



Nuclear Energy for Sustainable Power Systems: An Integrated Assessment Using Life Cycle and Multi-Criteria Decision Approaches

Vipin Kumar Sharma^{1*}, Satyam Shree¹, Nakkeeran E.²

¹Department of Chemical Engineering, Indian Institute of Technology, Tirupati, Pin Code – 517619, Andhra Pradesh, India

²K.P.R. Institute of Engineering and Technology, Arasur, Coimbatore, Pin Code - 641407, Tamil Nadu, India

Received date: 01/04/2026, Acceptance date: 27/08/2026

DOI: <http://doi.org/10.63015/6hs-2498.3.2>

*Corresponding Author: vipinshrm4@gmail.com, ch21d005@iittp.ac.in

Abstract

The transition toward secure, low-carbon electricity generation requires energy technologies to be evaluated simultaneously in terms of environmental performance, technical reliability, economic viability, resource requirements, and strategic value. Although nuclear power is widely recognized as a low-carbon and high-capacity-factor technology, its overall benefits remain sensitive to fuel-cycle characteristics, system boundaries, economic assumptions, and decision criteria. This study presents a transparent literature-based comparative assessment of nuclear power using an integrated life-cycle assessment (LCA) and multi-criteria decision analysis (MCDA) framework. The environmental assessment was performed on a cradle-to-grave basis using 1 kWh of net electricity as the functional unit, while the MCDA incorporated 14 technical, environmental, economic, resource, and strategic indicators. Min–max normalisation and equal baseline weighting were applied, followed by a $\pm 20\%$ weight-perturbation analysis over 130 simulations to examine ranking robustness. Literature-derived median life-cycle greenhouse-gas emissions were approximately 12 g CO₂-eq/kWh for nuclear, compared with 11, 48, 490 and 820 g CO₂-eq/kWh for wind, solar photovoltaic, natural gas and coal, respectively. The resulting MCDA scores were 0.746 for nuclear, 0.706 for wind, 0.643 for solar PV, 0.566 for natural gas, and 0.404 for coal. Nuclear retained the first position in 93.8% of sensitivity simulations, indicating robust performance within the defined decision space. The findings demonstrate that nuclear power can provide a strong combination of low life-cycle emissions, high energy density and reliable electricity generation, while limitations associated with capital intensity, radioactive-waste management and deployment conditions must remain integral to sustainability assessments.

Keywords: Nuclear Energy; Life Cycle Assessment; Multi-Criteria Decision Analysis; Low-Carbon Energy; Energy Sustainability; Energy Security.

1. Introduction and Literature Survey

Growing global energy demand is occurring alongside the increasing urgency to reduce climate-related impacts [1]. Conventional electricity generation based predominantly on coal, petroleum-derived fuels, and natural gas remains an important source of electricity but is associated with substantial greenhouse-gas emissions, atmospheric pollutants, and ecological impacts [2]. In this context, nuclear power has gained increasing attention as a component of low-carbon energy portfolios because of its ability to provide large-scale electricity with very low direct CO₂ emissions during normal operation [3]. The underlying conversion process is based on controlled nuclear fission, in which the splitting of fissile nuclei releases a large quantity of thermal energy. This heat is subsequently transferred through the reactor heat-transfer system and used to produce steam, which drives a turbine coupled to an electrical generator. The combination of high energy density and sustained power production distinguishes nuclear generation from several variable renewable technologies and makes it relevant to energy systems seeking to reduce carbon intensity while maintaining dependable electricity supply.

The generated heat is transferred to a working fluid, producing steam that drives a turbine-generator system to convert thermal energy into electrical power [4]. Unlike solar photovoltaic and wind technologies, whose electricity production varies with solar irradiance and wind availability, nuclear reactors can operate continuously for extended periods under controlled operating conditions [5]. This high availability and stable power output provide dependable generation for the electricity grid and can support system frequency stability, load balancing, and the integration of variable renewable energy sources [6].

Air pollution used to be very limited in the case of nuclear energy production, i.e. the emission of CO₂, SO_x, NO_x and PM used to be very limited. Thus, it helps in terms of Global Warming and Climate Change control also. [7]. Power generation with the help of uranium as a fuel also helps in huge energy generation within very limited space in comparison to other methods of electrical energy production like coal-based and wind farm-based [8][9]. Nowadays, many latest technologies are available for nuclear reactor construction in stepwise procedures, which are safer, easier and less costly compared to old methods used for the same requirements. (Tiwari R., 2008; L. Rajesh, 2025). Because of this shift, governments now consider atomic energy as an option to balance stable supplies, climate goals, and growth needs at once [12].

Recent research has increasingly examined nuclear power from a multidimensional perspective encompassing environmental impacts, economic performance, technological development, and its position relative to alternative energy technologies [13]. A central challenge in contemporary energy planning is to expand reliable electricity generation while limiting greenhouse-gas emissions and associated environmental degradation [14]. Within this context, nuclear power is distinguished by its comparatively low life-cycle carbon intensity and negligible direct atmospheric emissions during normal reactor operation. It was reported that the operational phase of nuclear generation produces very limited direct greenhouse-gas emissions and conventional air pollutants [15][16], although emissions associated with mining, fuel processing, plant construction, and waste management remain relevant to a complete life-cycle assessment. It was identified that nuclear generation is an important complement to variable renewable technologies [17], particularly where

continuous electricity supply is required. Similarly, the expansion of nuclear generation is associated with potential reductions in environmental pressure through displacement of higher-emission electricity sources [18] [19]. An additional advantage is the comparatively high operational availability of nuclear reactors, which allows electricity production to remain largely independent of short-term meteorological variations [20]. The high energy density of nuclear fuel further permits substantial electricity production from relatively small quantities of fuel and land compared with many energy-generation pathways [21], which further highlights the relevance of nuclear generation for maintaining energy-supply security [22], particularly in developing energy systems where electricity demand and infrastructure requirements are increasing. Recent studies have consequently shifted attention toward integrated nuclear–renewable configurations rather than treating the technologies as mutually exclusive options. It was demonstrated that coordinated operation of nuclear and renewable generation can improve grid reliability while potentially reducing overall system costs [23], whereas favourable characteristics of nuclear generation were reported when evaluated alongside solar and wind alternatives [24]. The relevance of nuclear power in long-term energy-system planning is aimed at limiting emissions while maintaining dependable electricity availability [25]. From an economic perspective, it was indicated that the long operating lifetimes and high utilisation rates of nuclear facilities can improve their long-term economic performance [26][27], although substantial initial capital requirements remain an important constraint. The potential for combined heat and power applications provides an additional pathway for improving energy utilisation; it was reported that efficiencies exceeding 80% for

suitable cogeneration configurations, demonstrating the possibility of simultaneously supplying electricity and useful thermal energy [28].

The contribution of nuclear power to deep decarbonization has also received considerable attention because of its potential to provide low-carbon electricity while supporting energy-intensive applications. Applications were identified extending beyond conventional electricity generation, including low-carbon hydrogen production and energy supply for industrial sectors that are difficult to decarbonise [29][30]. Technological development is further broadening the potential deployment envelope through advanced reactor concepts, including Generation IV systems and small modular reactors (SMRs), which incorporate enhanced safety characteristics, modular construction approaches, and greater flexibility for integration with evolving energy systems through comparative evaluation of alternative electricity-generation pathways [31][32][33]. It was demonstrated that nuclear technology can perform favourably when environmental, economic, and social dimensions are considered simultaneously. It was additionally reported that complex nonlinear relationships between nuclear-energy utilisation and ecological indicators, suggesting that the environmental consequences of nuclear deployment cannot be adequately represented by a single parameter or short-term observation [34]. Collectively, the literature indicates that nuclear power can contribute substantially to reliable low-carbon electricity supply and long-term energy-system resilience; however, its broader deployment remains conditioned by several unresolved considerations, including severe-accident risk, radioactive-waste management, large upfront investment requirements, project-

delivery challenges, and public acceptance. These factors highlight the need for a systematic assessment that considers environmental, technical, economic, and strategic dimensions concurrently rather than evaluating nuclear power solely based on operational emissions or electricity-generation capacity [35].

The present study does not seek to introduce a new reactor technology or a site-specific process model. Its contribution lies in integrating published life-cycle evidence with a transparent multi-criteria screening framework and explicit sensitivity analysis [36]. This structure enables technical, environmental, economic and strategic attributes of nuclear power to be examined within a common decision framework while identifying the dependence of the resulting ranking on indicator selection and weighting assumptions [37].

2. Methodology

The generated methodological framework, as mentioned in Figure 1, summarises the systematic procedure adopted to evaluate the benefits and broader role of nuclear energy through an integrated literature-based approach. The process begins with structured identification of relevant studies from major scientific databases, followed by screening and selection to retain literature directly related to nuclear power, life-cycle

performance, multi-criteria assessment, and low-carbon energy systems. Information concerning assessment methods, performance indicators, reported findings, and study conclusions is subsequently extracted using a standardised framework to improve consistency during comparative evaluation. The selected evidence is then examined through life-cycle assessment (LCA) to characterise environmental performance across the relevant energy chain and through multi-criteria decision analysis (MCDA) to incorporate technical, environmental, economic, resource, and strategic considerations within a common decision framework. Equal weighting is used for the baseline MCDA assessment, while sensitivity analysis examines the influence of changes in criterion importance on the resulting technology rankings [38], [39]. A quality-control stage is incorporated to check source reliability, consistency of extracted information, and methodological robustness before synthesis of the findings. The final analytical stage integrates the evidence to establish comparative trends among nuclear and alternative electricity-generation technologies and to identify their implications for reliable, low-carbon energy planning. This structured sequence provides a transparent basis for interpreting the diverse evidence reported in the literature while reducing dependence on a single performance indicator or isolated technological characteristic [40], [41].

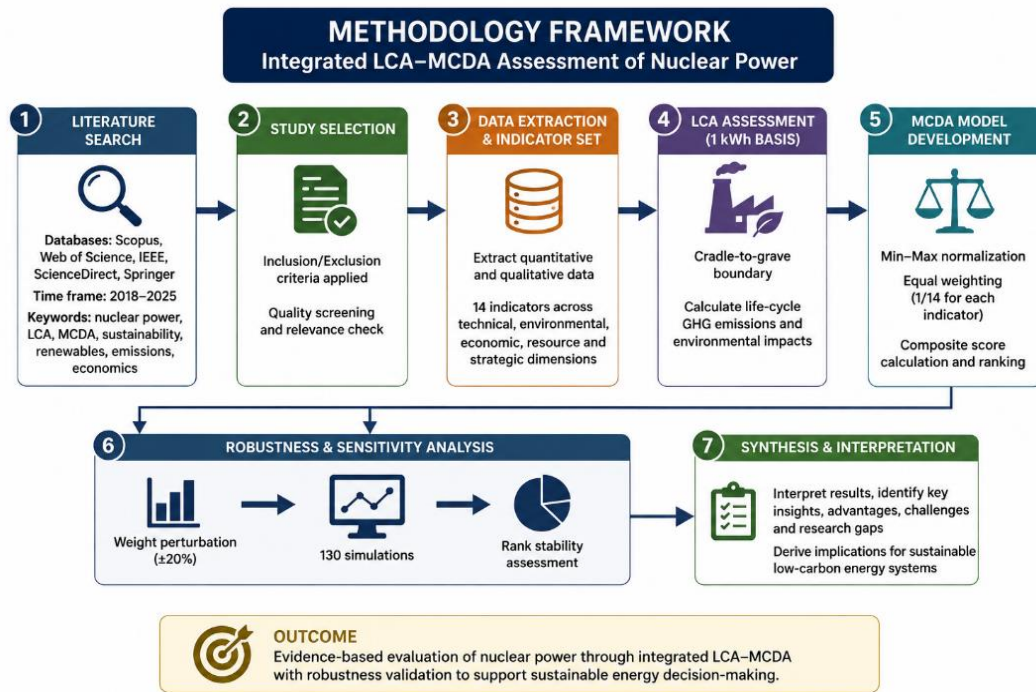


Figure 1. Methodological Framework for the Integrated Review and Assessment of Nuclear Energy Benefits

2.1 Research Framework and Approach

This research takes a close look at nuclear power using clear comparisons and structured analysis, especially how it fits into long-term sustainability, stable energy supply, and its effect on nature. Instead of gathering new numbers, it builds understanding by reviewing existing information, weighing different outcomes, and applying balanced scoring methods across several factors [42]. Information pulled from worldwide sources - such as figures tracked by the International Energy Agency (IEA) - helps measure just how much nuclear contributes to overall energy use and electric output around the globe. Its way of working follows paths laid out in current academic work that explores shifting toward cleaner grids and lower-emissions setups [43].

This work is a literature-based comparative assessment of nuclear power against selected electricity-generation technologies. The analysis integrates three complementary components: (i) a cradle-to-grave synthesis of published life-cycle greenhouse-gas (GHG) results, (ii) a transparent multi-criteria decision analysis (MCDA) based on published performance indicators, and (iii) sensitivity testing of the decision weights. The study therefore does not claim to constitute a site-specific process LCA, an expert-elicited preference model, or a reactor-level techno-economic design. Its purpose is to identify the conditions under which the commonly reported technical, environmental and strategic advantages of nuclear power remain evident when multiple indicators are considered simultaneously [44].

2.2 Data Collection and Source Integration

Most of the study relies on existing information like worldwide energy summaries, academic papers that have been checked by experts, and detailed technical numbers. From broad statistical visuals (Figure 2(a) and 2(b)), patterns in how power sources are shared and where electricity comes from were drawn out. Instead of relying only on one kind of source, newer studies about how well nuclear energy works, its effect on nature, along with cost aspects, found their way into the review, helping keep things accurate and up to date [45][46]. When different kinds of data come together, the overall picture becomes stronger and more trustworthy.

The functional unit for the comparative environmental assessment is 1 kWh of net electricity delivered by the generation technology. A cradle-to-grave perspective is adopted. For nuclear power, the boundary includes uranium mining and milling, conversion and enrichment, fuel fabrication, reactor construction, electricity generation,

spent-fuel and radioactive-waste management, and decommissioning [47]. For the comparator technologies, the corresponding fuel supply, plant construction, operation, decommissioning and waste-related stages are included where reported by the source study. The principal impact indicator is life-cycle GHG emissions, expressed as g CO₂-eq/kWh. Recent literature shows that reported nuclear values vary with uranium ore grade, enrichment route, electricity mix, reactor technology and system boundary; consequently, a single value is not treated as universal. A 2024 critical review reported a nuclear lifecycle range of 3.7–110 g CO₂-eq/kWh with a median of 12 g CO₂-eq/kWh, while a 2023 parametric LCA reported a global 2020 average of 6.1 g CO₂-eq/kWh and a broad scenario range [40]. These differences demonstrate why the present study reports literature-derived values together with their methodological context rather than presenting a single deterministic emission factor.

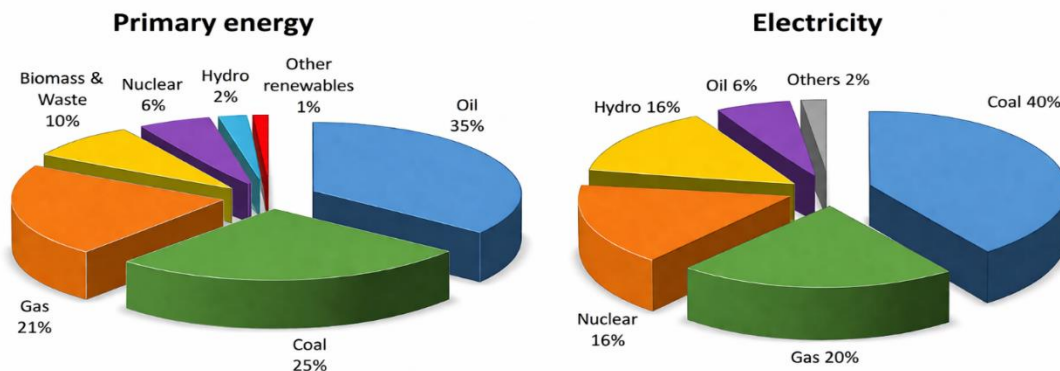


Figure 2(a) Primary energy and 2(b) Electricity supply [48]

2.3 Evaluation of Nuclear Energy Principles

The fundamental principles governing nuclear energy systems, such as safety, environmental protection, resource efficiency, transparency, and non-proliferation, were systematically analysed

as qualitative indicators. These principles form the basis for evaluating nuclear energy within a sustainability framework. The study applies a qualitative scoring approach to assess how effectively nuclear energy aligns with global sustainability goals, consistent

with methodologies adopted in recent nuclear policy and sustainability research.

2.4 Multidisciplinary Assessment Framework

Nuclear energy systems involve a wide range of scientific and engineering disciplines categorised into health, energy, and environmental domains (Figure 3). This study adopts a multidisciplinary evaluation

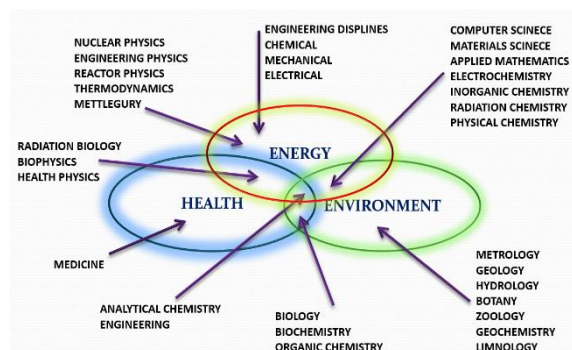


Figure 3. Division of scientific engineering disciplines and major categories

Multi-criteria decision analysis (MCDA) requires the performance values of different technologies to be transformed to a common dimensionless scale before the criteria can be aggregated. In the present literature-based assessment, min-max normalisation is used because the criteria are expressed in different units and have different directions of preference. The normalised value x'_{ij} ranges from 0 to 1, where a higher value represents a more favourable performance.

2.4.1 Normalisation of beneficial criteria

For a beneficial criterion, a higher raw value represents better performance. Examples include capacity factor, conversion efficiency, energy return on energy invested (EROI), and employment generation. The normalised score is calculated as:

$$x'_{ij} = (x_{ij} - x_{\min,j}) / (x_{\max,j} - x_{\min,j})$$

where x_{ij} is the reported value of technology i for criterion j ; $x_{\min,j}$ is the minimum value

approach, considering radiological safety, thermal efficiency, environmental impact, and socio-economic implications. Such an integrated framework is essential for capturing the holistic benefits of nuclear energy and is supported by recent interdisciplinary studies in nuclear engineering and energy systems analysis [49].

among the technologies being compared for criterion j ; $x_{\max,j}$ is the corresponding maximum value; and x'_{ij} is the resulting dimensionless normalised score. A technology with the maximum value receives a score of 1, whereas the technology with the minimum value receives a score of 0.

2.4.2 Normalisation of cost-type criteria

For a cost-type criterion, a lower raw value represents better performance. Examples include life-cycle greenhouse-gas emissions, water consumption, land requirement, capital cost, levelized cost of electricity (LCOE), external cost, SO_x, NO_x and PM_{2.5} emissions. The direction of preference is therefore reversed using:

$$x'_{ij} = (x_{\max,j} - x_{ij}) / (x_{\max,j} - x_{\min,j})$$

Under this formulation, the lowest-cost or lowest-impact technology receives a normalised score of 1 and the highest-cost or highest-impact technology receives a score of 0. The same transformation is applied independently to each criterion so that environmental, technical, economic and strategic indicators can be compared on a common scale.

2.4.3 Equal-weighting approach

The baseline MCDA assigns equal importance to all n criteria because the present study does not contain a defensible stakeholder survey, expert-elicitation

dataset, or nationally agreed policy preference structure from which unequal weights could be derived. Equal weighting avoids introducing subjective preferences that cannot be independently verified. The weight assigned to each criterion is therefore:

$$w_j = 1 / n$$

$$\sum_{j=1}^n w_j = 1$$

For the 14-criterion screening framework used in this study, $n = 14$ and therefore each criterion receives a baseline weight of $1/14 = 0.07143$. The weights are dimensionless and represent the relative contribution of each criterion to the aggregate screening score.

2.4.4 Overall MCDA score

After normalisation, the performance of each technology is aggregated using a weighted linear combination. The overall score for technology i is calculated as:

$$S_i = \sum_{j=1}^n w_j x'_{ij}$$

where S_i is the overall MCDA score of technology i , w_j is the normalised weight of criterion j , and x'_{ij} is the normalised performance of technology i under criterion j . Because the weights sum to unity and the normalised scores lie between 0 and 1, S_i also lies between 0 and 1. A larger S_i indicates a more favourable overall performance within the selected criteria and assumptions; it does not represent an absolute measure of sustainability.

2.4.5 Illustrative calculation

For illustration, consider a beneficial criterion for which the minimum and maximum reported values are 20 and 80 units, respectively. If technology i has a value of 50 units, its normalised score is:

$$x'_{ij} = (50 - 20) / (80 - 20) = 0.50$$

For a cost-type criterion with the same minimum and maximum values, a technology value of 50 units gives:

$$x'_{ij} = (80 - 50) / (80 - 20) = 0.50$$

These examples demonstrate that the normalisation procedure changes only the direction and scale of the original criterion; it does not change the relative ordering of the technologies within that criterion.

2.4.6 Interpretation and reproducibility

The normalisation and weighting procedure is intentionally simple and transparent. It permits the MCDA result to be reproduced from the reported performance matrix without requiring proprietary software or undocumented expert judgements [50]. Because the outcome depends on the selected criteria, source data, system boundaries and weighting assumptions, the resulting score is interpreted as a comparative screening indicator rather than as a universal sustainability index. Sensitivity analysis is subsequently used to examine whether reasonable changes in criterion weights alter the technology ranking. Summary of the MCDA normalisation and aggregation procedure is as defined in Table 1.

Table 1. Summary of the MCDA normalisation and aggregation procedure*

Step	Purpose	Expression	Interpretation
1	Beneficial criterion	$x'_{ij} = (x_{ij} - x_{\min,j}) / (x_{\max,j} - x_{\min,j})$	Higher raw value is preferred
2	Cost-type criterion	$x'_{ij} = (x_{\max,j} - x_{ij}) / (x_{\max,j} - x_{\min,j})$	Lower raw value is preferred
3	Equal weighting	$w_j = 1/n; \sum w_j = 1$	All criteria receive equal baseline importance
4	Aggregation	$S_i = \sum w_j x'_{ij}$	Higher S_i indicates better screening performance

***Methodological note:** The equations above define the calculation procedure used in the revised literature-based MCDA framework. The baseline equal-weighting assumption is adopted because no stakeholder or expert preference dataset was available for this study.

2.5 Sustainability Indicator-Based Comparative Analysis

Depending on the specific evidence being discussed regarding nuclear energy against other energy sources (coal, gas, hydro, wind, and solar PV) was conducted using

sustainability indicators categorised into economic, environmental, and social dimensions (Figure 4). Key indicators include lifecycle greenhouse gas emissions, land use, cost of electricity, reliability, and social acceptance.

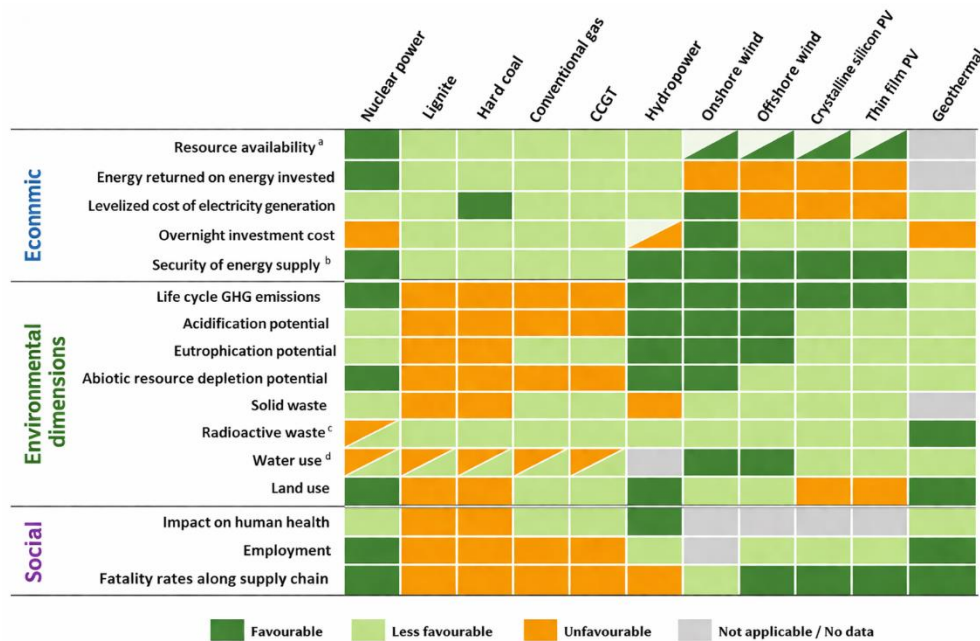


Figure 4. Selection of sustainability indicators for sources of power

2.6 Process-Based Analysis of Nuclear Fuel Cycle

The methodology includes a process flow analysis of nuclear fuel production

and the nuclear fuel cycle, based on the flowsheet of nuclear ore processing (Figure 5). Each stage—mining, milling, conversion, enrichment, fuel fabrication,

reactor operation, and waste management—was evaluated in terms of efficiency, environmental impact, and resource utilisation. This process-based

approach is consistent with literature-based comparative lifecycle assessment (LCA) methodologies widely used in nuclear energy research [51].

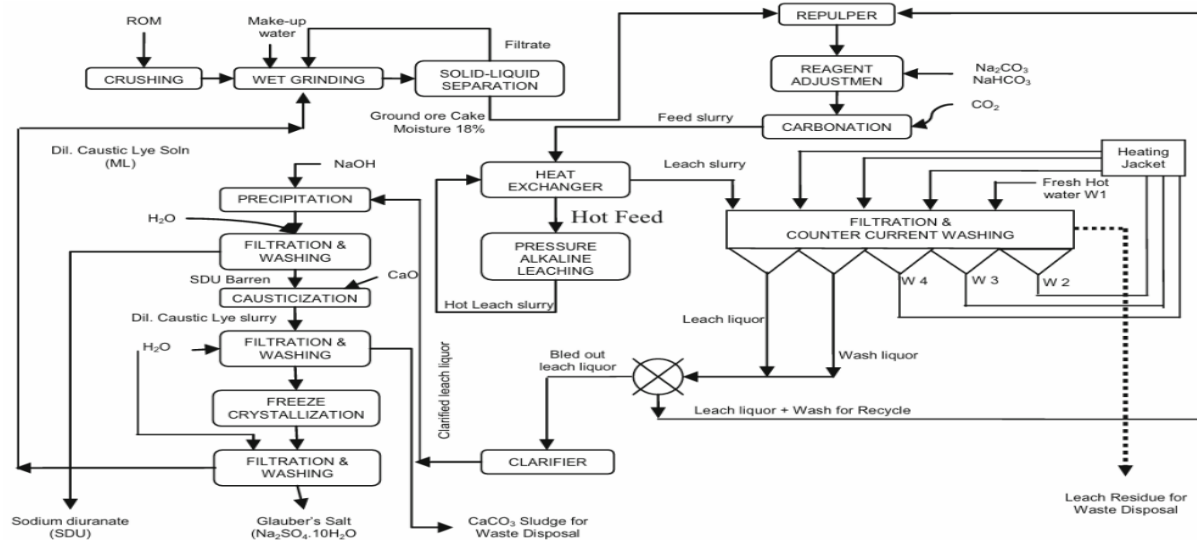


Figure 5. Process flowsheet adopted for nuclear ore processing [52]

2.7 Case Study: Indian Nuclear Power Programme

A case study approach was employed to analyse the three-stage nuclear power programme of India (Figure 6). The study evaluates the strategic utilisation of uranium and thorium resources, focusing on long-term energy security and sustainability [53].

The methodology involves a policy and technological assessment of pressurised heavy water reactors (PHWRs), fast breeder reactors (FBRs), and advanced thorium-based systems. This approach is aligned with recent studies on national nuclear energy strategies [54].

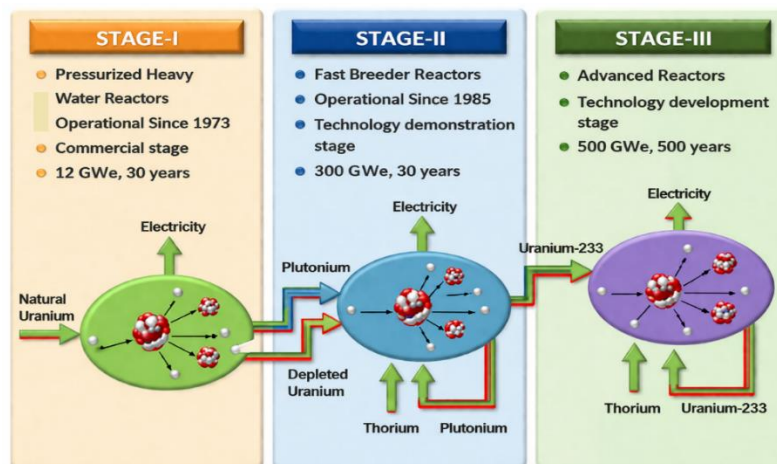


Figure 6. Three-stage nuclear power programme of India [55]

2.8 Analysis of Public Acceptance Factors

Public perception and acceptance of nuclear energy were analysed using a socio-technical evaluation framework, considering factors such as safety concerns, environmental awareness, regulatory trust, and policy support (Figure 7).

A qualitative assessment method was

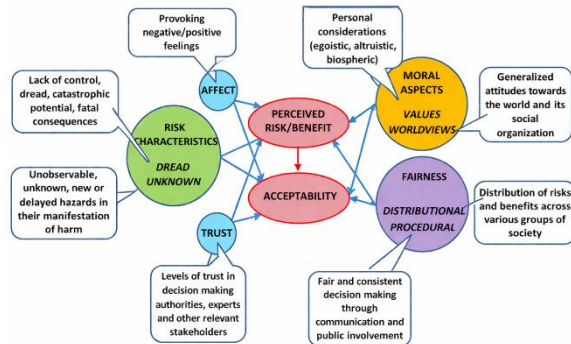


Figure 7. Factors influencing public acceptance of nuclear energy

applied to evaluate the influence of these factors on nuclear energy deployment. This approach is supported by recent research emphasising the role of societal acceptance in energy transition pathways. Uncertainty in the MCDA is examined through a weight-perturbation analysis. Each baseline criterion weight is independently perturbed within $\pm 20\%$, and the resulting weights are renormalised so that their sum remains unity. Several random weight sets are evaluated using a fixed random seed to ensure reproducibility. The stability of the technology ranking is expressed as the proportion of simulations in which each technology occupies each rank. This procedure does not represent a probabilistic forecast of future energy systems; rather, it tests whether the baseline ranking is highly dependent on small changes in decision priorities.

2.9 Benefit Identification and Categorisation The benefits of nuclear energy were systematically categorised into

technical, environmental, economic, and socio-political dimensions, based on the compiled dataset [17]. Parameters such as high energy density, low emissions, reliability, economic competitiveness, and energy security were analysed. A descriptive-analytical method was used to synthesise these benefits and correlate them with global energy transition goals. Similar categorisation approaches have been adopted in recent review studies.

2.10 Validation through Literature Correlation

The findings of this study were validated through cross-referencing with recent peer-reviewed literature (2020–2025). Comparative insights were drawn to ensure consistency with global research trends in nuclear energy systems, sustainability, and decarbonization. This step enhances the scientific credibility and generalizability of the results. The results are interpreted as comparative evidence rather than as an absolute hierarchy of energy technologies. Nuclear power is considered advantageous where high availability, low lifecycle GHG emissions and compact energy infrastructure are important. Conversely, capital intensity, construction duration, radioactive-waste management and public acceptance remain material constraints. The interpretation therefore distinguishes technology-level characteristics from context-dependent deployment outcomes [29].

3. Results and Discussion

3.1 Global Energy Mix and Role of Nuclear Energy

The analysis of global energy statistics (Figure 2(a) and 2(b)) indicates that fossil fuels still dominate primary energy consumption, whereas nuclear energy contributes a smaller but significant share of low-carbon electricity generation. Despite its lower percentage in primary energy, nuclear power plays a

disproportionate role in clean electricity supply due to its high capacity factor.

3.2 Sustainability-Based Comparative Assessment The literature-based life-cycle comparison indicates that nuclear power belongs to the low-carbon group of electricity-generation technologies, although its life-cycle emissions are not zero. Recent reviews report substantial variation in nuclear values because uranium ore grade, enrichment technology, electricity supply used in the fuel cycle, reactor configuration and system boundaries differ among studies. A 2024 synthesis reported median lifecycle emissions of approximately 12 g CO₂-

eq/kWh for nuclear power, compared with 820 g CO₂-eq/kWh for pulverised coal, 490 g CO₂-eq/kWh for combined-cycle gas, 48 g CO₂-eq/kWh for utility-scale photovoltaic generation and 11 g CO₂-eq/kWh for onshore wind. These values indicate a large lifecycle emissions advantage for nuclear power relative to fossil generation, while also showing that nuclear and renewable technologies occupy overlapping low-carbon ranges. A comparative evaluation was performed using sustainability indicators. The numerical dataset in Table 2 is taken from a published comparative Indian power-generation sustainability assessment.

Table 2. Comparative Performance of Energy Sources

Criterion	Coal	Gas	Nuclear	Solar PV	Wind
Land use (acre/MW)	0.91	0.75	0.24	5.0	27.5
Water use (m ³ /MWh)	2.44	0.75	5.7	0.95	0.03
Efficiency (%)	37.5	58.6	35.0	13.9	35.0
Capacity factor (%)	80.0	50.0	80.0	16.1	25.0
EROI	32	28	75	4	16
CO ₂ (g/kWh)	918	351	9.21	52.9	9.84
SO _x (g/kWh)	1.88	0.46	0.03	0.13	0.002
NO _x (g/kWh)	0.42	1.76	0.02	0.1	0.002
PM _{2.5} (g/kWh)	0.12	0.1	0.004	0.02	0.006
Capital cost (crore INR/MW)	6.0	4.3	10.0	5.3	4.5
LCOE (INR/kWh)	2.95	2.62	2.44	2.44	2.43
External cost (INR/kWh)	1.47	1.0	0.21	0.32	0.1
Energy insecurity	0.5	0.5	0.4	0.7	0.5
Job generation (jobs/MW)	1.35	0.94	1.6	8.2	4.5

Note: The matrix is a screening dataset rather than a current plant-specific database. Beneficial criteria are efficiency, capacity factor, EROI and

- Nuclear power shows a strong overall sustainability profile within the present screening framework; however, the relative ranking depends on the selected indicators, weighting assumptions, technology configuration and deployment context.
- Renewable sources exhibit low emissions but suffer from variability and storage dependency.
- Fossil fuels remain dominant but are environmentally unsustainable

3.3 Life Cycle Assessment (LCA) of Nuclear Energy

A literature-based comparative Life Cycle Assessment (LCA) approach was used to evaluate environmental impacts across the nuclear fuel cycle (Figure 5). LCA Equation can be defined as:

The total life-cycle emissions are expressed as:

$$E_{total} = E_{mining} + E_{processing} + E_{construction} + E_{operation} + E_{decommissioning}$$

- Operational emissions are negligible, with most emissions arising from construction and fuel processing.
- Total life-cycle emissions are significantly lower than those of fossil fuels.

Under the equal-weight baseline, nuclear power obtains a screening score of 0.746 and ranks first, followed by wind (0.706), solar PV (0.643), natural gas (0.566), and coal (0.404). In 130 $\pm 20\%$ weight-perturbation simulations, nuclear retained the first position in 93.8% of trials and moved to second place in the remaining trials. This result supports the robustness of the baseline screening result, but it does not imply that nuclear power is universally the preferred technology because the ranking remains conditional on the selected indicators and data source.

3.4 Multi-Criteria Decision Analysis (MCDA)

The screening MCDA considers 14 indicators grouped into technical, environmental, economic and strategic dimensions: land use, water use, conversion efficiency, capacity factor, energy return on energy invested (EROI), life-cycle CO₂ emissions, SO_x emissions, NO_x emissions, PM_{2.5} emissions, capital cost, levelized cost of electricity (LCOE), external cost, energy insecurity and employment generation. The comparative matrix is based on published energy-system data and is used only for

screening because values can vary by site, year, technology configuration and accounting boundary. A Multi-Criteria Decision Analysis (MCDA) model was applied using weighted sustainability indicators, and the ranking of energy sources is as mentioned in Table 3.

Table 3. MCDA Ranking of Energy Sources

Technology	Baseline score	Rank	Interpretation
Nuclear	0.746	1	Highest baseline screening score
Wind	0.706	2	Strong environmental performance
Solar PV	0.643	3	Strong environmental performance but lower availability
Natural gas	0.566	4	Intermediate overall profile
Coal	0.404	5	High environmental burden

3.5 Nuclear Fuel Cycle and Process Efficiency:

A looped system moves nuclear material through each step, recycling what it can. This setup keeps waste low while getting the most out of raw inputs. Results show that reprocessing cuts down unused potential. Efficiency climbs when spent fuel gets repurposed instead of discarded. The path shown in Figure 5 wraps back on itself, feeding outputs into new cycles. Resource recovery becomes steady, not one-time. Each stage connects, so nothing runs off track. A tiny bit of fuel creates lots of power. What matters is how much you get out versus what goes in. Efficiency shows up clearly when space or weight limits exist. A small amount of nuclear fuel creates a big impact on society in terms of energy production. Waste generation through nuclear energy generation is also much less in comparison to other energy production

methods [56]. Advanced reprocessing sustainability.

3.6 Analysis of India's Nuclear Energy Program A look at the three-part nuclear plan (Figure 6) shows how thorium might be 3. Thorium-based Reactors. Energy security is strengthened by maximizing the utilisation of domestically available resources while reducing dependence on external energy supplies. Such an approach supports a progressive transition toward a stable, resource-efficient, and environmentally sustainable energy system.

3.7 Public Views and Social Tech Influences

Factors influencing public acceptance (Figure 7) include:

- Safety perception
- Environmental awareness
- Policy transparency

Even with new technology, people slowly analyse the importance of nuclear energy and adopt it in future.

3.8 Technical, strategic and environmental interpretation

The principal technical advantage identified in the comparative assessment is high availability. Nuclear generation typically operates at high capacity factors, allowing substantial annual electricity production from a relatively compact generating site. Environmental performance is characterized by low lifecycle GHG emissions and very low routine atmospheric emissions during electricity generation. Strategically, nuclear power can diversify electricity supply and reduce exposure to fossil-fuel price and import risks. These advantages must be evaluated alongside high upfront capital requirements, long project development periods, spent-fuel management, decommissioning obligations, and the need

used over time. Each phase builds on what came before it, moving step by step toward that goal.

1. PHWR (Uranium-based)

2. Fast Breeder Reactors

for sustained regulatory and public confidence, as mentioned in Table 4.

Table 4. Categorisation of Nuclear Energy Benefits

Category	Key Benefits
Technical	High energy density, reliability
Environmental	Low emissions, no air pollutants
Economic	Stable costs, job creation
Strategic	Energy security, reduced imports

The high energy density of nuclear fuel enables substantial electricity generation from comparatively small fuel inventories, while reactor systems can sustain power production over extended operating periods. During normal operation, nuclear generation produces negligible direct carbon emissions, providing a marked advantage over coal- and oil-fired power plants. Although nuclear projects require substantial initial capital investment, their long operating lifetimes and high-capacity factors can support relatively predictable long-term electricity generation costs. In addition, nuclear facilities require highly trained personnel for reactor operation, maintenance, safety management, and specialized engineering activities, thereby creating skilled employment opportunities throughout the plant life cycle [30]. The principal technical advantage identified in the comparative assessment is its high availability and ability to provide continuous electricity generation. Nuclear power exhibits substantially lower life-cycle GHG emissions than coal- and natural-gas-based electricity generation in the literature dataset considered in this study [57]. It lines up close to wind and solar

when it comes to emissions. A steady player in cutting carbon emissions. This represents its importance in terms of low-carbon and

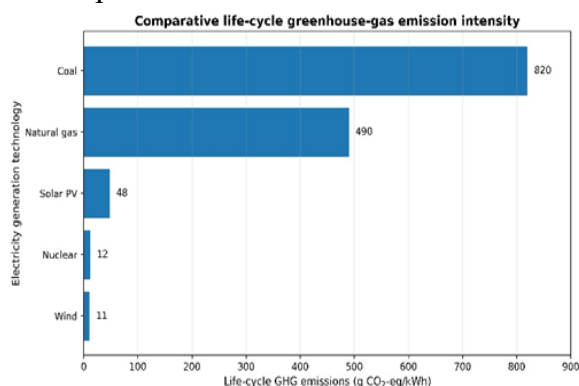


Figure 8. Comparative median life-cycle greenhouse-gas emission intensity of selected electricity-generation technologies.

sustainable energy options in future energy systems. Figure 8 therefore presents these literature-derived median values.

4. Conclusions: This study provides a transparent literature-based assessment of the principal benefits and limitations of nuclear power within a multi-dimensional sustainability framework. The revised analysis distinguishes clearly between published life-cycle evidence and the authors' comparative screening calculations. The literature indicates that nuclear power has a low life-cycle greenhouse-gas intensity relative to coal and natural gas, while its environmental performance is broadly within the low-carbon range occupied by wind and solar technologies. The MCDA screening, based on explicitly reported criteria, min-max normalisation, and equal baseline weights, produced scores of 0.746 for nuclear, 0.706 for wind, 0.643 for solar PV, 0.566 for natural gas and 0.404 for coal. A $\pm 20\%$ weight-perturbation analysis retained nuclear in first position in 93.8% of 130 simulations, indicating that the baseline result is reasonably robust within the tested decision space. The findings should not, however, be interpreted as evidence that

nuclear power is universally superior to all other energy technologies. Its overall performance depends on reactor design, fuel-cycle characteristics, uranium resource quality, financing conditions, construction performance, waste-management strategy and national electricity-system requirements. Nuclear power is therefore most appropriately considered as one component of a diversified low-carbon portfolio, particularly where firm electricity supply and system reliability are important. Future research should replace literature-derived screening data with harmonised country-specific inventories, probabilistic LCA, life-cycle costing and stakeholder-informed MCDA. Such work would provide a stronger basis for comparing nuclear power with renewable generation, storage and other low-carbon technologies under defined national transition scenarios. The graphical abstract in Figure 9 provides a concise visual synthesis of the study framework used to examine the role of nuclear power within a low-carbon and secure electricity system. The assessment begins with the growing requirement for dependable electricity generation capable of simultaneously addressing environmental constraints, energy security, and increasing demand, followed by an integrated evaluation in which nuclear power is compared with wind, solar photovoltaic, natural gas, and coal. The figure additionally presents a $\pm 20\%$ criterion-weight perturbation exercise comprising 130 sensitivity cases and indicates that nuclear power retains the first position in 122 cases, corresponding to a reported ranking stability of 93.8%. This sensitivity component is important because it demonstrates that the comparative outcome is not evaluated solely from a single fixed weighting configuration, although the reported stability remains

Integrated LCA–MCDA Assessment of Nuclear Power for a Sustainable Low-Carbon Energy Future

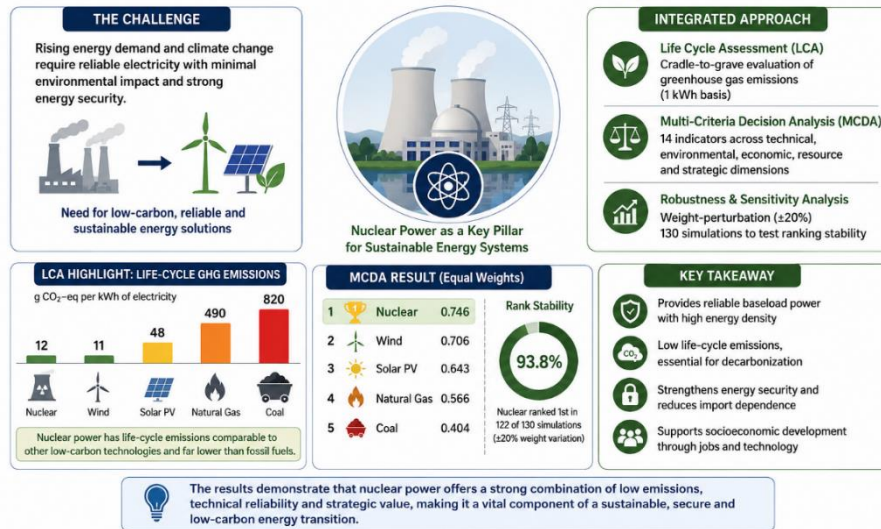


Figure 9. Integrated LCA–MCDA Assessment of Nuclear Power for a Sustainable Low-Carbon Energy Future

conditional on the selected criteria, input data, normalisation method, and weighting range. The final section of the graphical abstract emphasises the principal implications of the assessment: nuclear generation combines high energy density and dependable electricity supply with comparatively low life-cycle carbon emissions, while also contributing to energy-security objectives and reducing reliance on imported fuels. Its potential socioeconomic contribution through skilled employment and technological development further strengthens its strategic relevance. At the same time, the graphical representation is intended to position nuclear power as a component of a diversified energy portfolio rather than as an exclusive substitute for renewable generation. Overall, the figure summarises the study's central finding that nuclear power can provide a technically dependable and environmentally favourable option for supporting long-term electricity decarbonization when its benefits are evaluated across multiple dimensions rather than through emissions performance alone.

4.1 Key Findings:

The present assessment indicates that nuclear power can make a substantial contribution to reliable electricity generation while maintaining a comparatively low environmental burden. The integrated evaluation shows that its combination of sustained generation capability and low life-cycle emissions provides advantages over fossil-fuel-based electricity pathways, particularly in the context of long-term decarbonization. At the same time, nuclear generation can complement variable renewable sources such as solar and wind by providing a more consistent electricity supply when renewable output fluctuates. The findings therefore support nuclear power as an important component of a diversified energy portfolio, particularly where reliability, environmental performance, and long-term energy security are considered together. Nevertheless, its broader deployment must be assessed alongside capital requirements, radioactive-waste management, safety considerations, and site-specific conditions. Overall, the study identifies nuclear energy as a technically viable low-carbon generation pathway with potential to contribute

meaningfully to future energy-system resilience and emissions reduction.

4.2 Scientific Contributions:

- Established a multi-dimensional evaluation framework integrating literature-based LCA and MCDA.
- Demonstrated nuclear energy's superior sustainability performance.
- Provided process-level insights into fuel cycle efficiency and resource utilisation.

4.3 Practical Implications:

- Nuclear energy can play a central role in achieving net-zero emissions.
- It provides stable baseload power, essential for renewable integration.
- National programs (e.g., India's three-stage strategy) offer scalable models for long-term energy planning [58].

4.4 Limitations and Future Scope:

High capital costs and waste management require further innovation. Future work should focus on: Advanced reactors (SMRs, Gen-IV) Hybrid nuclear-renewable systems AI-based optimisation of nuclear operations. Nuclear energy, when combined with robust safety frameworks and technological advancements, represents a cornerstone of sustainable and secure energy systems for the future.

Abbreviations

AI	Artificial Intelligence
CO	Carbon Monoxide
FBR	Fast Breeder Reactor
Gen-IV	Generation-IV
GHG	Greenhouse Gas
IEA	International Energy Agency
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Analysis
MT	Metric Ton
MWh	Megawatt-hours
NOx	Nitrogen Oxides

PHWR	Pressurised Heavy Water Reactor
PV	Photo Voltaic
SMR	Small Modular Reactors
SOx	Sulfur Oxides

Acknowledgment: We thank the management of the Department of Chemical Engineering, Indian Institute of Technology, Tirupati, for encouraging research activity. We also thank the management, editors, and reviewers of The Current Natural Sciences & Engineering (CNS&E) Journal for the selection and publication of our research work.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

No, I declare that the authors have no competing interests or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Ethical Approval

Not Applicable

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent to Publish

Consent for publication was obtained from all individuals for this technical paper.

Data Availability Statement

The data used to support the findings of this study are included in the article.

References:

- [1] B. N. K. Reddy and S. K. Thamida, V. K. Sharma, "Engineering study of water jacket system in place of a spiral heat exchanger at mining and mineral ore processing industry," *SSRN Electronic Journal*, 2025, doi: 10.2139/ssrn.5214564.
- [2] V. K. Sharma, "Integrated process design and safety analysis for caprolactam production via the cyclohexanone route: Oxime reactor balancing, beckmann rearrangement, and packed bed reactor mechanical engineering," *Next Materials*, vol. 13, p. 103256, Oct. 2026, doi: 10.1016/j.nxmte.2026.103256.
- [3] Sharma V.K., "Climate Action through CO2 Capture in Nuclear & Mineral Industries," Apr. 26, 2022, *Climate Change Research Institute, New Delhi, New Delhi*.
- [4] Sharma V.K., "Environmental Benefits of Nuclear Energy," May 30, 2020, *SRMIST, Kancheepuram, Kancheepuram, Tamil Nadu*.
- [5] V. K. Sharma, "Evaluation of Air Pre-Heater System on Vis-Breaker Heaters," 2025. doi: 10.2139/ssrn.5211899.
- [6] Sharma V.K., "Optimizing Material of Construction for Agitators in High-Temperature, High-Pressure Leach Reactors Handling Abrasive Mineral Slurries," *Research & Development in Material Science, RDMS.001024*, vol. 21, no. 5, pp. 2629–2631, May 2025, doi: 10.31031/RDMS.2025.21.001024.
- [7] Sharma V. K., Rani N., "Instrumental Analysis of Corrosion on Stainless Steel," in *CHEMTECHNIK'09*, Chennai, Tamilnadu: Satyabama University, Chennai, Aug. 2009.
- [8] V. K. Sharma, "Aspects in Mining & Mineral Science for Nuclear Fuel Production in India," *Aspects in Mining & Mineral Science*, vol. 13, no. 5, Jul. 2025, doi: 10.31031/AMMS.2025.13.000821.
- [9] V. K. Sharma, "Technical Review on Various Separation Methods Used in Mineral Ore Processing Plant," *Research & Development in Material Science*, vol. 22, no. 3, Sep. 2025, doi: 10.31031/RDMS.2025.22.001039.
- [10] Sharma V. K., Tiwari R., "Pump Efficiency Evaluation & Overview of Catalytic Cracking Unit," in *PANSOPHY'08*, Sriperumbudur, Tamilnadu: Sri Venkateswara College of Engineering, Sriperumbudur, Sep. 2008.
- [11] Sharma V. K., L. Rajesh, "Case study of air quality at Tummalapalle Mill and effective actions for improvement," *SSRN Electronic Journal*, 2025, doi: 10.2139/ssrn.5218143.
- [12] Reddy B. N. K., Sharma V. K., Thamida S.K., "Detailed calculations for rainwater recharge system, considering the storm water runoff and geological formation," in *PEEC-2023, ISBN No: 978-93-95855-02-3*, vol. 6, JNAFAU Hyderabad, Ed., Hyderabad: Pure Earth Foundation &

- 3520/2, Chotani Manjil, Nicholson Road Mori Gate, Delhi -110006, 2023, pp. 40–46.
- [13] Thamida S. K., Reddy B. N. K., Sharma V. K., “Scaled-Up Carbonation of Pitchblende and Uraninite Process Liquor Using Flue Gas: Kinetic Modelling and Comparative Analysis,” 2025. doi: 10.2139/ssrn.5197260.
- [14] Sharma V. K. , Thamida S. K. , Reddy B. N. K., Kumar M., “Liquefied Petroleum Gas: A Comprehensive Review of Its Manufacturing and Refining Routes.,” *Progress Petrochem Sci., PPS*, 000656, DOI: 10.31031/PPS.2025.07.000656, vol. 7, no. 2, pp. 785–792, May 2025, doi: 10.31031/PPS.2025.07.000656.
- [15] M. D. Mathew, “Nuclear energy: A pathway towards mitigation of global warming,” *Progress in Nuclear Energy*, vol. 143, p. 104080, Jan. 2022, doi: 10.1016/j.pnucene.2021.104080.
- [16] Z. Mohmandi and N. Najibi, “Examining the Advantages and Disadvantages of Nuclear Energy,” *Journal of Natural Sciences – Kabul University*, vol. 8, no. 2, pp. 121–140, Sep. 2025, doi: 10.62810/jns.v8i2.394.
- [17] J. Gierszewski, Ł. Młynarkiewicz, T. R. Nowacki, and J. Dworzecki, “Nuclear Power in Poland’s Energy Transition,” *Energies (Basel)*, vol. 14, no. 12, p. 3626, Jun. 2021, doi: 10.3390/en14123626.
- [18] I. Khan, D. Tan, S. T. Hassan, and Bilal, “Role of alternative and nuclear energy in stimulating environmental sustainability: impact of government expenditures,” *Environmental Science and Pollution Research*, vol. 29, no. 25, pp. 37894–37905, May 2022, doi: 10.1007/s11356-021-18306-4.
- [19] M. Sadiq, F. Wen, and A. A. Dagestani, “Environmental footprint impacts of nuclear energy consumption: The role of environmental technology and globalization in ten largest ecological footprint countries,” *Nuclear Engineering and Technology*, vol. 54, no. 10, pp. 3672–3681, Oct. 2022, doi: 10.1016/j.net.2022.05.016.
- [20] J. Krūmiņš and M. Kļaviņš, “Investigating the Potential of Nuclear Energy in Achieving a Carbon-Free Energy Future,” *Energies (Basel)*, vol. 16, no. 9, p. 3612, Apr. 2023, doi: 10.3390/en16093612.
- [21] Sharma V. K., Rajesh L., “Safety Management at Tummalapalle Mill,” in *DAE Safety & Occupational Health Professional Meet (DAE SOHPM)*, Variable Energy Cyclotron Centre (VECC), Ed., Mumbai: Atomic Energy Regulatory Board (AERB), Nov. 2018, pp. 213–216. doi: <https://dx.doi.org/10.2139/ssrn.5218145>.
- [22] R. G. Abrefah, S. A. Zakaria, and F. Ameyaw, “Exploring Nuclear Energy Potential for Sustainable Development and Energy Security in Ghana: Challenges, Opportunities and Strategic Imperatives,” *Science and Technology of Nuclear Installations*, vol. 2025, no. 1, Jan. 2025, doi: 10.1155/stni/5515993.

- [23] M. A. Arefin, M. T. Islam, F. Rashid, K. Mostakim, N. I. Masuk, and Md. H. I. Islam, "A Comprehensive Review of Nuclear-Renewable Hybrid Energy Systems: Status, Operation, Configuration, Benefit, and Feasibility," *Frontiers in Sustainable Cities*, vol. 3, Sep. 2021, doi: 10.3389/frsc.2021.723910.
- [24] A. A. Al Kindi, M. Aunedi, A. M. Pantaleo, G. Strbac, and C. N. Markides, "Thermo-economic assessment of flexible nuclear power plants in future low-carbon electricity systems: Role of thermal energy storage," *Energy Convers. Manag.*, vol. 258, p. 115484, Apr. 2022, doi: 10.1016/j.enconman.2022.115484.
- [25] R. Taylor, W. Bodel, A. Banford, G. Butler, and F. Livens, "Sustainability of Nuclear Energy—A Critical Review from a UK Perspective," *Sustainability*, vol. 16, no. 24, p. 10952, Dec. 2024, doi: 10.3390/su162410952.
- [26] Q. Wang, J. Guo, R. Li, and X. Jiang, "Exploring the role of nuclear energy in the energy transition: A comparative perspective of the effects of coal, oil, natural gas, renewable energy, and nuclear power on economic growth and carbon emissions," *Environ. Res.*, vol. 221, p. 115290, Mar. 2023, doi: 10.1016/j.envres.2023.115290.
- [27] G. Jia *et al.*, "Economic Analysis of Nuclear Energy Cogeneration: A Comprehensive Review on Integrated Utilization," *Energies (Basel)*, vol. 18, no. 11, p. 2929, Jun. 2025, doi: 10.3390/en18112929.
- [28] V. K. Sharma, S. K. Thamida, and B. N. K. Reddy, "Process liquor carbonation and simulation on an industrial scale, harnessing exhaust gas from light diesel oil fired boilers in mining and ore processing plants," *Sci. Rep.*, vol. 15, no. 1, p. 33778, Sep. 2025, doi: 10.1038/s41598-025-00060-z.
- [29] L. Liu *et al.*, "The role of nuclear energy in the carbon neutrality goal," *Progress in Nuclear Energy*, vol. 162, p. 104772, Aug. 2023, doi: 10.1016/j.pnucene.2023.104772.
- [30] T. Zhang, Y. Ma, and A. Li, "Scenario analysis and assessment of China's nuclear power policy based on the Paris Agreement: A dynamic CGE model," *Energy*, vol. 228, p. 120541, Aug. 2021, doi: 10.1016/j.energy.2021.120541.
- [31] Reddy B.N.K., Sunil T., and Sharma V.K., "Case Study on Advanced Separation Techniques used in Alkali Leaching based Mineral Processing Plant," *ICSPT 2023, IIT Patna, AIJR Publisher*, DOI: 10.21567/abstracts.165, Jan. 2024.
- [32] Reddy B.N.K., Kumar T.S., and Sharma V.K., "Evaluation of evaporation characteristics concerning environmental parameters for recycled water facility in mineral processing industry," in *9th Digital Earth Summit-2022*, ISDE, Ed., Chennai, Tamilnadu: Institute of Remote Sensing, Anna University, Sep. 2022, p. 75.
- [33] F. Al Mubarak, R. Rezaee, and D. A. Wood, "Economic, Societal, and Environmental Impacts of Available Energy Sources: A Review," *Eng.*, vol. 5, no. 3, pp. 1232–1265, Jun. 2024, doi: 10.3390/eng5030067.

- [34] A. Jahanger, M. R. Hossain, J. C. Onwe, S. O. Ogwu, A. Awan, and D. Balsalobre-Lorente, "Analyzing the N-shaped EKC among top nuclear energy generating nations: A novel dynamic common correlated effects approach," *Gondwana Research*, vol. 116, pp. 73–88, Apr. 2023, doi: 10.1016/j.gr.2022.12.012.
- [35] G. Vaidyanathan and R. D. Kale, "India's nuclear power program: a critical review," *Sādhanā*, vol. 47, no. 3, p. 181, Aug. 2022, doi: 10.1007/s12046-022-01953-9.
- [36] N. Nakagawa, S. Kosai, and E. Yamasue, "Life cycle resource use of nuclear power generation considering total material requirement," *J. Clean. Prod.*, vol. 363, p. 132530, Aug. 2022, doi: 10.1016/j.jclepro.2022.132530.
- [37] V. K. Sharma, P. Sriharsha, L. K. Rao, and S. Sarkar, "Flocculant Study for Neutral and Leached Slurries from Ore Processing of Pressurised Alkali Leaching-based Plant," *Results in Engineering*, p. 111862, Jul. 2026, doi: 10.1016/j.rineng.2026.111862.
- [38] Md. Sahabuddin and I. Khan, "Multi-criteria decision analysis methods for energy sector's sustainability assessment: Robustness analysis through criteria weight change," *Sustainable Energy Technologies and Assessments*, vol. 47, p. 101380, Oct. 2021, doi: 10.1016/j.seta.2021.101380.
- [39] A. Nagarkatti and A. K. Kolar, "Life Cycle Based Sustainability Index of Coal Power Plants in India," *International Journal of Sustainable Development and Planning*, vol. 16, no. 2, pp. 237–249, Apr. 2021, doi: 10.18280/ijstdp.160204.
- [40] D. Le Boulch, M. Buronfosse, Y. Le Guern, P.-A. Duvernois, and N. Payen, "Meta-analysis of the greenhouse gases emissions of nuclear electricity generation: learnings for process-based LCA," *Int. J. Life Cycle Assess.*, vol. 29, no. 5, pp. 857–872, May 2024, doi: 10.1007/s11367-024-02293-y.
- [41] B. Liu *et al.*, "Critical review of nuclear power plant carbon emissions," *Front. Energy Res.*, vol. 11, Sep. 2023, doi: 10.3389/fenrg.2023.1147016.
- [42] T. S. Kumar and B. N. K. Reddy, "Study of waste management treatment facilities using advanced Membrane Bio Reactor (MBR) technology," *Pollution Study*, vol. 6, no. 2, p. 3309, Apr. 2025, doi: 10.54517/ps3309.
- [43] T. Sunil Kumar and B. N. K. Reddy, "Carbonation and modeling study for process liquor in batch mode using flue gas in the mining and mineral processing industry," *Chemical Papers*, vol. 78, no. 7, 2024, doi: 10.1007/s11696-024-03379-5.
- [44] T. Gibon and Á. Hahn Menacho, "Parametric Life Cycle Assessment of Nuclear Power for Simplified Models," *Environ. Sci. Technol.*, vol. 57, no. 38, pp. 14194–14205, Sep. 2023, doi: 10.1021/acs.est.3c03190.
- [45] R. Sinha, S. K. Thamida, and B. N. K. Reddy, "An Overview of the Hydrocarbon Sector in India for Carbon Capture Scope," *Advances in Environmental and Engineering Research*, vol. 06, no. 02, pp. 1–14,

- May 2025, doi: 10.21926/aeer.2502022.
- [46] S. K. Satpati, P. Sriharsha, J. D. Kannan, L. K. Rao, S. Sarkar, and M. S. Rao, "Trial of Pilot Scale Nanofiltration Unit for Improvement of Precipitation Circuit at Tummalapalle Mill," *Current Natural Sciences and Engineering*, vol. 2, no. 1, pp. 528–543, Feb. 2025, doi: 10.63015/7n-2453.2.1.
- [47] H. C. Jenkins-Smith, C. L. Silva, M. C. Nowlin, and G. deLozier, "Reversing Nuclear Opposition: Evolving Public Acceptance of a Permanent Nuclear Waste Disposal Facility," *Risk Analysis*, vol. 31, no. 4, pp. 629–644, Apr. 2011, doi: 10.1111/j.1539-6924.2010.01543.x.
- [48] OECD, "Risks and Benefits of Nuclear Energy, NEA No. 6242," 2007. Accessed: Apr. 01, 2026. [Online]. Available: https://www.oecd-nea.org/ndd/pubs/2007/NDD_2007_%206242-risks_benefits_nuclear_energy.pdf
- [49] Rajesh N. V., Rao L. K. Reddy TCS, "Technical modifications of alkali leaching circuit to improve slurry throughput into the autoclave," in *CHEMCON*, ID: DMFDPD-183, CSCE, 74th Annual Session of Indian Institute of Chemical Engineers (IChE) and I. of M. & M. T. CSIR, Eds., Bhubaneswar: Indian Chemical Engineering Congress, Dec. 2021, p. 877.
- [50] Reddy T.C.S., Rao M. S. Rajesh N.V., "Effectiveness of autoclave agitator in alkali leaching based ore processing plant," in *77th ATM IIM*, KIIT and IIM, Eds., Bhubaneswar: Indian Institute of Metals, Nov. 2023.
- [51] L. Zhan, Y. Bo, T. Lin, and Z. Fan, "Development and outlook of advanced nuclear energy technology," *Energy Strategy Reviews*, vol. 34, p. 100630, Mar. 2021, doi: 10.1016/j.esr.2021.100630.
- [52] S. Siddique, K. Srinivas, N. R. Mandre, R. Venugopal, and S. K. Srivastava, "Improvements in Autoclave Heat Recovery Circuit in Uranium Ore Processing Mill at Tummalapalle, India," *Transactions of the Indian Institute of Metals*, vol. 68, no. 4, 2015, doi: 10.1007/s12666-014-0494-4.
- [53] V. R. Namboori, C. R. Tunga, K. Lankalapalli, S. Sarkar, and M. SrinivasaRao, "Technical modification of alkali leaching circuit to improve slurry throughput into the autoclave," *Suranaree Journal of Science and Technology*, vol. 30, no. 4, 2023, doi: 10.55766/sujst-2023-04-e0998.
- [54] S. Mohd Fadzil *et al.*, "Nuclear policy-nuclear fuels for peaceful, safer co-generation and environmentally benign applications," *International Journal of Engineering & Technology*, vol. 9, no. 3, pp. 724–757, Aug. 2020, doi: 10.14419/ijet.v9i3.30930.
- [55] T. Kamei, "Recent Research of Thorium Molten-Salt Reactor from a Sustainability Viewpoint," *Sustainability*, vol. 4, no. 10, pp. 2399–2418, Sep. 2012, doi: 10.3390/su4102399.
- [56] M. V. Ramana, "Technical and social problems of nuclear waste," *WIREs*

- Energy and Environment*, vol. 7, no. 4, Jul. 2018, doi: 10.1002/wene.289.
- [57] Y. Devarajan and C. Thiagarajan, “Innovative materials for enhancing safety, efficiency, and sustainability in nuclear waste management,” *Kerntechnik*, vol. 90, no. 3, pp. 261–274, Jun. 2025, doi: 10.1515/kern-2025-0009.
- [58] U. Shukla and R. Bajpai, “Nuclear power plants in India: achieving clean and green energy,” *International Journal of Nuclear Energy Science and Technology*, vol. 13, no. 1, p. 87, 2019, doi: 10.1504/IJNEST.2019.10020882.