:

- **Step 1**: Selection of an experienced engineering/consultant firm to develop a roadmap for implementing a nuclear program.
- **Step 2**: Define a clear training roadmap for the professionals participating in the project's initial phase.
- **Step 3**: Start in parallel the training program for the professionals, engineers, and from other fields that will participate in preparing the call for bid and selecting the integrated supplier. This phase has a substantial participation of highly skilled professionals, engineers, and the consultant firm.

4.5.1. Paths to Technology

Access to technology can be implemented in two ways, as shown:

(a) Bidding process among suppliers from their countries, such as the U.S.A., Canada, France, Korea, Japan, China, and Russia.

(b) Or through an agreement between countries.

In the case of Brazil, the SOE Electrobras/Eletronuclear utility oversaw the project's implementation. In the 1960s, with the support of the consulting firm Nuclear Utilities Service – NUS - from the U.S., it prepared all the specifications and requirements. In 1970, an international bidding process selected the supplier for the first unit of the Central Nuclear Almirante Álvaro Alberto, Angra 1 project, a 609 MWe Westinghouse 2-loop PWR [61]. While constructing the two subsequent Angra nuclear plants in Central Nuclear Almirante Álvaro Alberto, Unit 2 (1275 MWe in operation) and Unit 3 (1,340 Mwe, under construction), where an agreement was reached between the Brazilian and German governments [62]. A brief of Brazilian development of a non-nuclear weapons development can be seen in [63,64].

4.5.2. Technical Capabilities

The development of capabilities for a specific nuclear segment program must start as soon as the country decides to pursue nuclear energy options.

These capacities shall comprise the preparation of technical professionals for the following tasks:

- Site selection
- Licensing
- Quality Assurance
- Engineering
- Erection and Civil Construction
- Safety, Security, and Safeguards
- Operation
- Nuclear waste management and decommissioning

A vast array of specialists in several disciplines must be trained to develop these capacities.

The training program shall consider the following:

- Engineering/Consult developed a detailed course including all systems and requirements of a nuclear power plant.
- University develops specific disciplines, such as Nuclear Engineering, Nuclear physics, etc.

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- Licensing training in collaboration with foreign licensing authorities, such as US NRC [65], and [66] TÜV.
- Site selection, with the support of the Electric Power Research Institute (EPRI), EPRI Program, as an example [67].
- On-the-job training in the selected Engineering and Construction Companies contracted by the owner Utility.
- Visit Nuclear Power Plants in construction and operation and be a trainee in these plants for an extended period.
- Solid and lengthy training program for the operations and maintenance crews in all disciplines required for plant operation.

4.5.3. Human Resources Requirements

Nuclear energy generation and uses can be an engine for creating jobs, directly and indirectly, in both professional positions and trades. A large nuclear power plant (~1,000 MWe) employs between 500 and 1,000 workers and drives about 4 to 5 times that much in secondary jobs (both in the supply chain and the local community) in the United States. Employment in the nuclear industry comes with higher earnings, as workers at U.S. nuclear power plants receive the highest median wage in the power sector, as detailed in the "*Wages, Benefits, and Change: A Supplemental Report to the Annual USA. Energy and Employment Report*" [68]. For some jobs, a college degree is required (e.g., nuclear engineers, electrical engineers, administrator roles, etc.), but many jobs are not, such as reactor operators, technicians, and security officers.

Meeting the workforce demands requires a holistic approach that targets all parts of the workforce pipeline: attracting the future workforce into the field, providing opportunities for both vocational training and academic education, supporting re-skilling and continuing education for those in the middle of careers, and enabling entrepreneurial training and incubation of startups to help build out the nuclear ecosystem. Further, given the risks and the perceptions related to nuclear, it would be valuable to provide leadership training to help inform decision-makers in the public sector, manufacturing companies, the financial industry, the media, and academic institutions, among others, about nuclear energy benefits and risks. Retraining or "up-skilling" by providing nuclear training to technical experts in other fields (e.g., fossil fuel workers) can satisfy some of the workforce's needs.

As noted, the need to satisfy the workforce demands all the roles that the government may assume (regulator, champion, and owner/operator) are all equally important and will come from the same pool of individuals. For example, the technical capabilities the regulatory body needs to evaluate compliance or ensure radiological safety are the same as those of the reactor operators.

As described in detail by the IAEA, building the national capabilities to provide the needed education and training for a sustained workforce will require significant education, training, and experience by national personnel. This goal can be accomplished by recruiting experienced foreign staff to collaborate with national personnel and encouraging them to work in foreign organizations to enhance national capacity. To ensure a consistent supply of a highly skilled workforce, the country must bolster its education and training capabilities while devising a strategy to retain skilled professionals [36].

The journey towards achieving zero carbon in our world demands the collaboration of world-class nuclear technical teams comprising influential nuclear experts working alongside business and industry professionals. Building solid relationships with government facilities and private and public nuclear industries is crucial. Over the last 30-40 years, significant strides have been made in advance by technical teams to the demonstration and execution of nuclear energy reactors in energy markets, marking a pivotal moment in our history.

Nuclear technical team experts are growing to engage with the open market and investment in our energy future. Government investment must increasingly focus on integrating with the private sector to complete the demonstration of advanced technology and complete qualifications for safety and security. In addition, major nuclear countries and their governments need to develop a strategy for engaging in the growth of the private sector of nuclear technology for less industrialized countries.

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In the U.S., there is a growing need for technology teams, mainly in Universities and Labs, to engage and partner with the private sector and investors for its energy future.[4]

4.6. Access to Finance

A nuclear power plant's financing, construction, and operation entail two distinct aspects of the financial structure [69]. On one side, there is the consideration of the structure and security of future revenues derived from the sale of electricity and capacity, power sector ancillary services [70,71], and other services and products. These additional offerings may include heating, medical isotopes used in cancer and tumor diagnosis and treatment, medical equipment sterilization, and industrial applications.

On the other side is the financial structure concerning the capital required for the plant's construction. This capital investment is made up front, well in advance of any revenue generation.

NE projects are highly capital-intensive projects. They have extended licensing, design, and construction periods, which can go up to ten or more years for a large reactor. The power plant will not deliver revenue until the project operates in this time frame. This is different than a solar PV plant that can be built in modules that start operation at different stages and obtain revenues within two or three years from the initial idea that was envisaged. As a result, in a nuclear energy project, securing the financial resources for the construction will require in advance long-term revenue commitments that the project, during its construction and once in operation, have a secure stream of revenues to pay back to lenders and investors, plus a proper return on the investment. The time to produce gains for a SMR or microreactor can be shortened as the reactor can be shipped and assembled on-site, much like a PV plant.

Capital cost - the cost of licensing, designing, engineering, and constructing the plant - represents a large percentage of the cost of a large nuclear reactor. The U.S. Energy Information Administration estimated that for light water nuclear plants to go into service in 2027, a 2,156 MWe plant, with capacity factors of 90%, capital cost (overnight capital cost), plus fixed O&M and transmission costs, can make up 88% of total costs. As a result, the costs are: a) well above the 30% of total costs in a natural gas combined cycle, with size ranging from 418-1,083 MWe, with a capacity factor of 87%, where the most significant cost share goes to fuel; and, b) and below the 100% of total costs in a solar or wind plant, size ranging 150-400 MWe with capacity factors ranging between 28% and 44% [72]. Moreover, due to the inherent characteristics of nuclear plants, which involve more extensive licensing, designing, engineering, and construction periods, the cost of capital during the construction phase accumulates to form the total cost of the plant. However, in the case of SMRs or microreactors, the capital costs required to achieve a similar electricity generation capacity can be spread over a more extended period. This is possible because countries can deploy the capacity in smaller segments, such as 120 MWe instead of 1,200 MWe, allowing for incremental additions based on their specific needs and funding capabilities.

Furthermore, depending on the engineering, procurement, and construction (EPC) and financial contracts in place, the capital costs can be distributed among various stakeholders in the supply chain. For instance, the burden of financing the equipment necessary to manufacture the reactor modules may fall on the plant manufacturers. This allocation of capital costs helps mitigate the financial burden on any single entity and promotes collaboration among stakeholders.

Depending on a country's business environment, risk factors, and regulatory framework, various schemes can be implemented to ensure that investors and lenders have a reliable revenue stream to cover the capital and operational costs associated with a nuclear power plant.

In many instances, utilities responsible for operating nuclear power plants are state-owned or joint ventures with the private sector. In these cases, there is often an explicit guarantee or backup mechanism in place to secure the future revenue stream for the plant. This ensures investors and lenders regarding the stability of their investments.

[4] Known as Non-Federal Strategic Partnership Project (SPP).

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Additionally, countries may leverage their development agencies and multilateral development banks to facilitate syndicated loans and equity for nuclear power projects. These organizations have been instrumental in mobilizing financial resources and supporting the successful implementation of such projects.

The specific approach to securing investments and loans for nuclear power plants may vary depending on the country's unique circumstances. Still, it typically involves a combination of government support, partnerships with private entities, and collaboration with development agencies and multilateral development banks.

The deregulation of the power industry that started in the 1980s created new markets where electricity (energy and capacity) is traded by predefined rules, with energy and not always capacity markets and sometimes payments for other preconceived ancillary services [73].

In general, restructuring electricity markets has resulted in greater emphasis on short-term marginal and variable operational costs. This shift tends to benefit technologies with higher variable costs rather than fixed or capital costs. Consequently, in a competitive market where technologies must contend on an hour-by-hour basis, those with a more significant proportion of variable costs and operational flexibility, such as gas turbines, are positioned to participate in the market selectively. They can choose to operate when energy prices are high, maximize their profitability, and abstain from operation when prices are low. This ability to cherry-pick the market based on price conditions gives them a distinct advantage.

Chile can be seen as a showcasing the evolution of the power sector. In the early 1980s, Chile spearheaded the liberalization of power markets [73]. Presently, the main electric system in Chile boasts over 650 generation units connected and centrally managed by the Independent System Operator (ISO) of the power grid. The operation of power plants adheres to the merit order based on their short-term marginal costs. Consequently, run-of-the-river hydroelectric, modern solar photovoltaic, and wind power units are consistently prioritized due to their zero fuel costs, displacing conventional hydroelectric dams, coal, and gas turbines. Hydroelectric dams are dispatched strategically, operating with a marginal cost determined by the opportunity cost of utilizing stored water. They come into play either as peak units or to complement supply during periods when variable generation, such as solar and wind, is unavailable. Introducing new solar and wind technologies has reshaped the role of coal-fired and large hydroelectric power plants, initially designed for baseload, leading to challenges when integrating a substantial amount of new solar and wind generation into the grid. This integration can result in inefficient and variable operation or operation at a technical minimum for coal-fired and large hydroelectric power plants.

Like big hydroelectric and coal plants, nuclear power plants are sizable, capital-intensive units with extended licensing and construction periods intended to provide baseload, boasting capacity factors well above solar and wind [72]. Established large and capital-intensive power units, having recouped their initial high sunk costs, do not face the same challenges as potential new units of a similar scale. These potential units, however, must secure sufficient revenues to sustain a financing scheme covering their investment, operation, and maintenance costs over the next 30 to 40 years.

In markets where variable generation, with its lower short-term variable or marginal costs, can dominate and potentially impede the entry of substantial capital-intensive power units, establishing new projects becomes challenging. Nevertheless, there are instances where a secured revenue and operation scheme can provide the necessary assurance for these units to generate sufficient revenues to cover their investment and operational costs. A reliable mechanism guaranteeing revenue streams makes it more feasible for capital-intensive projects to proceed and operate successfully within the market.

In various regions, there is a growing reconsideration of the regulatory regime to support and sustain nuclear energy or to preserve existing nuclear power plants. Regulatory models, such as the Regulated Asset Base (RAB), are gaining increased attention due to their ability to provide long-term price or rate of return guarantees. This approach ensures that investments in nuclear power plants are adequately compensated, securing their continued operation.

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A notable example is Connecticut, where officials agreed in 2019 to procure power from the State's Millstone nuclear plant for ten years. This agreement provided Dominion Energy, the plant's operator, with a fixed price, offering the necessary certainty to keep Millstone operational. By delivering stability and predictability in revenue generation, this regulatory model plays a crucial role in supporting the viability of nuclear power plants and encouraging their continued operation.

Among financial models, various options can be explored to address the high upfront costs associated with nuclear projects, including Public-Private Partnerships (PPPs), Build-Operate-Transfer (BOT) schemes, and international financing. The Akkuyu Nuclear Power Plant in Turkey, with its $20 billion investment BOT model, showcases the effectiveness of combining various public financing sources through international collaboration to fund large-scale, capital-intensive nuclear projects. This instance underscores the critical importance of government support and the involvement of global financial institutions in securing financing for nuclear plants, given the challenges associated with private funding. Despite innovative financing models addressing the economic fundamentals of nuclear energy—such as high upfront costs and extended payback periods—remains crucial for ensuring the long-term viability of these projects. While mechanisms like green bonds present opportunities to align nuclear projects with climate finance, ongoing public concerns regarding safety and waste management pose barriers to private investment. Nevertheless, the Akkuyu project illustrates that a mix of financing strategies can facilitate progress in the nuclear sector amid financial hurdles. Currently, a diverse array of public financing mechanisms is vital for pushing forward nuclear initiatives, pending significant changes in technical and economic conditions. This case highlights both the possibilities and persistent challenges in funding sophisticated nuclear infrastructure [74].

4.7. Building Critical NE infrastructure

Developing NE necessitates thorough government planning and a solid commitment to building essential infrastructure. This involves outlining a comprehensive business model encompassing procurement, engineering, construction, and operation. Additionally, the roles of the government, private sector, local industry, and engagement with the site and surrounding region should be clearly defined.

Government planning is crucial in establishing the necessary frameworks and policies to facilitate the successful implementation of NE projects. This includes strategic decisions regarding site selection, regulatory processes, licensing requirements, and environmental considerations. The government's role also involves setting clear objectives, ensuring safety and security standards, and establishing long-term energy plans incorporating NE as a significant component.

Collaboration with the private sector is vital, as it brings expertise, technical know-how, and financial resources. Partnerships with local industries can drive economic growth, job creation, and technology transfer. Engaging with the site and regional stakeholders, such as local communities, environmental groups, and other relevant parties, is essential to address concerns, ensure transparency, and foster public acceptance.

Governments can establish the foundation for successful NE infrastructure development by delineating a robust business model and distinctly defining the roles and responsibilities of various stakeholders. This approach promotes effective collaboration, minimizes risks, and establishes a sustainable path toward utilizing nuclear energy.

4.7.1. Development of Local Industry

Before the bidding process, several crucial decisions must be made, including developing local industry capabilities and participation [75]. The case of the Angra Nuclear Power Plant in Brazil highlights two contrasting approaches to fostering local capabilities:

- Angra Nuclear Power Plant - Unit 1:

The utility and the primary supplier contract followed a lump-sum arrangement and an engineering, procurement, and construction (EPC) contract. As a result, the decision-making power

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rested with the contractor, who would naturally prioritize their interests. Consequently, local participation in this project was limited and reached 6% [61].

- Angra Nuclear Power Plant - Unit 2:

Unit 2 is currently in operation, and Unit 3 is currently under construction and is part of a more extensive agreement with Germany encompassing eight units [62,76,77]. In the contracts for Units 2 and 3, a crucial requirement was imposed to increase the participation of the Brazilian industry.

In response to this requirement, large companies were established and aligned with the objectives of promoting local industry participation. Small and medium-sized industries revitalized their manufacturing capabilities, often partnering with foreign suppliers. Notable examples include Nuclebrás Equipamentos Pesados S.A. (Nuclep), which built a new plant dedicated to manufacturing heavy equipment like reactor vessels, steam generators, and pressurizers. Indústrias Nucleares do Brasil - SA (INB) [78] also constructed a new facility to produce nuclear fuel [79].

Through this approach, the participation of local suppliers in Unit 2 reached 67%, showcasing a substantial increase compared to Unit 1. Looking ahead, for Unit 3, which is scheduled to begin operations in 2028, an even higher local participation rate of 70% is anticipated.

These contrasting cases exemplify the importance of deliberate decision-making and contractual arrangements that prioritize the development of local industry capabilities. By fostering collaboration and promoting investments in local manufacturing, countries can significantly increase domestic participation in nuclear projects, leading to economic growth and technological advancement.

Argentina represents another case of successful development of local industry. While nuclear energy primarily served peaceful electricity generation, there were contemplations of military applications, such as a nuclear submarine, though these ideas never materialized. Government policy emphatically prioritized nuclear self-sufficiency, rejecting external controls like those imposed by the IAEA. Despite the explicit focus on peaceful applications, Argentina's nuclear program aroused international suspicions [80].

Argentina operates three nuclear reactors, contributing approximately 7% to its electricity production. The inception of its commercial nuclear power program dates to 1974, with the initiation of the first operational reactor. Also, notably, Argentina is advancing in nuclear technology with the construction of CAREM25, a small power reactor prototype designed locally. Additionally, plans are underway to construct another reactor, which the China National Nuclear Corporation will facilitate.

Bangladesh and UAE are recent commers, where Bangladesh's Rooppur and the UAE's Barakah Nuclear Power Plants also provides practical insights into overcoming challenges in transitioning to nuclear energy. These examples demonstrate the importance of international cooperation, financing, and public acceptance strategies. Rooppur's collaboration with Russia and Barakah's adherence to stringent safety standards, contracted to Korea Electric Power Corporation (KEPCO), underpin the necessity of robust project management and regulatory oversight. These cases also underscore the tailored approaches required to navigate less industrialized countries' socio-political, financial, and technological hurdles, offering valuable lessons on public engagement, safety protocols, and integration into national energy grids [81,82].

Other recent advancements and initiatives include:

- In December 2023, South Africa announced plans to build new nuclear power stations to address its energy crisis. The project has initiated its bidding process and is expected to take over a decade to complete. However, the plan has faced criticism due to alleged corruption [83].
- In September 2024, Nigeria and China signed an agreement to enhance cooperation in the Belt and Road initiative, human resources development, and nuclear energy [84].
- In August 2024, Ghana signed an agreement with a U.S. developer to deploy a NuScale VOYGR-12 small modular reactor (SMR), marking the country's first venture into atomic power [85].
- Rwanda's Nuclear Testing Facility: In September 2023, Rwanda signed a deal with Canadian German company Dual Fluid Energy Inc. to build its first small-scale nuclear reactor to test a new approach to low-carbon energy [86].

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4.7.2. Regional Development

In less industrialized countries, it is common for nuclear power plant sites to be located away from densely populated areas. Following this approach, the selected location and its surrounding region must undergo development and the implementation of essential infrastructure. This includes, but is not limited to, housing and living quarters for the personnel involved in the plant's construction and operation, establishing healthcare facilities, schools, telecommunication and electrical systems, shopping centers, recreational areas, sports facilities, and access roads.

Additionally, it is crucial for the utilities involved to support the local communities, contribute to the development of the local workforce, and improve the infrastructure of nearby cities. By creating a supportive and safe environment for the local population and any incoming personnel, the utilities can foster a sense of community and ensure the well-being of those residing near the nuclear power plant. This includes providing employment and skills training opportunities and contributing to the overall growth and enhancement of the local infrastructure.

4.7.3. Future Energy Demands and Large Reactors for Technological Needs

The rising electricity demand for power data centers, particularly for generative AI, has recently intensified interest in nuclear power due to its scalability and high-capacity factor. A notable example is Microsoft's recent consideration of a partnership with Exelon to restart the Three Mile Island reactor to generate electricity for AI operations [87]. This trend may drive a renewed interest in larger reactors—where countries like South Korea, Russia, and China excel—as they provide economies of scale for industries requiring substantial energy, such as data centers. In contrast, SMRs, though flexible and suitable for smaller grids, are still under development and have not been approved or are in the commercial stage.

4.7.4. Engineering, Construction, and Operation

Developing the local labor force is a crucial aspect to consider when implementing a nuclear project. This development should encompass various technical disciplines and primary services, and to ensure its success, specific requirements should be established during the preparation of the bidding process. The bidding documents and subsequent contracts should outline the milestones for the local labor force, including procedures, training programs, technology transfer, and engineering, construction, and commissioning activities.

An exemplary case highlighting the achievements in local labor force development is Unit 2 of the Angra Nuclear Power Plant. The participation of the local labor force in various areas was as follows:

- Civil Construction: 100%
- Engineering: 42%
- Mechanical and Electrical Erection: 84%
- Commissioning: 26%

The overall local content participation, considering supply and services, reached 67%.[5] This successful development of the local labor force in Brazil led the country to become an exporter of services and goods to the international nuclear market.

By prioritizing the involvement and training of local workers, a nuclear project can have significant socio-economic impacts, fostering job creation, skills development, and technology transfer. This approach benefits the project itself and contributes to the overall growth and capabilities of the local workforce, positioning the country as a competitive player in the global nuclear industry.

[5] All percentages refer to costs.

5. Conclusion and Policy Implications

This paper introduces a comprehensive framework intended to guide less industrialized nations in adopting nuclear energy (NE) for peaceful purposes. It enriches the academic discourse by integrating technical, economic, social, policy, and regulatory dimensions into a unified approach, showcasing NE's critical role in fostering economic growth, scientific advancement, and sustainable development. This study highlights NE's broad applications and outlines strategic approaches to overcome its adoption challenges through innovation and planning. Serving as an invaluable resource for practitioners, this work provides specific strategies for effective governance, stakeholder engagement, safety protocols, expertise development, and securing financial investment. It advocates for a robust NE initiative as a key driver of transformative development, leading to enhanced energy security, economic resilience, and environmental sustainability. By offering scholarly and practical insights, this paper positions NE as a fundamental component of future development strategies within the global energy landscape, emphasizing its indispensable contributions. Future research could focus on developing localized NE implementation models that account for the unique socio-economic conditions of less industrialized countries, further contributing to the nuanced understanding of NE's role in sustainable global development.

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