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From energy choices to SMR deployment: A system-level comparative assessment of nuclear power (SMRs), fossil fuels, and renewable energy options in Iran

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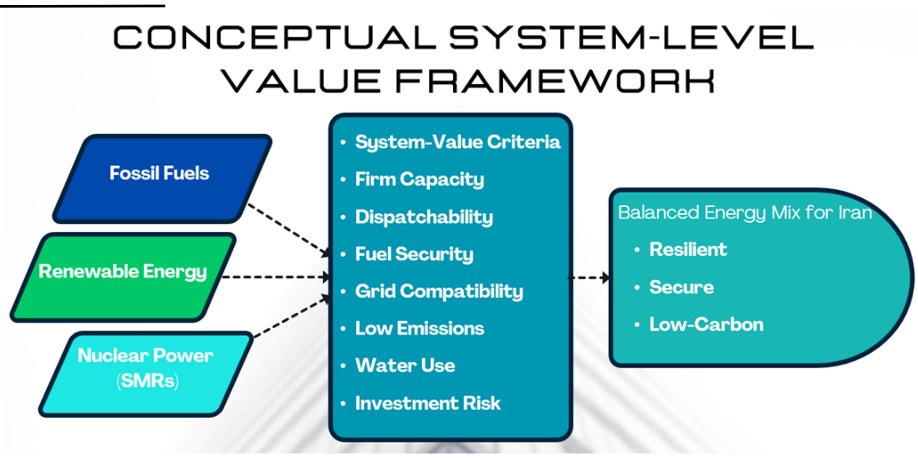
Abstract

Energy planning in countries heavily reliant on fossil fuels demands analytical frameworks that go beyond conventional cost-based comparisons. Iran's power system—despite its abundant oil and natural gas resources—is increasingly strained by rising electricity demand, seasonal gas supply constraints, aging thermal infrastructure, and growing environmental pressures. In this context, assessing energy technologies not by their standalone generation costs, but by their system-level value, has become critical to ensuring long-term reliability and sustainability.

This paper presents a system-level comparative assessment of fossil fuels, renewable energy, and nuclear power—with a specific focus on Small Modular Reactors (SMRs)—to evaluate their potential contributions to Iran's future energy mix. The analysis integrates technological performance, economic viability, regulatory readiness, and market deployment pathways, emphasizing how each option supports grid stability, fuel security, flexibility, and decarbonization.

The findings show that fossil-based generation is losing system value due to supply-side pressures and unpriced environmental costs. Renewables deliver clear emission benefits but are limited by intermittency, grid integration challenges, and dependence on backup capacity. In contrast, SMRs offer a balanced profile: firm low-carbon output, modular and phased investment, enhanced passive safety, and synergy with non-electric applications—particularly nuclear desalination, which aligns with Iran's water-energy nexus. The study concludes that SMRs can serve as a strategic complement to renewables and a viable transitional option for reducing fossil dependence—provided that enabling regulatory, institutional, and financing conditions are established.

Graphical Abstract



1. Introduction

Energy systems worldwide are undergoing a structural transformation driven by the combined imperatives of decarbonization, energy security, and evolving electricity demand patterns [1, 2]. In this context, conventional energy planning frameworks—traditionally anchored in cost-centric indicators such as the levelized cost of electricity (LCOE)—have become increasingly insufficient for capturing the multidimensional performance of energy technologies within modern, interconnected power systems [3]. Recent studies emphasize that the contribution of an energy technology cannot be adequately assessed without accounting for its system-level value, which encompasses attributes such as firm capacity, dispatchability, fuel supply security, grid stability, environmental externalities, and resilience to supply disruptions [4, 5]. These dimensions gain particular importance as power systems integrate higher shares of variable renewable energy sources. Although renewables offer clear advantages in terms of emissions reduction, their inherent intermittency introduces operational challenges related to reserve adequacy, system balancing, and flexibility requirements [6]. Iran represents a strategically relevant case within this global transition. Despite abundant domestic fossil fuel resources, the country's electricity sector faces increasing pressures from rising demand, seasonal natural gas supply constraints, aging thermal power infrastructure, and growing environmental concerns [2, 7]. The long-standing reliance on natural gas–fired power generation—while historically cost-effective—has exposed structural vulnerabilities related to fuel availability during peak demand periods, declining plant efficiency, and escalating environmental impacts [8]. In parallel, renewable energy deployment, particularly solar photovoltaic and onshore wind power, has gained momentum in Iran due to favorable resource availability and declining capital costs. However, the large-scale integration of variable renewables remains constrained by limited grid flexibility, insufficient energy storage capacity, and the need for complementary backup generation, which collectively reduce their ability to provide firm and dispatchable capacity at the system level [9, 10]. Within this context, nuclear power has re-emerged internationally as a firm low-carbon energy option capable of delivering stable electricity with high capacity factors and minimal lifecycle greenhouse gas emissions [1, 4]. While conventional large nuclear power plants offer proven operational performance, their deployment is often challenged by high upfront capital requirements, extended construction timelines, and exposure to financing and project execution risks—factors that are particularly relevant in developing economies such as Iran [5]. Recent attention has therefore shifted toward Small Modular Reactors (SMRs) as a more flexible and scalable nuclear deployment pathway. Characterized by modular design, reduced unit capacity, enhanced passive safety features, and the potential for phased construction, SMRs offer an alternative approach to nuclear power development that may better align with evolving grid conditions and investment constraints [9, 11]. From a system perspective, modular deployment enables phased investment strategies that reduce upfront financial exposure and improve alignment between capacity expansion and demand growth. Moreover, SMRs offer additional system-level value through non-electric applications such as nuclear desalination and industrial process heat, which are particularly relevant for water-scarce and energy-intensive regions of Iran [10].

Against this backdrop, this study moves beyond simplified cost-based comparisons to conduct a system-level comparative assessment of fossil fuels, renewable energy sources, and nuclear power—with a specific focus on SMRs—in the Iranian context. By integrating technological characteristics, economic considerations, regulatory readiness, and market deployment pathways, the analysis aims to clarify how different energy options contribute to overall system performance and whether SMRs can serve as a complementary component within a diversified, resilient, and low-carbon energy mix for Iran.

Fig. 1 conceptually illustrates the system-level assessment framework adopted in this study, highlighting how different energy options are evaluated through key system-value criteria prior to their integration into Iran's future energy mix.

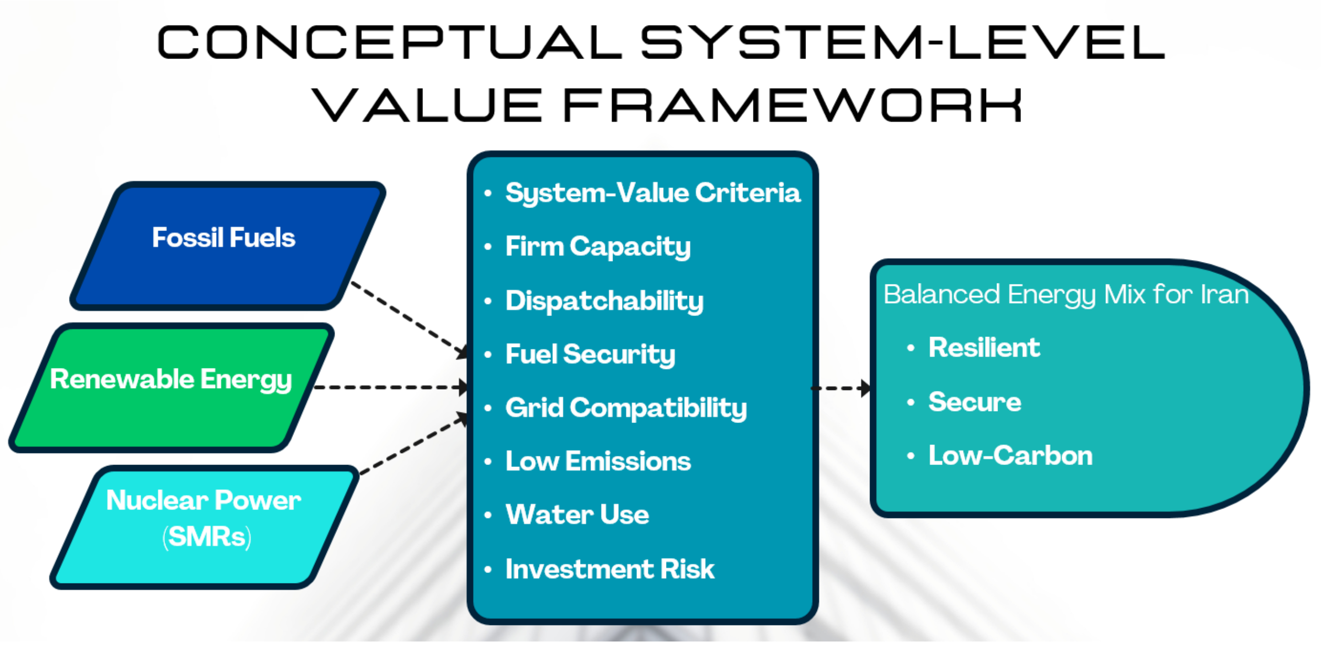


Fig. 1. Conceptual system-level value framework illustrating how fossil fuels, renewable energy sources, and SMR-based nuclear power are evaluated through key system-value criteria before contributing to a balanced, resilient, and low-carbon energy mix for Iran.

2. Methodology

This study adopts a system-level comparative assessment framework to evaluate alternative energy options for Iran beyond conventional cost-based metrics. The methodology is designed to capture the multidimensional contribution of energy technologies to overall power system performance, rather than assessing technologies as isolated generation units. This approach aligns with recent international studies emphasizing system-level analysis under high renewable penetration and energy security imperatives [1, 3, 6]

2.1. System-Level Assessment Framework

This study adopts a system-level assessment approach to compare fossil fuels, renewable energy sources, and nuclear power—specifically Small Modular Reactors (SMRs)—within the context of Iran's electricity system. Rather than relying solely on technology-specific cost metrics, the methodology evaluates energy options based on their contribution to overall system performance, recognizing that power systems operate as interconnected and interdependent structures rather than as isolated generation assets [2, 3].

The system-level framework employed in this study is conceptually illustrated in Figure 1. It reflects a structured evaluation process in which alternative energy technologies are assessed through a consistent set of system-value criteria before being considered as components of a balanced national energy mix.

2.2. Selection of System-Level Criteria

The system-level criteria used in this analysis were selected based on recurring indicators emphasized in international energy system assessments and planning frameworks developed by the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA), and the OECD Nuclear Energy Agency (NEA) [2, 4, 5]. These criteria are widely recognized as critical for evaluating long-term power system reliability, security, and sustainability, particularly under conditions of increasing renewable energy penetration.

The criteria include:

- firm capacity,
- dispatchability,
- fuel supply security,
- grid compatibility,
- operational flexibility,
- lifecycle greenhouse gas emissions,
- water use intensity,
- investment risk,
- scalability and deployment flexibility,
- and the potential for non-electric applications.

The selection of these criteria is intended to capture both technical and systemic dimensions of energy performance, while avoiding technology-specific bias.

2.3. Qualitative Comparative Assessment Approach

Given the strategic and exploratory nature of this study, a qualitative comparative assessment approach is adopted. Numerical weighting or aggregation of criteria is deliberately avoided, as such methods often introduce subjective bias and may obscure structural tradeoffs between technologies. Instead, each energy option is evaluated consistently across the selected criteria based on documented operational characteristics, deployment experience, and findings reported in peer-reviewed literature and authoritative international reports [1, 6, 8].

This qualitative approach enables the identification of relative strengths, limitations, and complementarities among fossil fuels, renewable energy sources, and SMRs, rather than producing a single composite ranking that could oversimplify system interactions.

2.4. Data Sources and Analytical Scope

The analysis is based exclusively on secondary data derived from publicly available sources, including international energy outlooks, technology assessment reports, regulatory publications, and peer-reviewed journal articles published between 2022 and 2024. Key data sources include reports from the IEA, IAEA, OECD/NEA, and recent academic studies on SMR technology, economics, and deployment pathways [1-10]

The methodological scope is intentionally confined to system-level implications and does not extend to detailed project-level techno-economic modeling, site-specific feasibility analysis, or probabilistic risk assessment.

2.5. Comparative Synthesis and Visualization

The results of the system-level assessment are synthesized through two complementary visualization tools. First, a qualitative System-Value Matrix (**Table 1**) summarizes the comparative performance of energy options across the selected criteria, highlighting tradeoffs and complementarities relevant to portfolio-based planning. Second, a conceptual positioning diagram (**Fig. 2**) provides a qualitative visualization of how different technologies align along key system dimensions, namely decarbonization potential and dispatchability.

Together, these tools support a transparent and internally consistent comparison, reinforcing the analytical narrative presented in the Results and Discussion section.

2.6. Methodological Limitations

This study is subject to limitations inherent to qualitative system-level assessments. While the approach provides valuable insights into structural tradeoffs and strategic interactions, it does not replace detailed quantitative modeling required for investment decision-making at the project level. Nevertheless, the methodology is appropriate for informing high-level energy system analysis and comparative evaluation under conditions of uncertainty and evolving technological pathways.

3. Results and discussion

3.1. System-Level Performance of Fossil Fuel–Based Power Generation

Fossil fuel–based power generation, predominantly natural gas–fired plants, currently constitutes the backbone of Iran's electricity system, supplying more than 80% of total electricity generation and the majority of firm capacity [2, 12]. This configuration has historically ensured short-term reliability and relatively low electricity prices under domestic fuel pricing schemes.

However, from a system-level perspective, the value of fossil fuel–based generation is increasingly undermined by structural vulnerabilities. Seasonal natural gas supply constraints—particularly during winter peak demand—have resulted in forced outages, load shedding, and operational instability, directly affecting energy security and system reliability [2, 13].

In addition to supply constraints, fossil fuel–based generation imposes significant external costs that are not reflected in conventional cost metrics. These include the opportunity cost of diverting domestically produced natural gas from higher-value export markets, increasing health and environmental damages associated with air pollutant emissions, and the high carbon intensity of the power sector, which constrains long-term decarbonization efforts [5, 14].

Furthermore, the aging thermal power plant fleet—much of which has been in operation for more than three decades—exhibits declining thermal efficiency, elevated forced outage rates, and rising maintenance expenditures. Collectively, these factors contribute to a gradual erosion of system resilience. As summarized in Table 1, fossil fuel–based generation retains high dispatchability but exhibits declining system-level value across fuel security and sustainability dimensions.

3.2. System-Level Performance of Renewable Energy Sources

Renewable energy sources, primarily solar photovoltaic and onshore wind power, offer substantial advantages in terms of near-zero operational emissions, abundant domestic availability, and declining capital costs [2]. Iran's high solar irradiance levels and favorable wind resources provide strong technical potential for renewable deployment.

Despite these advantages, the system-level contribution of variable renewable energy remains constrained by inherent intermittency and non-dispatchability. Unlike conventional generation technologies, solar and wind power lack intrinsic inertia and firm capacity, necessitating complementary investments in grid reinforcement, energy storage, and fast-ramping backup generation to maintain system stability [6, 14].

These integration requirements introduce additional system costs that are often underestimated or excluded in standalone levelized cost comparisons. As indicated in Table 1, renewable energy technologies score highly in terms of emissions reduction and fuel security but exhibit limitations with respect to firm capacity, dispatchability, and grid compatibility.

Accordingly, while renewable energy sources are indispensable for long-term decarbonization, their role within the power system remains primarily complementary rather than foundational in the absence of firm low-carbon capacity.

3.3. Nuclear Power and the Strategic Role of SMRs

Nuclear power provides firm, dispatchable, and low-carbon electricity with high capacity factors and minimal lifecycle greenhouse gas emissions [1, 4]. Conventional large nuclear power plants offer long-term operational stability and strong fuel security; however, their deployment is constrained by high capital intensity, extended construction schedules, and exposure to financing and execution risks, particularly in developing economies such as Iran [5].

Small Modular Reactors (SMRs) address several of these limitations through modular factory-based fabrication, phased deployment strategies, and enhanced passive safety features [15, 16] .From a system-level standpoint, SMRs retain the core advantages of nuclear energy—firm capacity, dispatchability, and fuel security—while offering improved scalability and compatibility with existing grid infrastructure.

To clarify these system-level tradeoffs, Figure 2 qualitatively positions fossil fuels, renewable energy sources, and SMR-based nuclear power across the dimensions of decarbonization potential and dispatchability. As illustrated, SMRs occupy an intermediate and stabilizing position, combining firm low-carbon generation with operational flexibility that complements variable renewable energy.

Beyond electricity generation, SMRs provide additional system-level value through non-electric applications such as seawater desalination and industrial process heat supply. These capabilities are particularly relevant for Iran, where water scarcity and energy-intensive industrial demand coexist. In southern coastal regions, the co-location of SMR-based power and desalination facilities could simultaneously enhance electricity reliability and freshwater availability [10].

To further illustrate these system-level tradeoffs, Figure 2 qualitatively positions fossil fuels, renewable energy sources, and SMR-based nuclear power across the dimensions of decarbonization potential and dispatchability.

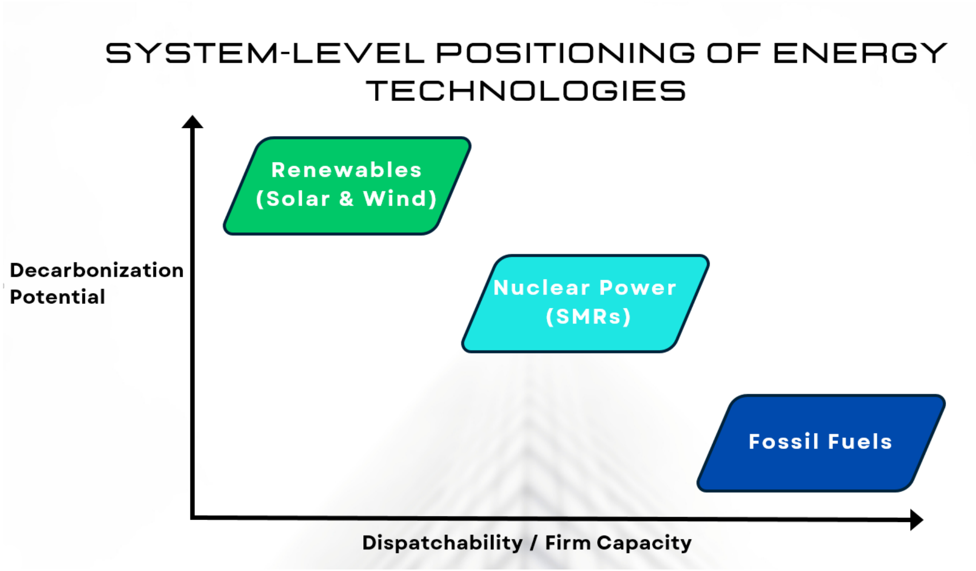


Fig. 2. Conceptual positioning of major energy technologies across system-level dimensions of decarbonization potential and dispatchability. Fossil fuels provide firm but carbon-intensive power, renewable energy offers low emissions with limited dispatchability, while SMR-based nuclear power occupies a balanced position by combining firm capacity with low-carbon performance.

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3.4. Comparative System-Value Matrix

To synthesize the findings, a qualitative System-Value Matrix is presented in Table 1, comparing fossil fuels, renewable energy sources, and SMR-based nuclear power across key system-level criteria. The matrix is designed to identify structural tradeoffs and complementarities rather than to produce a single aggregated ranking.

As shown in Table 1, fossil fuels maintain high dispatchability but face declining performance in fuel security and sustainability. Renewable energy technologies excel in emissions reduction but are constrained by intermittency and limited firm capacity. In contrast, SMRs demonstrate balanced system-level performance, offering firm low-carbon capacity, moderate investment risk, and additional non-electric applications that enhance overall system value.

Table 1. System-Level Value Matrix for Major Energy Options in Iran.

System-Level Criterion	Fossil Fuels (Natural Gas–Based)	Renewable Energy (Solar & Wind)	Nuclear Power (SMRs)
Firm Capacity	High (declining under fuel constraints)	Low	High
Dispatchability	High	Low	High
Fuel Security	Medium–Low (seasonal gas shortages)	High (domestic resources)	Very High
Grid Compatibility	High (existing infrastructure)	Medium–Low (integration challenges)	High
Operational Flexibility	Medium	Low	Medium–High
Lifecycle Greenhouse Gas Emissions	High	Very Low	Very Low
Water Use Intensity	High	Low	Medium
Investment Risk	Medium (fuel price & policy risk)	Medium (market & integration risk)	Medium–Low
Scalability & Phased Deployment	Low	High	High
Construction & Deployment Time	Short–Medium	Short	Short–Medium
Non-Electric Applications	None	Limited	High (desalination, process heat)
Overall System-Level Value	Declining	Complementary	Balanced / High

3.5. Implications for Iran's Energy Transition

The comparative analysis confirms that no single technology can independently satisfy all system-level requirements. Fossil fuels remain critical in the near term but exhibit declining long-term system value. Renewable energy sources are essential for emissions reduction yet require complementary firm capacity to ensure reliability.

Within this portfolio-based perspective, SMRs emerge as a potential system stabilizer rather than a direct substitute for existing technologies. The results suggest that integrating SMRs alongside renewable energy sources may enhance system resilience, reduce dependence on fossil fuels during peak periods, and support a more balanced transition toward a low-carbon energy system under Iran's technical and institutional constraints.

4. Conclusion

This study presented a system-level comparative assessment of fossil fuels, renewable energy sources, and nuclear power—with a specific focus on Small Modular Reactors (SMRs)—to evaluate their potential roles within Iran's evolving electricity system. Moving beyond conventional cost-based metrics, the analysis emphasized system-level value by examining how different energy technologies contribute to reliability, flexibility, fuel security, environmental performance, and overall system resilience.

The results indicate that fossil fuel–based power generation, while currently dominant, exhibits declining long-term system-level value due to fuel supply constraints, aging infrastructure, environmental externalities, and increasing vulnerability during peak demand periods. Renewable energy sources offer substantial benefits in terms of emissions reduction and domestic resource availability; however, their inherent intermittency and limited dispatchability constrain their ability to independently provide firm capacity at the system level.

Within this comparative framework, SMR-based nuclear power demonstrates a balanced system-level performance. By combining firm low-carbon electricity generation with modular deployment, enhanced safety characteristics, and improved grid compatibility, SMRs address several structural limitations associated with both fossil fuels and variable renewable energy sources. In addition, their capability to support non-electric applications—such as seawater desalination and industrial process heat—further enhances their system-level relevance in contexts characterized by water scarcity and energy-intensive industrial demand.

Importantly, the findings do not suggest a single-technology solution to Iran's energy challenges. Rather, the analysis highlights the importance of portfolio-based planning in which different technologies perform complementary roles. From this perspective, SMRs emerge as a potential system stabilizer that can support renewable energy integration while mitigating reliability and emissions tradeoffs associated with continued reliance on fossil fuel–based generation.

This study is subject to limitations inherent to qualitative system-level assessments and does not replace detailed techno-economic modeling or site-specific feasibility analysis. Nevertheless, the system-level framework adopted here provides a transparent and structured basis for comparing energy options and may inform future analytical work on integrated energy planning and technology deployment pathways under conditions of uncertainty.

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Author contributions

A.K. conceived the core research idea, developed the system-level assessment framework, conducted the comparative analysis, interpreted the results, and prepared the original draft of the manuscript. **N.M.S.** and **A.B.S.** supervised the research process, provided technical and scientific guidance, and contributed to the critical review and refinement of the manuscript. All authors reviewed and approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No new data were generated in this study. The analysis is based exclusively on publicly available reports and literature sources.

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