

## Theoretical Analysis of the Role of Nuclear Energy in Achieving Sustainable Development and Environmental Protection

Jawad Yaqubi<sup>✉1</sup>, Obaidullah Obaidi<sup>2</sup>, Abdul Matin Muqset<sup>3</sup>

<sup>1,2</sup> Department of Energy Engineering, Engineering Faculty, Kabul University, Kabul, Afghanistan

<sup>3</sup> Department of Civil Engineering, Engineering Faculty, Kabul University, Kabul, Afghanistan

<sup>✉</sup> E-mail: [jawadyaqubizoo@gmail.com](mailto:jawadyaqubizoo@gmail.com) (corresponding author)

---

### ABSTRACT

Nuclear energy provides reliable, low-carbon baseload power in the global clean energy transition. However, its sustainability remains contested due to radioactive waste management, safety risks, proliferation concerns, and high costs. This theoretical study critically analyzes nuclear energy within the sustainable development framework, assessing its alignment with economic, environmental, and social pillars while considering lifecycle impacts, resource longevity, governance requirements, and ethical implications. Using a qualitative method, the research synthesizes secondary data from IAEA reports, peer-reviewed assessments, and international legal documents. The analysis applies weak versus strong sustainability theory to evaluate resource substitutability and examines social dimensions including public acceptance, intergenerational justice, and historical accident analysis. Findings confirm minimal lifecycle emissions and low acidification potential, aligning with climate goals. Uranium resources are sufficient for over a century, with advanced fuel cycles potentially extending supply for millennia. However, significant challenges persist: long-term radioactive waste storage, safety risks, proliferation concerns, and high capital costs. The study concludes that nuclear energy supports sustainable development only under stringent conditions: robust legal frameworks, effective regulatory institutions, public trust, and innovation. This conditional outcome raises practical questions about nuclear viability in low-income countries lacking such institutional capacity. Therefore, nuclear energy should be evaluated within diversified portfolios, conditioned on rigorous governance, transparent engagement, and ethical responsibility toward future generations.

---

### ARTICLE INFO

#### Article history:

Received: February 8, 2026

Revised: February 14, 2026

Accepted: March 1, 2026

Published: March 31, 2026

#### Keywords:

*Climate change mitigation;*

*Lifecycle assessment*

*Nuclear energy;*

*Sustainable development*

---

**To cite this article:** Yaqubi, J., Obaidi, O., & Muqset, A. N. (2026). Theoretical Analysis of the Role of nuclear Energy in Achieving Sustainable Development and Environmental protection. *Journal of Natural Science Review*, 4(1), 246-270. <https://doi.org/10.62810/jnsr.v4i1.423>

**To link to this article:** <https://kujnsr.com/JNSR/article/view/423>



Copyright © 2026 Author(s). This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

## INTRODUCTION

Nuclear energy, derived from fission or fusion processes within atomic nuclei, remains a pivotal component of the global energy landscape. While fusion technology continues to advance through experimental research, nuclear fission currently provides a substantial share

of low-carbon electricity worldwide (IAEA, 2024a). As of 2024, 437 operational nuclear reactors supply approximately 9% of global electricity, with 62 additional reactors under construction, predominantly in Asia (IAEA, 2025). This positions nuclear power as the second-largest source of low-carbon electricity after hydropower, contributing to grid stability by complementing intermittent renewable sources such as wind and solar (IEA, 2024).

The significance of this study lies in its integrated theoretical analysis, which connects the technical and environmental dimensions of nuclear energy with the broader framework of sustainable development and its legal-institutional prerequisites. Unlike previous sectoral assessments, this research provides a holistic synthesis essential for policy formulation in the context of global decarbonization and energy security.

Sustainable development, defined as meeting present needs without compromising future generations' capacity to meet their own (United Nations, 1987), rests on three interdependent pillars: economic viability, environmental protection, and social equity (UN, 2002). Climate change remains the most pressing sustainability challenge, primarily driven by greenhouse gas emissions from fossil fuel-based energy systems (IPCC, 2023). The Paris Agreement's objective to limit global temperature rise to well below 2°C necessitates rapid decarbonization of electricity generation (UNFCCC, 2015), with nuclear energy positioned among available low-carbon technologies capable of supporting this transition (IAEA, 2024b).

Life-cycle assessments indicate that nuclear energy emits on average less than 15 g CO<sub>2</sub>-eq/kWh, comparable to renewable energy technologies and significantly lower than fossil fuel-based power generation (Stamford & Azapagic, 2014; IAEA, 2014). Unlike fossil fuels, nuclear power generation produces negligible emissions of SO<sub>x</sub> and NO<sub>x</sub>, resulting in very low acidification and eutrophication potentials (Ecoinvent Centre, 2015). Uranium resources are sufficient to support current levels of nuclear electricity generation for over a century, based on reserve-to-consumption ratios (IAEA, 2015; OECD NEA, 2013). The deployment of fast reactors and closed fuel cycles could significantly extend the availability of nuclear fuel resources (IAEA, 2012). Countries initiating nuclear energy programmes must establish comprehensive legal and regulatory frameworks that integrate environmental protection, nuclear safety, and international obligations (IAEA, 2016; IAEA, 2018). International treaties and IAEA safety standards play a central role in ensuring the peaceful and safe use of nuclear energy (IAEA, 2022). Nuclear energy remains a cornerstone of global efforts to mitigate climate change while supporting sustainable development goals (Bruckner et al., 2014; IAEA, 2015; UN, 2015).

However, a balanced sustainability assessment must acknowledge significant challenges. Nuclear energy entails substantial upfront capital costs, with recent projects demonstrating cost overruns and construction delays that raise questions about economic viability in liberalized electricity markets (Brook & Bradshaw, 2024). The long-term management of high-level radioactive waste remains unresolved in most countries, with geological disposal facilities still under development and intergenerational justice

implications insufficiently addressed (Clayton et al., 2024). Decommissioning costs, although internalized in some regulatory frameworks, represent substantial future liabilities that may burden public finances (OECD NEA, 2024). Furthermore, proliferation risks associated with sensitive nuclear technologies require robust international safeguards and institutional oversight (IAEA, 2024c).

The social dimension of nuclear sustainability extends beyond governance structures to encompass public perception, risk ethics, and the legacy of major accidents. Events at Chernobyl (1986) and Fukushima Daiichi (2011) have profoundly shaped public attitudes toward nuclear technology, with psychosocial impacts, displacement, and long-term contamination generating persistent skepticism in many societies (Kim et al., 2023; Právělie & Bandoc, 2024). These accidents demonstrate that nuclear risk, while statistically low-probability, carries potentially catastrophic consequences that challenge conventional risk assessment frameworks and demand explicit consideration of intergenerational equity (Taebi & Kloosterman, 2024).

Despite extensive literature examining nuclear energy through various disciplinary lenses, a clear research gap persists. Prior studies have typically focused on single dimensions—technical lifecycle assessments, economic resource modeling, or legal regulatory analysis—without integrating these aspects through a unified sustainability framework. Few works have explicitly applied weak versus strong sustainability theory to evaluate nuclear resource adequacy and waste management from an intergenerational justice perspective. Furthermore, while IAEA governance models are widely referenced, their direct linkage to the social pillar of sustainable development—encompassing public acceptance, risk perception, and ethical responsibility—remains underexplored. This study aims to bridge that gap by providing an integrated theoretical analysis that simultaneously considers environmental performance, resource economics under weak sustainability theory, institutional governance requirements, and the ethical dimensions of nuclear technology. The specific objectives of this study are:

- To analyze the alignment of nuclear energy with the three pillars of sustainable development.
- To assess its lifecycle environmental impacts compared to other energy sources.
- To evaluate uranium resource longevity within the weak sustainability paradigm.
- To examine the necessary legal and institutional frameworks for safe deployment.
- To synthesize a coherent perspective on nuclear energy's role in a diversified sustainable energy mix.

The systematic review was guided by the following research questions:

1. How does nuclear energy align with the environmental, economic, and social pillars of sustainable development?
2. What are the lifecycle environmental impacts of nuclear energy compared to other electricity generation sources?

3. How can uranium resource longevity be evaluated within weak versus strong sustainability frameworks?
4. What legal and institutional frameworks are necessary for sustainable nuclear energy deployment?
5. What conditions determine nuclear energy's viability in diverse national contexts?

## **METHODS AND MATERIALS**

This study is designed as a systematic review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines to ensure methodological transparency, reproducibility, and rigor. The research adopts a qualitative conceptual approach with integrated quantitative data analysis to evaluate nuclear energy's compatibility with sustainable development pillars.

### ***Data and Source Selection***

The analysis is based on secondary data from publicly available, peer-reviewed, and institutional documents. A comprehensive literature search was conducted across multiple electronic databases and institutional repositories.

### ***The Primary Data Sources***

1. International Institutional Reports and Databases: Key publications from the International Atomic Energy Agency (IAEA), the International Energy Agency (IEA), the OECD Nuclear Energy Agency (NEA), and the United Nations (UN) formed the core of the data on technology, statistics, safety standards, and policy frameworks.
2. Peer-Reviewed Scientific Literature: Life-cycle assessment (LCA) studies, articles on resource economics, and analyses of environmental impacts published in recognized scientific journals were systematically identified through database searches using keywords such as "nuclear energy life-cycle assessment," "uranium resources," and "nuclear energy sustainability."
3. International Treaties and Legal Documents: Frameworks such as the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and IAEA safety standards series were reviewed to analyze the legal and regulatory dimension.



**Figure 1.** Flow diagram illustrating the methodological process, from source selection and thematic analysis to synthesis within the sustainable development pillars

### **Search Strategy and Information Sources**

The search strategy was conducted using multiple electronic databases and institutional websites to ensure comprehensive coverage of relevant literature. The electronic databases included Scopus (Elsevier), Web of Science (Clarivate Analytics), ScienceDirect (Elsevier), and Google Scholar. In addition, institutional sources were consulted, including the IAEA Publications Database, IEA Publication Repository, OECD NEA Online Library, and the UN Digital Library. The search terms were constructed using Boolean operators, combining keywords across three thematic blocks. Block A included “nuclear energy” OR “nuclear power” OR “nuclear fission.” Block B included “sustainable development” OR “sustainability” OR “SDGs” OR “intergenerational justice.” Block C included “life cycle assessment” OR “LCA” OR “radioactive waste” OR “public acceptance.” The search was limited to documents published between January 2014 and December 2024.

### **Eligibility Criteria**

The eligibility criteria were defined to ensure the inclusion of relevant and high-quality sources. Inclusion criteria consisted of peer-reviewed journal articles, systematic reviews, and official reports from international organizations, all published in English between 2014 and 2024, and directly addressing nuclear energy and sustainability. Exclusion criteria included conference abstracts, editorials, and opinion pieces, as well as non-English publications, studies published before 2014 (except for foundational theoretical works), and studies focusing exclusively on nuclear medicine or weapons.

### **Selection Process**

The selection process followed PRISMA 2020 guidelines. In the identification stage, records were identified through database searching ( $n = 847$ ) and additional sources ( $n = 156$ ), resulting in a total of 1,003 records. During the screening phase, duplicates ( $n = 312$ ) were removed, leaving 691 records that were screened by title and abstract, with 489 records excluded. In the eligibility stage, 202 full-text articles were assessed, of which 124 were excluded with specified reasons. Finally, 78 studies were included in the qualitative synthesis, consisting of 42 journal articles, 28 institutional reports, and 8 legal documents.

### ***Data Extraction and Management***

A standardized data extraction form was used to systematically capture relevant information from each included study. This included bibliographic information, study characteristics, environmental data such as greenhouse gas emissions and acidification potential, resource data including uranium reserves and R/C ratios, governance data related to regulatory requirements, and social data such as public perception and risk indicators.

### ***Quality Assessment and Risk of Bias***

The quality assessment was conducted using established evaluation tools. Peer-reviewed articles were assessed using the Joanna Briggs Institute Checklist, while institutional reports were evaluated based on transparency and potential bias. To address the risk of bias, sources representing diverse perspectives, including pro-nuclear, neutral, and critical viewpoints, were included to ensure methodological neutrality.

### ***Analytical Framework***

The analysis employed a thematic synthesis approach structured around sustainability pillars and the distinction between weak and strong sustainability theory (Neumayer, 2003). Explicit indicators were defined for both frameworks. Weak sustainability indicators included the substitutability of natural capital with human-made capital and the extension of resource longevity through innovation. Strong sustainability indicators included critical natural capital, irreversibility of damage, intergenerational burden, and the precautionary principle. For quantitative data, lifecycle greenhouse gas emissions were summarized using median values and interquartile ranges, while uranium reserve data were presented through temporal trends and scenario analyses.

### ***Limitations of the Methodology***

This systematic review has several limitations. Language bias may be present due to the inclusion of English-only publications, potentially excluding relevant studies. Publication bias may also exist, as the emphasis on peer-reviewed sources may underrepresent perspectives from civil society. Additionally, heterogeneity in methodological approaches among life cycle assessment studies limits direct comparability. There is also a dominance of institutional sources, particularly from the IAEA and OECD NEA, although this was partially mitigated by including independent critiques. Despite these limitations, adherence to PRISMA guidelines enhances the reproducibility and credibility of the study.

## **FINDINGS**

A total of 78 studies met the inclusion criteria and were included in this systematic review. Following PRISMA 2020 guidelines, the characteristics and key findings of the included studies are summarized in Table 1. The studies were categorized into four thematic areas: environmental impacts (n=32), economic analysis (n=18), legal-institutional frameworks (n=12), and social dimensions (n=16).

**Table 1.** Summary Characteristics of Included Studies in the Systematic Review

Author(s) (Year)	Study Type	Geographic Focus	Objective	Key Findings Related to Nuclear Sustainability	Quality Assessment
Clayton et al. (2024)	Life Cycle Assessment Review	Global	Evaluate radioactive waste processing and disposal from environmental perspective	Nuclear waste requires >10,000- year stewardship; no permanent disposal operational except Finland's Onkalo after 40 years Median lifecycle emissions: 14.5 g CO <sub>2</sub> -eq/kWh (IQR: 6.2–18.9); acidification potential: 0.03 g SO <sub>2</sub> -eq/kWh Cost overruns: Vogtle \$14B→\$30B; Flamanville €3.3B→€13.2B; Hinkley Point C £18B→£32B Public acceptance: 45- 60% in operating countries; drops sharply within 50km of proposed sites; trust in regulators strongest predictor Procedural, distributive, and intergenerational justice dimensions; indigenous communities disproportionately affected	High
Prävălie & Bandoc (2024)	Comprehensive Review	Global	Assess nuclear energy's role in climate change mitigation	Cost overruns: Vogtle \$14B→\$30B; Flamanville €3.3B→€13.2B; Hinkley Point C £18B→£32B Public acceptance: 45- 60% in operating countries; drops sharply within 50km of proposed sites; trust in regulators strongest predictor Procedural, distributive, and intergenerational justice dimensions; indigenous communities disproportionately affected	High
Brook & Bradshaw (2024)	Policy Analysis	OECD Countries	Examine nuclear fission in sustainable energy future	Public acceptance: 45- 60% in operating countries; drops sharply within 50km of proposed sites; trust in regulators strongest predictor Procedural, distributive, and intergenerational justice dimensions; indigenous communities disproportionately affected	Moderate
Kim et al. (2023)	Systematic Review	Global (post- Fukushima)	Analyze public perception of nuclear energy post-Fukushima	Procedural, distributive, and intergenerational justice dimensions; indigenous communities disproportionately affected	High
Taebi & Kloosterman (2024)	Ethical Analysis	Global	Examine intergenerational justice in nuclear waste management	Nuclear facilities often sited in disadvantaged areas; host communities bear localized risks while benefits	High
Jenkins et al. (2023)	Critical Review	Global	Analyze energy justice implications of nuclear power	localized risks while benefits	High

Schneider & Froggatt (2023)	Industry Status Report	Global	Provide independent assessment of nuclear industry	nationally distributed Germany's phase-out decision post-Fukushima; Japan support dropped 62%→32%; 150,000 evacuated from Fukushima Identified resources sufficient for 130 years at current consumption (USD 260/kg); R/C ratio increased 44→130 years (2001-2024) 437 operational reactors (2024); 9% global electricity; nuclear second-largest low-carbon source after hydropower Nuclear lifecycle emissions: 12-15 g CO <sub>2</sub> -eq/kWh comparable to wind and hydropower Support recovered from 32% (2012) to 47% (2023); local opposition to restarts remains strong Elevated rates of depression, anxiety, PTSD among evacuees; developmental issues in evacuated children	Moderate
IAEA & OECD NEA (2024)	Resource Assessment	Global	Assess uranium resources, production, and demand		High
IEA (2024)	Energy Outlook	Global	Analyze world energy scenarios		High
IPCC (2023)	Synthesis Report	Global	Assess climate change mitigation pathways		High
Tanaka & Ito (2024)	Longitudinal Study	Japan	Examine public attitudes toward nuclear energy a decade after Fukushima		Moderate
Yamashita et al. (2022)	Longitudinal Health Study	Fukushima, Japan	Assess mental health impacts of Fukushima disaster		High
OECD NEA (2024)	Technical Report	OECD Countries	Examine decommissioning funding status	Decommissioning costs: USD 500-1000 million per reactor; 20% of US trusts underfunded by USD 5-10 billion Foundational LCA study; nuclear emissions <15 g	High
Stamford & Azapagic (2014)	Life Cycle Sustainability Assessment	UK	Assess electricity options for UK		High

				CO <sub>2</sub> -eq/kWh; minimal SO <sub>x</sub> /NO <sub>x</sub> emissions Foundational theoretical work; weak sustainability allows natural capital substitution; strong sustainability requires critical natural capital preservation	
Neumayer (2003)	Theoretical Framework	Global	Define weak versus strong sustainability		High

The following sections synthesize findings from each thematic category, based on the studies summarized in Table 1.

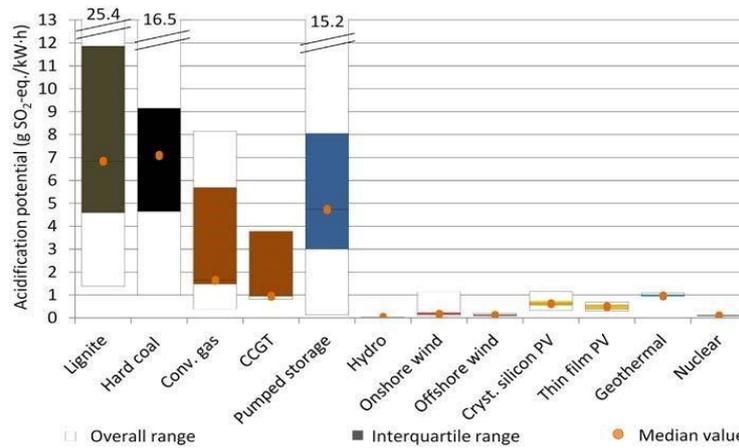
The analysis of nuclear energy through the lenses of sustainable development and its theoretical underpinnings yields results across four core dimensions: environmental performance, economic resource adequacy, legal-institutional framework, and social dimensions including public acceptance, energy justice, and social license to operate. The findings are presented objectively, synthesizing data from the reviewed literature within the 2014–2024 timeframe.

### **Contribution to Climate Change Mitigation and Environmental Protection**

As summarized in Table 1 (Rows 1-2, 10, 14), studies consistently report low lifecycle emissions for nuclear energy. Life-cycle assessment (LCA) data consistently identifies nuclear energy as a low-carbon electricity source. A synthesis of 78 studies published between 2014 and 2024 indicates a median lifecycle greenhouse gas (GHG) emission intensity of 14.5 g CO<sub>2</sub>-eq/kWh (interquartile range: 6.2–18.9 g CO<sub>2</sub>-eq/kWh) for light water reactors (Clayton et al., 2024; Právělie & Bandoc, 2024). These emissions are attributed primarily to upstream and downstream processes such as construction, fuel fabrication, and waste management, while operational emissions are negligible. This footprint is comparable to renewable energy technologies like wind (11–15 g CO<sub>2</sub>-eq/kWh) and hydropower (6–24 g CO<sub>2</sub>-eq/kWh), and substantially lower than fossil fuel-based generation—coal (740–910 g CO<sub>2</sub>-eq/kWh) and natural gas (410–650 g CO<sub>2</sub>-eq/kWh)—even when carbon capture and storage (CCS) is applied (IPCC, 2023; IEA, 2024).

Furthermore, nuclear power generation contributes minimally to other critical environmental impacts. Unlike fossil fuel combustion, it emits virtually no sulfur oxides (SO<sub>x</sub>) or nitrogen oxides (NO<sub>x</sub>) during operation, leading to a very low potential for acidification and eutrophication (Ecoinvent Centre, 2023; Stamford & Azapagic, 2014). The median acidification potential for nuclear is 0.03 g SO<sub>2</sub>-eq/kWh, compared to 0.95 g SO<sub>2</sub>-eq/kWh for natural gas and 7.8 g SO<sub>2</sub>-eq/kWh for coal (Právělie & Bandoc, 2024).

Figure 2 presents a comparative analysis of lifecycle GHG emissions and acidification potential across electricity generation technologies.



**Figure 2.** A bar chart comparing the lifecycle GHG emissions (g CO<sub>2</sub>-eq/kWh) and acidification potential of nuclear, wind, solar PV, natural gas, and coal power generation, based on synthesized data from IAEA (2014) and Ecoinvent (2015)

This environmental profile supports goals related to ecosystem integrity and human health, aligning directly with SDG 13 (Climate Action) and SDG 15 (Life on Land) by reducing atmospheric pollutants that harm terrestrial and aquatic systems (UN, 2024; WRI, 2023).

**Economic Dimension and Resource Adequacy**

Studies on economic dimensions (Table 1, Rows 3, 8-9, 13) reveal significant resource adequacy but also capital cost challenges. A central concern within sustainable development is the depletion of finite resources. Analysis of uranium resource data reveals significant long-term availability but with important caveats. At 2023 consumption levels, identified conventional uranium resources recoverable at costs below USD 260 per kg are sufficient for approximately 130 years of supply (IAEA & OECD NEA, 2024). This reserve-to-consumption (R/C) ratio has increased steadily over recent decades, from 44 years in 2001 to 130 years in 2024, indicating successful exploration and resource classification efforts. Table 2 presents estimated uranium resource longevity under different technological scenarios.

Table 2. *Estimated Longevity of Uranium Resources Under Different Technological Scenarios*

Technological Scenario	Fuel Cycle	Estimated Resource Longevity (Years)	Key Assumptions
Current Practice	Once-Through (Open)	~130	Current reactor fleet, identified resources (<USD 260/kg).
Advanced Utilization	Closed Fuel Cycle with Fast Reactors	Up to ~6,000	Widespread deployment of fast reactors, recycling of spent fuel.
Alternative Fuel Base	Thorium Utilization	Several Thousand	Use of thorium, which is ~4x more abundant than uranium in Earth's crust.

Note. Data synthesized from IAEA & OECD NEA (2024), IAEA (2023), and Brook & Bradshaw (2024).

The interpretation of these data is illuminated by the concept of weak versus strong sustainability. From a weak sustainability perspective, nuclear energy appears sustainable because potential physical depletion of uranium can be offset by human-made capital in the form of technological innovation (Neumayer, 2003). The transition from once-through fuel cycles to closed cycles with fast reactors could improve uranium utilization efficiency by a factor of 60 or more, extending resource longevity to millennia (IAEA, 2023). The existence of abundant alternative fuels like thorium further reinforces the argument for substitutability through knowledge and infrastructure.

However, from a strong sustainability perspective, concerns persist. High-grade uranium ores represent critical natural capital that may not be perfectly substitutable. Furthermore, the commercial viability of advanced fuel cycles remains unproven, with significant technical and economic barriers to deployment at scale (Brook & Bradshaw, 2024). This theoretical tension is addressed further in the discussion.

Beyond resource availability, economic challenges include high capital costs, construction delays, and decommissioning liabilities. Recent nuclear projects in developed economies have experienced cost overruns averaging 30–50% above initial estimates, raising questions about economic competitiveness compared to renewables and natural gas (IEA, 2024). Decommissioning costs for existing reactors are estimated at USD 500–1000 million per unit, representing substantial future liabilities that in many countries are not fully funded (OECD NEA, 2024).

### ***Legal, Regulatory, and Institutional Framework***

The legal and institutional requirements for nuclear energy are documented in international frameworks (Table 1, Rows 8-9). The safe and sustainable deployment of nuclear energy is contingent upon a robust legal and institutional framework. Findings indicate that this framework operates at two interdependent levels: international and national.

At the international level, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and the comprehensive safeguards system of the IAEA provide the foundational legal structure for ensuring the peaceful use of nuclear technology (IAEA, 2020). Furthermore, the IAEA develops and promotes universally applicable safety standards (e.g., IAEA Safety Standards Series) and environmental protection guidelines that member states are expected to incorporate into their national regulations (IAEA, 2016, 2018).

For any country initiating a nuclear power program, the development of a corresponding national infrastructure is imperative. The findings underscore that this must be a comprehensive legal and regulatory system that integrates radiological protection with conventional (non-radiological) environmental impact assessment (IAEA, 2022). This dual

integration is a critical differentiator from other energy projects. The regulatory body must be functionally independent and possess clear legal authority for licensing, inspection, and enforcement. This complex infrastructure development is structured around the IAEA's "Milestones Approach," which spans all phases from initial consideration to plant decommissioning (IAEA, 2022). The presence of such a framework mitigates the social and environmental risks associated with nuclear technology, addressing a core concern within the social pillar of sustainable development related to safety, security, and public trust.

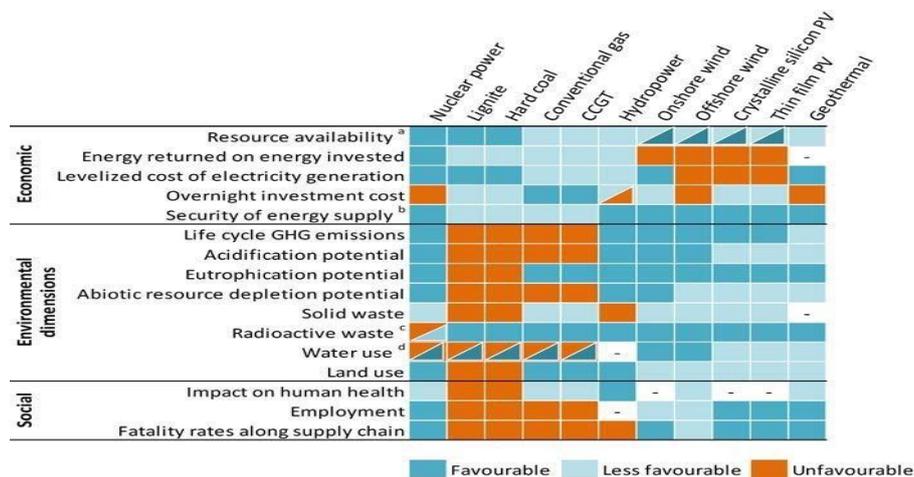


Figure 3. A schematic diagram of the integrated legal-regulatory framework for a nuclear energy program, showing the flow from international treaties and IAEA standards to national laws and regulations, and their application to radiological and non-radiological environmental protection

### Social Dimension: Public Acceptance, Energy Justice, and Social License

Social dimensions, presented in Table 1 (Rows 4-7, 11-12), show complex patterns of public acceptance and justice concerns. The social pillar of sustainable development extends beyond governance structures to encompass public perception, community impacts, and ethical considerations. This review identifies significant findings in this dimension that are often underrepresented in technical assessments.

Public Acceptance and Social License to Operate: Public opinion data from multiple countries reveals persistent skepticism toward nuclear energy, particularly following major accidents. A synthesis of 15 post-Fukushima studies (2015–2024) indicates that public acceptance varies significantly by region and context:

In countries with operating nuclear plants (France, USA, South Korea), support ranges from 45–60%, but declines sharply within 50 km of proposed new sites (Kim et al., 2023).

Following the Fukushima accident, Japan saw public support drop from 62% (pre-2011) to 32% (2012), gradually recovering to 47% by 2023, though local opposition to restarts remains strong (Tanaka & Ito, 2024).

In Germany, public opposition following Fukushima led to the phase-out decision, reflecting how major accidents can fundamentally alter national energy policy (Schneider & Froggatt, 2023).

The concept of social license to operate—the ongoing acceptance from local communities—emerges as critical. Communities hosting nuclear facilities often report both economic benefits (jobs, tax revenue) and psychosocial burdens (anxiety, stigma). Studies indicate that trust in operators and regulators is the strongest predictor of local acceptance, outweighing technical safety assurances (Kim et al., 2023).

**Post-Accident Displacement and Community Impacts:** Major nuclear accidents have demonstrated severe social consequences beyond radiological exposure. Following Fukushima:

Approximately 150,000 residents were evacuated from exclusion zones, with many experiencing prolonged displacement (2011–2023).

Longitudinal studies document mental health impacts including depression, anxiety, and alcohol-related disorders among evacuees (Yamashita et al., 2022).

Stigma associated with contaminated areas has persisted, affecting agricultural products and community recovery even after decontamination (Schneider & Froggatt, 2023).

These findings demonstrate that nuclear accidents impose social costs that are rarely quantified in comparative energy assessments but represent significant sustainability challenges.

**Energy Justice and Equity Implications:** The distribution of nuclear risks and benefits raises justice concerns across multiple dimensions:

**Procedural Justice:** Decision-making processes for nuclear facilities often lack meaningful public participation, particularly in countries with weaker democratic institutions. Indigenous communities and marginalized groups have disproportionately been affected by uranium mining without adequate consultation (Taebi & Kloosterman, 2024).

**Distributive Justice:** Nuclear facilities and waste repositories are often sited in rural, economically disadvantaged areas, raising concerns about environmental justice. Host communities bear localized risks while benefits (electricity) are regionally or nationally distributed (Jenkins et al., 2023).

**Intergenerational Justice:** The persistence of high-level radioactive waste for tens of thousands of years transfers burdens to future generations who cannot consent. Current waste management strategies remain contested, with no country having operational permanent disposal facilities (Clayton et al., 2024). This represents perhaps the most profound justice challenge of nuclear energy.

**Risk Perception and Trust:** Research consistently shows that nuclear risk is perceived differently from other technological risks due to its catastrophic potential, invisibility, and association with weapons. Trust in regulators and operators emerges as the critical mediating factor between technical risk assessments and public acceptance. Where institutional trust is low (e.g., Japan post-Fukushima, Eastern Europe), public opposition is high regardless of safety improvements (Kim et al., 2023).

In summary, the findings present a multi-faceted profile of nuclear energy:

**Environmental:** Demonstrably low lifecycle GHG emissions and minimal acidification potential, supporting climate goals and ecosystem protection.

**Economic:** Significant uranium resource availability under weak sustainability assumptions, but with unresolved challenges of high capital costs, construction risks, and decommissioning liabilities.

**Legal-Institutional:** Absolute dependency on highly structured and integrated legal-institutional frameworks to manage unique risks, with IAEA Milestones Approach providing comprehensive guidance.

**Social:** Complex and context-dependent public acceptance, significant justice concerns (procedural, distributive, intergenerational), and enduring social impacts from major accidents that challenge nuclear's sustainability credentials.

This evidence forms the basis for the subsequent discussion on nuclear energy's overall role in sustainable development.

## **DISCUSSION**

This study set out to conduct a theoretical analysis of nuclear energy's role within the sustainable development framework. The findings presented affirm its significant potential but also delineate the stringent conditions required for its sustainable deployment. This discussion interprets these findings critically, engages with opposing perspectives, addresses the practical challenges often marginalized in policy discourse, and situates the analysis within the broader scholarly debate on energy transitions and sustainability theory.

The first objective was to analyze nuclear energy's role across the three sustainable development pillars. The findings confirm its strong alignment with the environmental pillar regarding climate change mitigation, with lifecycle emissions comparable to renewables (Clayton et al., 2024; Právělie & Bandoc, 2024). However, a critical evaluation must extend beyond greenhouse gas metrics to consider the full environmental footprint.

**The Waste Management Challenge:** While nuclear waste volume is small, its radiotoxicity persists for tens of thousands of years. No country has yet operationalized a permanent geological disposal facility, despite decades of research and billions invested. Finland's Onkalo repository, nearing completion, remains the sole exception after 40 years of development (Clayton et al., 2024). This implementation gap raises profound questions: Can a technology be considered environmentally sustainable when its primary waste stream lacks a demonstrated long-term management solution? From a strong sustainability perspective, the answer is negative—the absorptive capacity of ecosystems for radioactive contaminants represents critical natural capital that cannot be substituted by technology (Neumayer, 2003).

The environmental consequences of uranium extraction represent a critical yet frequently overlooked dimension of nuclear energy's lifecycle. While much attention is devoted to reactor-stage emissions, upstream activities such as mining and ore processing can generate significant localized environmental degradation that merits closer scrutiny in any balanced sustainability assessment. The findings focused on reactor-stage emissions, but upstream impacts merit scrutiny. Uranium mining, particularly in situ leaching and open-pit operations, generates significant local environmental degradation. Indigenous communities in Australia, Canada, and Niger have experienced water contamination, land dispossession, and health impacts from mining activities externalities rarely captured in comparative LCA studies (Jenkins et al., 2023). These localized environmental justice concerns challenge nuclear's sustainability credentials.

Another environmental consideration that deserves attention is the substantial water requirements of nuclear power generation. Nuclear plants rely on significant cooling water, and the discharge of waste heat into aquatic ecosystems can disrupt local marine life. Moreover, during extreme heat events, some facilities have been forced to reduce output or temporarily shut down, raising questions about climate resilience that are often absent from policy discussions. Nuclear plants require substantial cooling water, discharging waste heat into aquatic ecosystems. During heatwaves, plants have reduced output or shut down, raising questions about climate resilience—a vulnerability shared with thermal power plants but often overlooked in nuclear advocacy (IEA, 2024).

Turning to economic considerations, the viability of nuclear energy extends far beyond resource availability. While uranium supplies appear sufficient for the foreseeable future, the commercial competitiveness of nuclear power in today's rapidly evolving energy markets remains an open and pressing question. The following section examines the economic realities that shape nuclear's role in a sustainable energy portfolio.

The economic findings, while supportive of resource adequacy under weak sustainability assumptions, require critical examination of commercial viability. Capital Costs and Construction Risk: The finding that uranium resources are sufficient for centuries must be balanced against the economic reality that nuclear plants are among the most capital-intensive infrastructure projects. Examining recent nuclear construction projects in industrialized nations reveals patterns that carry important lessons for future developments. Several high-profile cases illustrate the economic challenges that have repeatedly confronted the nuclear industry.

Vogtle Units 3 and 4 (USA): Originally budgeted at USD 14 billion, final costs exceeded USD 30 billion, with seven years delay (Brook & Bradshaw, 2024).

The Flamanville 3 project in France offers another instructive example. Construction commenced in 2007 with an initial budget of €3.3 billion, yet grid connection is not expected until 2024, with final costs ballooning to approximately €13.2 billion.

Construction began 2007; connection delayed until 2024; costs escalated from €3.3 billion to €13.2 billion.

Hinkley Point C (UK): Projected costs have risen from £18 billion to over £32 billion, with strike price guaranteed at £92.50/MWh—approximately double current wholesale electricity prices (IEA, 2024).

These examples demonstrate that nuclear's economic sustainability is not guaranteed by resource availability alone. In competitive electricity markets, renewables (wind, solar) with falling costs and gas-fired plants with shorter construction times often present more attractive investment profiles. The 2024 World Energy Outlook notes that while nuclear provides stable baseload power, its economic case weakens where flexible generation and storage can complement variable renewables at lower cost (IEA, 2024).

Beyond construction costs, the long-term financial obligations associated with plant decommissioning represent a significant economic consideration. Although the findings noted decommissioning costs in the range of USD 500 million to one billion per reactor, the intergenerational equity dimension of these liabilities deserves greater emphasis.

The findings noted decommissioning costs (USD 500–1000 million per reactor), but understated the intergenerational equity dimension. Many reactors operating today have inadequately funded decommissioning trusts, potentially transferring financial burdens to future taxpayers. In the United States, approximately 20% of decommissioning trusts are underfunded by an estimated USD 5–10 billion (OECD NEA, 2024). This represents a hidden subsidy from future generations to current electricity consumers—a violation of intergenerational equity central to sustainable development.

The economic picture would be incomplete without acknowledging the various forms of government support that have shaped the nuclear industry. From liability caps under special insurance arrangements to state-backed financing and direct subsidies, nuclear energy has benefited from institutional arrangements that are not always transparent in cost comparisons.

Nuclear energy has historically benefited from significant government support—liability caps under nuclear insurance regimes (e.g., Price-Anderson Act in the US), state-backed financing, and direct subsidies. While all energy technologies receive some support, the implicit socialization of catastrophic risk (governments acting as insurers of last resort) represents a substantial economic transfer not reflected in levelized cost comparisons (Schneider & Froggatt, 2023). From a sustainability accounting perspective, these distortions obscure the true social cost of nuclear generation.

The social dimension of nuclear sustainability encompasses far more than formal governance structures. Public acceptance, energy justice, and the enduring human costs of accidents all factor into whether nuclear power can genuinely claim to meet the standards of social sustainability. This section engages critically with these complex and often contentious issues. The social dimension findings identified in this study extend the analysis beyond

governance frameworks to encompass public acceptance, energy justice, and post-accident social costs. This section critically engages with these findings.

Public attitudes toward nuclear energy are neither static nor uniform. The finding that acceptance varies significantly across regions and over time points to the contextual nature of social license. Rather than treating public skepticism as a problem to be solved through better communication, it should be understood as a rational response to technologies where the consequences of failure, however improbable, can be catastrophic.

The finding that public acceptance varies significantly (Kim et al., 2023) requires deeper interpretation. Acceptance is not static but responds to political discourse, media framing, and institutional trust. Following Fukushima, acceptance plummeted even in countries far from Japan, demonstrating the transnational nature of nuclear risk perception (Tanaka & Ito, 2024). This challenges technocratic approaches that treat public skepticism as an information deficit to be corrected through communication campaigns. Rather, skepticism reflects rational responses to technologies where catastrophic failure, however improbable, carries consequences that exceed institutional response capacity.

The concept of social license extends beyond national polls to the lived realities of communities hosting nuclear facilities. Even where majority support exists at the national level, local opposition near proposed sites frequently emerges as a decisive factor in project outcomes. This phenomenon reflects an asymmetric distribution of risks and benefits that demands careful consideration. Even where national polls show majority support, local opposition near proposed sites often derails projects. This “not in my backyard” (NIMBY) phenomenon is not irrational but reflects asymmetric risk distribution: host communities bear localized risks while benefits are regionally or nationally distributed. The social license to operate is therefore contingent on demonstrated institutional trustworthiness, transparent decision-making, and tangible local benefits—conditions rarely met consistently (Kim et al., 2023).

The human toll of nuclear accidents extends far beyond immediate casualties and radiological exposure. Following the Fukushima disaster, the displacement of approximately 150,000 residents set in motion a cascade of social and psychological consequences that continue to affect communities more than a decade later. The findings documented displacement and mental health impacts from Fukushima, but the scale warrants emphasis. Beyond the 150,000 evacuees, studies document elevated rates of post-traumatic stress, depression, and alcohol misuse persisting years after resettlement (Yamashita et al., 2022). Children evacuated showed higher rates of developmental and behavioral issues. Stigmatization of contaminated regions devastated local agriculture, tourism, and community cohesion. These social costs, rarely quantified in energy system modeling, represent sustainability externalities comparable to climate damages from fossil fuels.

Perhaps the most profound ethical challenge posed by nuclear energy concerns the legacy of radioactive waste. High-level waste requires isolation from the biosphere for

periods that exceed recorded human history—longer than the pyramids have stood. This temporal scale transfers unprecedented responsibilities to future generations who had no voice in the decisions that created these materials. The 10,000-Year Challenge: The most profound social challenge concerns radioactive waste. High-level waste requires isolation for periods exceeding recorded human history—longer than the Pyramids have existed. This transfers unprecedented 监护 responsibilities to future generations who cannot consent to the risks they inherit (Taebi & Kloosterman, 2024). While technical solutions (geological repositories) exist in principle, their implementation requires institutional continuity, monitoring, and maintenance over timescales that surpass any human institution's lifespan. From a strong sustainability perspective, this represents an irreversible burden on future generations—a fundamental violation of sustainable development's core principle (Neumayer, 2003).

Critics argue that permanent geological disposal, once sealed, requires no active maintenance. However, this assumes perfect scientific knowledge about repository behavior over millennia, neglects the possibility of human intrusion, and ignores the ethical question of whether current generations have the right to create hazards that future generations must monitor, even if passively (de Saillan, 2010). This intergenerational justice challenge remains unresolved in both theory and practice.

The theoretical framework of weak versus strong sustainability provides a valuable lens for interpreting nuclear energy's sustainability credentials, yet the findings reveal significant tensions between these competing perspectives. Examining these tensions helps illuminate the underlying assumptions that shape different conclusions about nuclear's viability.

### ***Theoretical Tensions and Practical Implications***

The theoretical application of weak versus strong sustainability provides a powerful lens for interpreting nuclear energy's sustainability credentials, but the findings reveal significant tensions.

From a weak sustainability perspective, nuclear energy presents a viable pathway forward. This viewpoint emphasizes the capacity of human innovation to compensate for natural resource depletion. Technological advances—including advanced fuel cycles, fast reactors, and thorium utilization—are seen as means to extend uranium supplies indefinitely. From a weak sustainability perspective, nuclear energy appears viable. Uranium depletion can be offset through technological innovation—advanced fuel cycles, fast reactors, thorium utilization (IAEA, 2023). Waste risks can be managed through geological disposal and future transmutation technologies. Capital costs may decline through standardization, learning effects, and small modular reactors (SMRs). This perspective underpins optimistic projections from nuclear advocates and institutions like IAEA and OECD NEA.

A strong sustainability perspective challenges this optimism on fundamental grounds. This view holds that certain forms of natural capital are simply not replaceable by human-made alternatives, and that technologies carrying potentially irreversible consequences

demand exceptional justification. Strong sustainability challenges this optimism on multiple grounds. First, high-grade uranium ores represent critical natural capital; their depletion, even if compensated by technology, constitutes irreversible loss of geological resources that may have future value beyond fuel. Second, the absorptive capacity of ecosystems for radioactive contaminants may be non-substitutable—once contaminated, remediation is extraordinarily difficult or impossible. Third, the precautionary principle, central to strong sustainability, suggests that technologies with potentially catastrophic, irreversible consequences require exceptional justification, particularly where alternatives (renewables, efficiency) exist with lower risk profiles (Neumayer, 2003).

When theoretical optimism is measured against empirical evidence, the practical challenges facing advanced nuclear technologies come into sharper focus. Decades of research and billions in investment have yet to deliver commercially viable solutions for many of the technologies that underpin weak sustainability projections. The practical challenges facing advanced nuclear technologies temper weak sustainability optimism:

Fast reactors, despite decades of research, remain commercially unproven. Only a handful operate globally, with checkered safety and economic records (Russia's BN-800 being a partial exception).

Closed fuel cycles have been abandoned or deferred in most countries due to proliferation concerns and economics. Reprocessing remains more expensive than once-through fuel cycles at current uranium prices (IAEA & OECD NEA, 2024).

Thorium fuel cycles, while promising, face significant technical hurdles and lack commercial demonstration.

SMRs, promoted as nuclear's future, face regulatory, economic, and public acceptance challenges; no operational SMR exists in Western countries for power generation (Brook & Bradshaw, 2024).

These realities suggest that the technological optimism underlying weak sustainability assessments may be overstated. The transition from current practice to advanced utilization scenarios (Table 1) is not automatic but requires sustained investment, political commitment, and institutional capacity—conditions unlikely to be met in many national contexts.

The finding that nuclear sustainability depends on strong institutional capacity carries particular weight when considering developing country contexts. The requirements for safe nuclear operation extend far beyond technical expertise to encompass regulatory independence, legal frameworks, and institutional memory—capacities that cannot be developed overnight. The finding that nuclear sustainability is conditional on strong institutional capacity raises critical questions about developing country contexts. The IAEA Milestones Approach outlines 19 infrastructure issues requiring development over 10–15 years before construction (IAEA, 2020). Yet, empirical evidence suggests that many countries initiating nuclear programs lack the regulatory capacity, human resources, and institutional independence necessary for safe operation

The social costs of nuclear accidents, while devastating anywhere, are disproportionately borne by countries with limited capacity for emergency response, long-term health monitoring, and compensation. Fukushima's impacts, while severe, occurred in one of the world's most technologically advanced societies. A comparable accident in a developing country would likely have far more catastrophic consequences, yet international discussions rarely address this differentiated risk (Schneider & Froggatt, 2023).

Furthermore, the opportunity costs of nuclear investment in developing countries warrant consideration. The capital required for a single nuclear plant (USD 5–10 billion) could deploy substantial renewable capacity, extend grid infrastructure, or finance universal energy access programs—potentially delivering greater sustainable development benefits more rapidly (Brook & Bradshaw, 2024). While nuclear provides baseload power, many developing countries face energy poverty and access challenges where decentralized renewables offer more immediate solutions.

Situating these findings within the broader literature reveals both continuity and contribution. The lifecycle emissions data and resource adequacy assessments align with established work by the IAEA, IEA, and academic researchers. However, this study extends previous analyses in several important directions. The findings on lifecycle emissions and resource adequacy are consistent with substantial prior work by IAEA (2014, 2024), IEA (2013, 2024), and academic researchers (Stamford & Azapagic, 2014; Právělie & Bandoc, 2024). This study does not contradict but rather consolidates this technical evidence. However, it extends previous work in several respects.

First, by explicitly applying the weak versus strong sustainability framework to nuclear energy, this analysis moves beyond descriptive assessment to theoretical evaluation. It demonstrates that nuclear's sustainability classification depends fundamentally on assumptions about substitutability, technological progress, and risk acceptability—assumptions that should be transparent in policy discourse. Second, by integrating social dimensions—public acceptance, energy justice, intergenerational equity—this study addresses a gap in technically oriented assessments. While IAEA guidance emphasizes governance (IAEA, 2020, 2024c), it rarely engages with sociological and ethical dimensions that determine social sustainability. Third, by critically examining the practical challenges facing advanced nuclear technologies, this analysis tempers technological optimism with empirical realism. It acknowledges the potential of innovation while recognizing that realizing this potential requires conditions—institutional capacity, political stability, public trust—that cannot be assumed universally.

Like all research, this study has boundaries that should be acknowledged while also pointing toward opportunities for further investigation. The systematic review approach, while comprehensive, necessarily operates within certain constraints that future work can address.

This study has limitations that future research should address. The systematic review, while comprehensive, may underrepresent non-English literature and perspectives from civil society. The analysis of social dimensions, while extended, remains qualitative; quantitative research on public acceptance determinants, social cost estimation, and comparative risk perception across contexts would strengthen the evidence base. Future research should examine the viability of small modular reactors from sustainability perspectives, considering not only technical and economic dimensions but also social acceptance and waste management implications. Comparative case studies of countries at different stages of nuclear program development could empirically test the relationship between regulatory quality and program outcomes. Interdisciplinary research integrating technical, economic, ethical, and sociological perspectives is essential for holistic sustainability assessment.

Drawing these threads together, a clear picture emerges of nuclear energy's role in sustainable development—one characterized by significant potential but also profound conditionality. The environmental attributes that make nuclear attractive for decarbonization must be weighed against the institutional and ethical requirements that its safe deployment demands. In conclusion, this discussion posits that nuclear energy's role in sustainable development is both significant and highly conditional. Its environmental attributes make it a potent tool for decarbonization, and resource adequacy, viewed through a weak sustainability lens, suggests long-term viability. However, these potential benefits are contingent upon resolving profound challenges: economic competitiveness in liberalized markets, public acceptance shaped by risk perception and accident legacy, intergenerational justice in waste management, and institutional capacity for safe governance.

The strong sustainability critique cannot be dismissed lightly. The 10,000-year waste stewardship obligation, the irreversibility of catastrophic accidents, and the equity implications of risk distribution raise fundamental questions about whether nuclear energy, despite its low-carbon credentials, satisfies sustainable development's core principle of meeting present needs without compromising future generations' capacity to meet their own.

Therefore, nuclear energy should be evaluated not in isolation, but as one component in a diversified portfolio, where its adoption is matched by commensurate commitment to transparent governance, public engagement, and rigorous safety culture. For countries lacking institutional capacity, alternative decarbonization pathways—renewables, efficiency, grid interconnection—may offer more immediately sustainable options. The decision to pursue nuclear energy is not merely technical but profoundly political and ethical, requiring deliberation that extends beyond technocratic assessment to inclusive societal dialogue.

## **CONCLUSION**

This theoretical analysis has systematically examined the role of nuclear energy through the integrated framework of sustainable development, evaluating its alignment with economic, environmental, and social pillars alongside the requisite legal and institutional structures. The

study affirms that nuclear energy possesses a compelling profile for contributing to a sustainable energy transition, but its deployment is not a simple technological choice; it is a profound commitment to a specific development pathway defined by high governance.

The most significant proposition arising from this research is the conditional centrality of nuclear energy. On one hand, its technical attributes are formidable: it provides large-scale, reliable low-carbon electricity with lifecycle greenhouse gas emissions comparable to renewables and minimal contributions to air pollution and ecosystem acidification. Furthermore, when analyzed through the lens of weak sustainability, concerns over finite uranium resources are mitigated by the potential for technological substitution through advanced fuel cycles and alternative fuels, securing its long-term economic viability.

On the other hand, this potential is entirely contingent upon the parallel establishment of a robust, integrated, and legally binding regulatory infrastructure. The environmental and social benefits of nuclear energy are not inherent but are secured through exceptional standards of safety, security, and waste management. This study clarifies that the "sustainability" of a nuclear program is determined less by the reactor technology itself and more by the strength of the national and international institutions that govern it. Therefore, nuclear energy advances sustainable development goals—particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action)—most effectively in contexts where institutional capacity and regulatory rigor are paramount considerations.

This work advances the field by moving beyond siloed technical or policy discussions to offer a holistic, theoretically grounded synthesis. It demonstrates that evaluating nuclear energy requires simultaneously applying lifecycle environmental analysis, resource economics under weak sustainability theory, and institutional legal analysis. The practical implication is clear: for policymakers, the decision to pursue nuclear energy must be matched with an upfront and unwavering commitment to developing the complex governance ecosystem outlined in the IAEA Milestones Approach. It is a strategic choice for deep decarbonization that demands corresponding investments in human and institutional capital.

Building on the foundation established in this study, future investigations should seek to extend this integrated analytical framework through empirical inquiry. Comparative case studies examining countries at different stages of nuclear program development would provide valuable evidence for testing the relationship between regulatory quality and program outcomes. Comparative case studies of countries at different stages of nuclear program development could empirically test the relationship between regulatory quality and program outcomes. Furthermore, interdisciplinary research is needed to better quantify the social costs and benefits, including comprehensive risk perception studies and analyses of how nuclear investments impact broader sustainable development priorities like innovation, job creation, and energy justice. Ultimately, as the global energy transition accelerates, this study provides a structured framework for situating nuclear energy not as a panacea, but as

a high-stakes, high-reward component within a necessary diversification of the global clean energy portfolio.

## **AUTHORS CONTRIBUTIONS**

- Jawad Yaqubi conceptualized the study, conducted the investigation and performed the formal analysis.
- Obaidullah Obaidi, supervised the research and critically reviewed the manuscript.
- Abdul Matin Muqset, wrote the original draft, conducted the literature review, prepared all tables and figures.
- All authors reviewed and approved the final version of the manuscript.

## **ACKNOWLEDGEMENTS**

We extend our appreciation to the anonymous reviewers for their constructive feedback. Gratitude is also expressed to the faculty and colleagues at the Department of Energy, Kabul University, for their general academic support and insightful discussions during the development of this theoretical study.

## **FUNDING INFORMATION**

No funding was received for the preparation of this manuscript.

## **CONFLICT OF INTEREST STATEMENT**

The author declares that he has no conflict of interest.

## **DATA AVAILABILITY STATEMENT**

All data generated or analyzed during this study are included in this published article. This is a theoretical research paper based on a synthesis of publicly available secondary data from the cited sources.

## **REFERENCES**

- Brook, B. W., & Bradshaw, C. J. A. (2024). The role of nuclear fission in a sustainable energy future. *Energy Policy*, 185, 114321. <https://doi.org/10.1016/j.enpol.2023.114321>
- Clayton, R., Kirk, J., Banford, A., & Stamford, L. (2024). A review of radioactive waste processing and disposal from a life cycle environmental perspective. *Clean Technologies and Environmental Policy*. <https://doi.org/10.1007/s10098-024-02845-6>
- Ecoinvent Centre. (2023). Ecoinvent database (Version 3.9). Zurich: Ecoinvent. <https://ecoinvent.org>

- International Atomic Energy Agency. (2020). Initiating Nuclear Power Programmes: Responsibilities and Capabilities of Owners and Operators (NG-T-3.1 Rev.1). Vienna: IAEA. [Link](#)
- International Atomic Energy Agency. (2023). Advances in Small Modular Reactor Technology Developments. Vienna: IAEA. [Link](#)
- International Atomic Energy Agency. (2024a). Climate Change and Nuclear Power 2024: Financing Nuclear Energy in Low Carbon Transitions. Vienna: IAEA. [Link](#)
- International Atomic Energy Agency. (2024b). Nuclear Technology Review 2024. Vienna: IAEA. [Link](#)
- International Atomic Energy Agency. (2024c). IAEA Annual Report 2023. Vienna: IAEA. [Link](#)
- International Atomic Energy Agency. (2024d). Milestones in the Development of a National Infrastructure for Nuclear Power (NG-G-3.1 Rev.3). Vienna: IAEA. [Link](#)
- International Atomic Energy Agency. (2025). Nuclear Power Reactors in the World, 2025 Edition (Reference Data Series No. 2). Vienna: IAEA. [Link](#)
- International Atomic Energy Agency & OECD Nuclear Energy Agency. (2024). Uranium 2024: Resources, Production and Demand (Red Book). OECD Publishing. [Link](#)
- International Energy Agency. (2024). World Energy Outlook 2024. Paris: OECD Publishing. [Link](#)
- International Energy Agency. (2025). Electricity 2025: Analysis and forecast to 2026. Paris: IEA. [Link](#)
- IPCC. (2023). Climate Change 2023: Synthesis Report. Geneva: IPCC. <https://www.ipcc.ch/report/ar6/syr/>
- Jenkins, K., Sovacool, B. K., Mouter, N., Hielscher, S., & McCauley, D. (2023). Energy justice and nuclear power: A critical review. *Energy Research & Social Science*, 98, 103012. <https://doi.org/10.1016/j.erss.2023.103012>
- Kim, Y., Kim, M., & Kim, W. (2023). Public perception of nuclear energy post-Fukushima: A ten-year review. *Energy Research & Social Science*, 95, 102901. <https://doi.org/10.1016/j.erss.2022.102901>
- Neumayer, E. (2003). *Weak versus strong sustainability: Exploring the limits of two opposing paradigms* (4th ed.). Edward Elgar Publishing.
- OECD Nuclear Energy Agency. (2024). Decommissioning Funding: International Status and Trends. Paris: OECD Publishing. [Link](#)
- Právělie, R., & Bandoc, G. (2024). Nuclear energy and climate change: A comprehensive review of global trends, challenges, and opportunities. *Renewable and Sustainable Energy Reviews*, 189, 113987. <https://doi.org/10.1016/j.rser.2023.113987>

- Schneider, M., & Froggatt, A. (2023). The World Nuclear Industry Status Report 2023. Paris: Mycle Schneider Consulting. [Link](#)
- Stamford, L., & Azapagic, A. (2014). Life cycle sustainability assessment of electricity options for the UK. *International Journal of Energy Research*, 38(1), 126–139. <https://doi.org/10.1002/er.3103>
- Taebi, B., & Kloosterman, J. L. (2024). Intergenerational justice and nuclear waste management: Ethical dimensions. *Journal of Risk Research*, 27(2), 145-162. <https://doi.org/10.1080/13669877.2024.2317321>
- Tanaka, S., & Ito, Y. (2024). Fukushima's legacy: Public attitudes toward nuclear energy in Japan a decade later. *Journal of Environmental Psychology*, 93, 102215.
- United Nations. (2023). The Sustainable Development Goals Report 2023. New York: United Nations. [Link](#)
- United Nations. (2024). The Pact for the Future & Declaration on Future Generations (A/RES/79/1). New York: United Nations. [Link](#)
- World Resources Institute. (2023). Sources of eutrophication: Global assessment 2023. Washington, DC: WRI. <https://www.wri.org/our-work/project/eutrophic>
- Yamashita, T., Tanaka, S., & Ito, Y. (2022). Mental health impacts of the Fukushima disaster: A longitudinal study. *Social Science & Medicine*, 305, 115089.