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A Strategic Feasibility-to-Deployment Framework for Small Modular Reactors in Iran's Future Energy Mix: Integrating Techno-Economic Assessment, Site-Risk Analysis, Water–Energy Nexus and Safety Compliance

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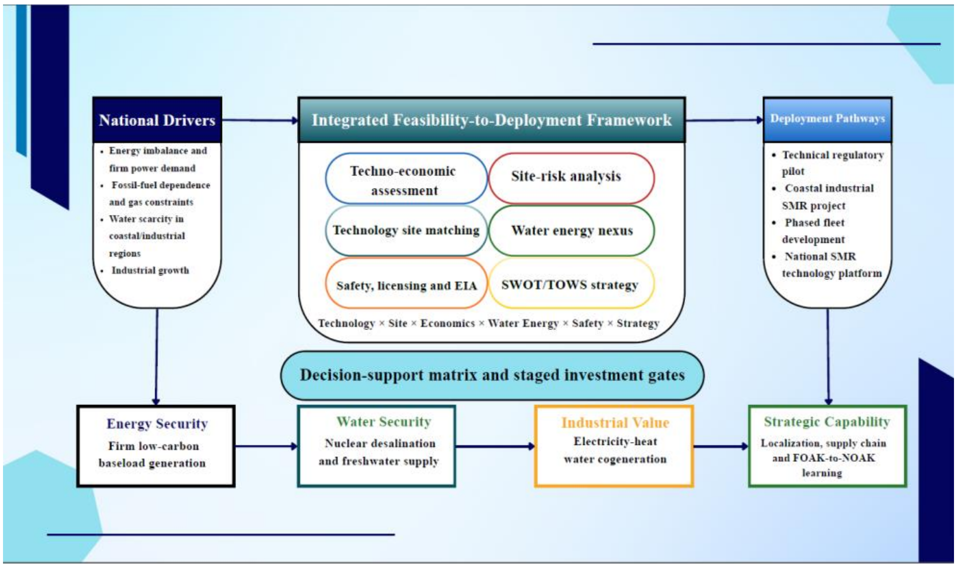
Abstract: Small modular reactors (SMRs) are increasingly considered potential components of resilient low-carbon energy systems, particularly where firm electricity, freshwater, and industrial heat are required simultaneously. This study develops a strategic feasibility-to-deployment framework for SMR deployment in Iran by integrating scenario-based techno-economic assessment, engineering-oriented site-risk screening, technology–site matching, water–energy nexus analysis, safety and licensing readiness, environmental impact assessment (EIA), geopolitical and supply-chain risk, multi-criteria decision analysis (MCDA), and SWOT/TOWS analysis. Four candidate technologies—ACP100, RITM-200N, KLT-40S, and VBER-300—are evaluated under differentiated deployment scenarios. The quantitative analysis yields indicative electricity-only levelized cost of electricity (LCOE) of 112.2–166.4 *USD/MWh* and project internal rates of return (IRR) of 15.1–15.7% under the stated base-case financial assumptions. When revenues from desalinated water, industrial heat, and capacity services are incorporated, the corresponding revenue-adjusted effective LCOE decreases to approximately 54.2–80.1 *USD/MWh*. Although subsidized gas-based generation may retain a short-term cost advantage, the results show that multipurpose SMR configurations can provide greater long-term strategic value by combining firm power, desalinated-water production, industrial heat, and reduced exposure to fuel-supply constraints. No single design dominates all applications: larger configurations offer lower unit costs and stronger economies of scale, whereas smaller configurations provide lower absolute capital exposure and greater flexibility for pilot, phased, or specialized deployment. The integrated assessment therefore supports a phased pathway beginning with a technical–regulatory pilot, followed by coastal industrial cogeneration and subsequent multi-unit deployment. The reported estimates are scenario-based and require refinement through project-specific financial modeling, site investigations, safety analysis, and licensing studies.

Graphical Abstract



1. Introduction

Energy systems worldwide are undergoing a structural transformation driven by the simultaneous growth of electricity demand, the need for decarbonization, the increasing importance of energy security, and the resilience of critical infrastructure. In this context, energy planning can no longer be based solely on fuel availability or electricity generation cost. Instead, energy-generation options must be assessed through a broad set of technical, economic, safety, environmental, grid-related, financial, and strategic criteria. The International Energy Agency emphasizes that emerging energy supply and demand trends should be evaluated simultaneously from the perspectives of energy security, emissions reduction, and economic development [1]. In this regard, nuclear energy, as a firm, low-carbon and dispatchable energy source, can contribute to secure energy transitions and complement variable renewable energy sources [2].

Iran is also facing a set of interconnected challenges across the energy, water, and industrial sectors. The country's electricity system remains significantly dependent on fossil fuels, while electricity demand, seasonal fuel-supply constraints, energy consumption in large industries, regional water stress, and the need for a reliable freshwater supply in southern and coastal areas continue to increase. Under these conditions, reducing dependence on fossil fuels, strengthening long-term energy security, ensuring sustainable freshwater supply, supporting industrial development, and improving the resilience of critical infrastructure have become strategic requirements for national energy planning.

Renewable energy sources, particularly solar and wind, can play an important role in reducing fossil-fuel consumption and diversifying electricity generation. However, their variable output may require complementary flexibility options—including energy storage, demand-side management, transmission reinforcement, flexible generation, or firm low-carbon capacity—to ensure reliable supply for electricity-intensive industries and seawater-desalination facilities. From this perspective, nuclear energy can complement renewable resources by providing firm, low-carbon, and high-capacity-factor generation within a more balanced and resilient energy system [2].

In this context, small modular reactors (SMRs) have emerged as a diverse class of advanced nuclear technologies that may address some of the financing, construction, siting, and deployment limitations associated with conventional large nuclear power plants. The International Atomic Energy Agency identifies SMRs and microreactors as potential sources of not only electricity, but also process heat, hydrogen, and energy for seawater desalination [3]. SMRs should therefore not be regarded merely as scaled-down versions of conventional nuclear power plants. When deployed in cogeneration configurations, they may function as multipurpose platforms for firm electricity generation, freshwater production, industrial heat supply, and regional infrastructure development.

The global SMR landscape includes a wide range of designs with different reactor types, power levels, fuel requirements, safety approaches, and deployment models. For Iran, technologies such as RITM-200N, ACP100, KLT-40S, and VBER-300 can be examined within a structured assessment framework. However, selection among these options should not be based solely on nominal power, reactor type, or vendor claims. Technology maturity, licensing pathway, fuel-cycle compatibility, cogeneration capability, site compatibility, localization potential, financing structure, supply-chain risk, and geopolitical constraints must be considered simultaneously. This approach is consistent with the logic of the OECD/NEA SMR Dashboard, which evaluates SMR deployment readiness not only from a technical perspective but also through licensing, siting, financing, supply chain, stakeholder engagement, and fuel dimensions [4].

From an economic perspective, SMRs present both opportunities and uncertainties. Smaller unit capacities, modular construction, phased implementation, and design repeatability may reduce absolute upfront investment exposure and facilitate incremental capacity additions. However, limited commercial experience, FOAK cost uncertainty, specialized supply-chain requirements, financing and licensing risks, and the scarcity of verified project-level cost data remain major barriers to definitive economic conclusions. Consequently, SMR deployment should not be assessed solely through electricity-only LCOE. In Iran's coastal and industrial regions, the simultaneous demand for electricity, freshwater, process heat, and capacity services may support a multi-product revenue structure. The techno-economic assessment should therefore consider not only generation cost, but also investment returns, financing conditions, contractual arrangements, and the system value generated by integrated electricity–water–heat production.

Furthermore, SMR deployment cannot be justified without site-risk analysis and technology–site matching. Each SMR technology has specific requirements in terms of cooling, fuel, unit capacity, deployment model, equipment transportation, grid connection, licensing, external hazards, and environmental sensitivity. Accordingly, a technology suitable for a coastal or industrial region may not necessarily be appropriate for inland, remote, or environmentally sensitive areas. Site-risk analysis and technology–site matching are therefore essential components in converting feasibility assessment into deployment-oriented decision-making.

Safety compliance, licensing readiness, and environmental impact assessment (EIA) are also fundamental conditions for SMR deployment. Although many SMR designs offer potential advantages such as passive safety systems, smaller radioactive inventories, modular construction, and compact layouts, these characteristics do not replace the need for formal licensing, safety analysis, safety documentation, EIA, waste management strategy, physical protection, and stakeholder engagement. IAEA SSR-2/1 Rev.1 defines the design safety requirements for nuclear power plants, emphasizing safety functions, safe operation throughout the design lifetime, safe decommissioning, and minimization of environmental impacts [5]. In addition, IAEA-TECDOC-1915 specifically addresses EIA considerations for SMR and shows that, although these technologies may create new deployment opportunities, they still require a coherent and rigorous EIA framework [6].

Despite the expanding international literature on SMRs, most existing studies concentrate on reactor-design reviews, generalized economic comparisons, market-development prospects, or the role of nuclear energy in low-carbon transitions. Comparatively limited attention has been devoted to integrated national frameworks that connect quantitative financial screening, engineering-oriented site-risk assessment, technology–site compatibility, multipurpose water–energy applications, licensing and environmental readiness, geopolitical and supply-chain exposure, and strategic deployment sequencing. This gap is particularly important for Iran, where subsidized fossil-fuel prices, regional water stress, industrial energy demand, financing constraints, vendor dependency, and site-specific engineering conditions interact simultaneously. The central research question is therefore not simply whether SMRs are suitable for Iran, but which technology–site combinations, business models, risk conditions, and implementation stages can support a realistic and economically defensible deployment pathway.

Accordingly, this paper develops a strategic feasibility-to-deployment framework for SMR implementation in Iran. The framework integrates scenario-based techno-economic assessment, engineering-oriented site-risk screening, technology–site matching, water–energy nexus evaluation, safety and licensing readiness, EIA, geopolitical and supply-chain risk analysis, Multi-Criteria Decision Analysis (MCDA), and strengths–weaknesses–opportunities–threats (SWOT) and threats–opportunities–weaknesses–strengths (TOWS) analysis-based strategic interpretation. The principal contribution of the study is not the isolated evaluation of individual reactor designs, but the integration of quantitative financial indicators, functional site roles, risk-adjusted technology selection, multipurpose business models, and phased implementation pathways within a unified Iran-specific decision-support framework. The framework is intended to support policymakers, regulators, investors, technology vendors, and energy planners in moving from broad feasibility assessment toward staged, reviewable, and deployment-oriented decision-making.

To clarify the research gap and position the contribution of the present study, **Table 1** compares the dominant approaches in the existing SMR literature with Iran-specific decision requirements and the integrated assessment developed in this paper. The comparison demonstrates that the proposed framework moves beyond reactor-design review and generalized economic assessment by connecting quantitative financial screening, functional site analysis, water–energy applications, safety and licensing readiness, geopolitical risk, and strategic deployment planning.

Table 1. Positioning of the Present Study Relative to the Existing Literature.

Assessment Dimension	Conventional SMR Studies	Iran-Specific Need	Approach of the Present Study
Technology	Review of reactor designs and technical features	Selection of technologies compatible with national conditions	Technology screening and technology–site matching
Economics	Focus on LCOE and CAPEX	Multi-product assessment of electricity, water, and heat, together with financial risk	Techno-economic assessment and multi-revenue business model
Siting	General site-selection analysis	Regional prioritization and definition of functional site roles	Site-risk analysis and regional deployment logic
Water–Energy Nexus	Desalination as a secondary application	Water scarcity and coastal industrial development	Strategic integration of electricity generation, desalination, and industrial heat
Safety and Licensing	General discussion of safety requirements	Integration of IAEA requirements, licensing, and EIA	Early inclusion of safety compliance and EIA in the feasibility framework
Policy and Strategy	Broad energy-policy analysis	Translation of feasibility-study outputs into deployment scenarios	SWOT/TOWS-based staged deployment pathway

Based on this comparison, the proposed framework evaluates SMRs not merely as electricity-generation technologies, but as strategic infrastructure at the intersection of energy, water, industry, safety, and investment.

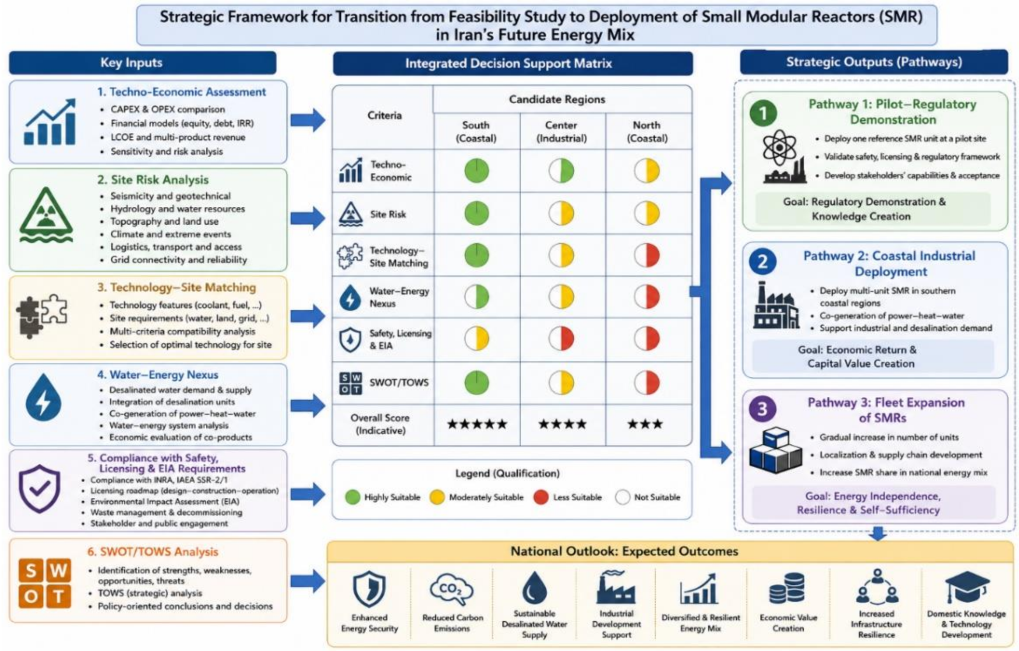


Fig. 1. Conceptual Framework for the Feasibility-to-Deployment Transition of SMRs in Iran.

Fig. 1 illustrates the proposed decision-support framework for transitioning from strategic feasibility assessment to staged SMR deployment in Iran. The principal analytical inputs include quantitative techno-economic assessment, engineering-oriented site-risk screening, technology–site matching, water–energy nexus evaluation, safety and licensing readiness, EIA, geopolitical and supply-chain risk, MCDA, and SWOT/TOWS analysis. Their integration produces three principal implementation pathways: a technical–regulatory pilot for institutional and licensing-risk reduction, coastal industrial deployment based on electricity–water–heat cogeneration, and phased multi-unit development supported by progressive localization and supply-chain capability.

2. Methodology

This study develops a structured decision-support methodology for transforming a conventional feasibility assessment into a deployment-oriented framework for SMRs in Iran's future energy mix. Within this approach, SMRs are evaluated not merely as electricity-generating technologies, but as multipurpose energy–water–industry infrastructure. Technology selection, site-risk screening, project economics, water–energy integration, safety and licensing readiness, environmental assessment, geopolitical exposure, and strategic planning are therefore treated as interdependent components of an integrated feasibility-to-deployment process.

The methodological design is aligned with international approaches to SMR deployment, which emphasize that successful implementation depends not only on technology readiness, but also on regulatory preparedness, site suitability, infrastructure maturity, supply-chain capability, qualified human resources, financing arrangements, stakeholder engagement, and a coherent long-term deployment strategy [7, 8]. In the Iranian context, these factors must additionally be considered in relation to subsidized fossil-fuel prices, water scarcity, industrial energy demand, vendor dependency, technology-transfer limitations, and sanctions-related procurement and financing risks.

Based on this perspective, the guiding research question is defined as follows:

Which SMR technology, at which site, under which techno-economic, safety, environmental, licensing, geopolitical, and strategic conditions, can be realistically integrated into Iran's future energy mix?

To address this question, the proposed methodology is organized into seven interconnected analytical layers:

- Techno-economic assessment;
- Site-risk analysis;
- Technology–site matching;
- Water–energy nexus assessment;
- Safety compliance, licensing readiness, and EIA;
- Multi-Criteria Decision Analysis (MCDA);
- SWOT/TOWS analysis and conversion of feasibility findings into staged deployment pathways.

Geopolitical and supply-chain risks are treated as cross-cutting constraints that may influence technology selection, project financing, fuel-cycle arrangements, licensing support, localization potential, and long-term operational sustainability across all seven analytical layers.

The overall logic of the framework is expressed as:

$$\text{Technology}\times\text{Site}\times\text{Economics}\times\text{Water-Energy}\times\text{Safety}\times\text{Strategy}\rightarrow\text{Deployment Pathway}$$

This structure enables the study to move beyond a descriptive feasibility assessment and develop a phased, risk-informed, and deployment-oriented decision pathway for SMR implementation in Iran.

2.1. Techno-Economic Assessment

The first analytical layer evaluates the candidate SMR technologies from a techno-economic and project-finance perspective. The assessment covers technology maturity, construction schedule, capital expenditure, operating and maintenance expenditure, fuel cost, capacity factor, electricity-generation cost, financing risk, modular deployment potential, localization capability, and opportunities for multi-product revenue generation.

The financial screening is conducted under a consistent base-case structure to enable comparison among the candidate technologies. Technology-specific inputs are applied for project capacity, capacity factor, capital cost, operating cost, project lifetime, refuelling cycle, electricity tariff, and revenues from desalinated water, industrial heat or steam, and capacity services. The resulting indicators include electricity-only LCOE, revenue-adjusted effective LCOE, net present value, project and equity internal rates of return, payback period, and debt-service coverage.

As summarized in **Table 2**, the selected indicators capture both conventional electricity-generation economics and the additional value that SMRs may create through modular deployment, cogeneration, and diversified revenue streams. Previous studies indicate that the economic viability of SMRs is not achieved automatically, but depends on modular construction, serial production, design standardization, construction-risk reduction, learning effects, financing conditions, and the transition from first-of-a-kind (FOAK) to nth-of-a-kind (NOAK) deployment [9, 10].

In this study, the economic assessment is not limited to an electricity-only business model. In coastal and industrial regions of Iran, SMRs may create additional value through desalinated-water production, industrial heat or steam supply, and capacity-related services. The total annual project revenue is therefore formulated as:

$$R_t=R_{electricity,\,t}+R_{water,\,t}+R_{heat,\,t}+R_{capacity,\,t} \tag{1}$$

Where R_t represents the total annual revenue, $R_{electricity,\,t}$ is the revenue from electricity sales, $R_{water,t}$ is the revenue from desalinated water sales, and $R_{heat,t}$ is the revenue from industrial heat or steam supply. This formulation reflects the multipurpose value proposition of SMRs and supports a broader economic assessment than a conventional electricity-only LCOE comparison. In particular, the revenue-adjusted effective LCOE is used as a supplementary planning indicator to illustrate how non-electric revenues may reduce the net cost allocated to electricity generation. It should not, however, be interpreted as a standardized substitute for conventional LCOE without clearly identifying the credited revenue streams and modelling assumptions.

The resulting indicators include total capital expenditure (CAPEX), CAPEX intensity, operating expenditure (OPEX), electricity-only levelized cost of electricity (LCOE), revenue-adjusted effective LCOE, net present value (NPV), project internal rate of return (project IRR), equity internal rate of return (equity IRR), weighted average cost of capital (WACC), payback period, and minimum debt-service coverage ratio (DSCR).

The output of this analytical layer is a comparative financial screening rather than a definitive investment appraisal. The reported results represent feasibility-level, scenario-based estimates and do not constitute vendor quotations, guaranteed EPC prices, or final project-finance forecasts.

Table 2. Key indicators for techno-economic assessment.

Indicator	Role in the methodology
Total CAPEX	Measures the absolute initial capital requirement of the project
CAPEX intensity	Expresses capital cost per unit of installed capacity
OPEX	Estimates annual operation and maintenance expenditure
Electricity-only LCOE	Measures the discounted cost of electricity before crediting non-electric revenues
Revenue-adjusted effective LCOE	Estimates the net electricity cost after crediting modelled water, heat, and capacity revenues
NPV	Evaluates the discounted net value generated over the project lifetime
project IRR	Assesses the return generated by total project cash flows
WACC	Represents the blended cost of debt and equity financing
Payback period	Indicates the time required to recover the initial investment
Minimum DSCR	Evaluates the project’s capacity to meet debt-service obligations
Construction Time	Captures schedule-related cost and implementation risk
Capacity Factor	Indicates generation stability and revenue-producing capability
FOAK/NOAK transition	Represents learning effects, standardization, and potential cost reduction
Multi-product Revenue	Captures revenues from electricity, water, industrial heat, and capacity services

2.2. Site-Risk Analysis and Technology–Site Matching

The second analytical layer evaluates candidate sites in terms of engineering risk, implementation feasibility, infrastructure readiness, and strategic value. Site-risk analysis is not limited to identifying natural or human-induced hazards. It is also used to determine the functional role that each candidate region may perform within a national SMR deployment programme.

A candidate location may, for example, be better suited to a technical–regulatory pilot intended to support site investigations, environmental assessment, preliminary safety documentation, and regulatory learning. Another location may have greater value for industrial or commercial deployment because of stronger grid connections, port infrastructure, seawater access, industrial demand, or more credible long-term offtake arrangements.

Candidate regions are therefore classified into four functional groups:

- ✓ Technical–regulatory reference sites;
- ✓ Coastal industrial sites;
- ✓ Grid-support sites;
- ✓ Long-term strategic sites.

The functional logic of this classification is presented in **Table 3**. The classification clarifies how different sites may contribute to the national SMR programme through distinct roles, including licensing learning, industrial cogeneration, grid support, regional development, and phased fleet expansion.

To strengthen the engineering basis of the site-selection process, the framework extends the assessment beyond geographical classification and incorporates structured regional site-risk screening. As summarized in **Table 4**, the screening considers seismic exposure, geotechnical and topographical suitability, grid accessibility, cooling-water availability, coastal and flooding hazards, heavy-component transportation, port and logistics capability, environmental sensitivity, industrial hazards, natural-hazard-triggered technological (NaTech) risks, and emergency-planning feasibility.

The screening conducted at this stage is intended to support strategic regional comparison and does not replace the detailed seismic, geological, geotechnical, hydrological, meteorological, environmental, and emergency-planning investigations required for nuclear site licensing. Consequently, the results should be interpreted as pre-feasibility-level indicators of practical deployability and engineering constraint rather than as final site-acceptance conclusions.

Technology–site matching is subsequently applied to evaluate the compatibility of each SMR design with the technical, infrastructural, environmental, regulatory, and strategic characteristics of each functional site category. This step is necessary because individual SMR technologies have different requirements with respect to unit capacity, cooling configuration, seawater demand, fuel and refuelling strategy, equipment dimensions, heavy-haul transportation, grid connection, cogeneration capability, licensing maturity, vendor support, and spent-fuel management.

Geopolitical and supply-chain exposure is also incorporated as a cross-cutting modifier of technology–site suitability. A technology may show strong physical compatibility with a coastal or industrial site, while its practical deployment score may be reduced by dependence on a single foreign vendor, restricted access to fuel-cycle services, spare parts, digital control systems, financing, or licensing support.

Accordingly, technology and site selection are performed simultaneously rather than as two independent decisions. This approach is consistent with multi-criteria decision-making principles, under which complex infrastructure alternatives are evaluated against multiple interacting criteria instead of a single technical or economic indicator [11].

Table 3. Technology–site matching logic.

Site Type	Strategic Role	Matching Logic
Technical–regulatory reference site	Risk reduction, licensing learning, PSAR, and EIA development	Suitable for testing safety, environmental, and institutional frameworks
Coastal industrial site	Cogeneration of electricity, water, and heat	Suitable for revenue-oriented projects with stable industrial offtakers
Grid-support site	Grid stability and electricity imbalance mitigation	Suitable for baseload generation and network support
Long-term strategic site	Regional development and technology platform	Suitable for phased deployment, localization, and fleet expansion

Table 4. Engineering-oriented site-risk screening matrix for candidate SMR regions.

Site / Region	Seismicity	Grid Access	Water/ Cooling	Port & Logistics	Environmental Sensitivity	Industrial / NaTech Risk	Overall Role
Bandar Khajeh-Nafas	Moderate	Moderate	Excellent	Moderate	Moderate	Low	Technical–regulatory reference
Assaluyeh		Excellent		Excellent		High	Industrial offtake
Bandar Abbas						Moderate	Coastal industrial / grid support
Chabahar / Makran		Good				Low	Long-term strategic
Central industrial regions	Low–Moderate		Limited	Limited	Low	Moderate	Selective grid/industry

2.3. Water–Energy Nexus Assessment

The third analytical layer treats the water–energy nexus as an independent decision criterion. In this study, the value of SMRs is assessed not only in terms of electricity generation but also through their potential contribution to freshwater production, industrial heat or steam supply, and integrated infrastructure resilience. This consideration is particularly relevant to Iran’s southern coastal and industrial regions, where sustained demand for electricity, freshwater, and process heat coincides with access to seawater and major industrial facilities.

Three principal SMR-based pathways are considered within the water–energy nexus assessment, as summarized in **Table 5**. These include electricity supply for reverse osmosis (RO) desalination, direct or indirect thermal-energy supply for multi-effect distillation (MED) and multi-stage flash (MSF) desalination, and integrated electricity–water–heat cogeneration.

Table 5. Water–Energy Nexus Pathways Considered in the Assessment.

Pathway	Description
Electricity supply for RO desalination	Use of firm SMR-generated electricity to support reverse-osmosis desalination systems
Heat supply for MED/MSF desalination	Use of SMR thermal output or extracted steam to support thermal desalination processes
Electricity–water–heat cogeneration	Integrated production and sale of electricity, desalinated water, and industrial heat or steam within a multipurpose business model

This analytical layer is directly connected to the techno-economic assessment because revenues from desalinated water and industrial heat may reduce project dependence on electricity-market revenues and improve overall bankability. The assessment therefore, considers not only the technical compatibility of the reactor and desalination process but also energy consumption, coupling configuration, potential water output, levelized cost of water, industrial demand, and the availability of long-term water and heat offtake agreements.

The resulting analysis provides the methodological basis for the subsequent comparison of SMR-powered and gas-powered desalination pathways under Iran-specific fuel-price and financing conditions.

2.4. Safety Compliance, Licensing, and EIA

The fourth analytical layer evaluates safety compliance, licensing readiness, and EIA as fundamental conditions for progressing from feasibility assessment to deployment. Safety is not treated as a final verification activity conducted after technology and site selection. Instead, it is incorporated from the beginning of the decision-making process and assessed in parallel with technology suitability, site conditions, project economics, and infrastructure readiness. This approach is particularly important for the first SMR project in Iran because the initial safety case, licensing process, environmental assessment, and regulatory interactions may shape the institutional framework, documentation requirements, licensing cost, public acceptance, and replicability of subsequent projects. The IAEA Milestones approach emphasizes that the development or expansion of a nuclear power programme requires progressive readiness across legal, regulatory, technical, organizational, safety, waste-management, human-resource, financial, and stakeholder-engagement areas [12]. Moreover, nuclear power plant design requirements and SMR-specific environmental assessment guidance emphasize the need for systematic safety analysis, external-hazard assessment, environmental protection, and lifecycle planning [5,6]. Each technology–site option is therefore assessed against the minimum safety, licensing, environmental, and institutional criteria summarized in **Table 6**.

The output of this analytical layer is a readiness assessment rather than a final licensing conclusion. Detailed licensing decisions must ultimately be supported by site-specific investigations, safety analyses, environmental studies, regulatory review, and formal approval by the competent national authorities.

Table 6. Safety, Licensing, and Environmental Readiness Assessment Criteria.

Area	Assessment Criterion
Design safety	Defence-in-depth, fundamental safety functions, passive and active safety systems, and accident analysis
Licensing pathway	Requirements for site approval, construction, commissioning, operation, and eventual decommissioning
EIA	Potential impacts on water, soil, air, ecosystems, marine environments, and local communities
External hazards	Natural, human-induced, and combined-hazard assessment, including NaTech events
Fuel and waste management	Fresh-fuel supply, spent-fuel management, radioactive-waste management, and long-term responsibilities
Nuclear safeguards and physical protection	Safeguards obligations, site security, access control, material protection, and human-induced threats
Emergency preparedness	Site-specific emergency planning, response infrastructure, and coordination with responsible authorities
Stakeholder engagement	Communication with local communities, industries, public authorities, and other project stakeholders
Quality assurance	Requirements traceability, configuration management, procurement control, inspection, and nuclear-grade documentation

2.5. Multi-Criteria Decision Analysis Framework

The fifth analytical layer integrates the outputs of the preceding assessments through an MCDA framework. The purpose of MCDA in this study is not to produce a purely mechanical or deterministic ranking. Rather, it is used to improve transparency in criterion definition, weighting assumptions, option scoring, and systematic comparison of heterogeneous technology–site alternatives. Multi-criteria decision-making methods are commonly used to evaluate infrastructure and energy-system alternatives against technical, economic, environmental, institutional, and strategic criteria [11]. The Analytic Hierarchy Process (AHP) is one possible method for deriving criterion weights [13]. However, because no formal national expert-elicitation campaign or dedicated AHP survey was conducted in this study, the baseline weights are treated as scenario-based planning assumptions informed by literature review, engineering judgment, and the deployment-oriented objectives of the framework. The proposed baseline MCDA structure is presented in **Table 7**.

Table 7. Proposed base-case MCDA structure.

Criterion Group	Proposed Weight	Key Indicators
Technology	20%	Technology maturity, design experience, fuel requirements, safety characteristics, vendor capability, and technology dependence
Techno-economics	20%	CAPEX, OPEX, electricity-only LCOE, effective LCOE, IRR, NPV, WACC, construction time, and debt-service capability
Site	20%	Engineering feasibility, infrastructure readiness, cooling-water availability, grid access, logistics, constructability, and external hazards
Water–energy nexus	15%	Desalination potential, industrial heat supply, levelized cost of water, cogeneration compatibility, and multiproduct value
Safety and licensing	15%	Safety compliance, licensing readiness, EIA, emergency preparedness, safeguards, and waste management
Strategic fit	10%	Energy and water security, localization, geopolitical and supply-chain exposure, policy alignment, and long-term programme value

For implementation of the framework, criterion-level performance is converted to a common five-point scale, where 1 represents very low suitability and 5 represents very high suitability. Cost, risk, dependency, and delay-related indicators are reverse-scored so that higher normalized values consistently represent more favourable performance.

The overall score of each option is calculated as follows:

$$S_j = \sum_{i=1}^{n} w_i \times x_{ij} \tag{2}$$

Where S_j is the total score of option j, w_i is the weight of criterion i, and x_{ij} is the score assigned to option j under criterion i. The aggregated score is interpreted together with engineering constraints, licensing requirements, geopolitical exposure, and strategic considerations rather than being used as a stand-alone investment or technology-selection decision.

To evaluate the sensitivity of the framework to alternative planning priorities, the baseline weights are varied under the scenarios summarized in **Table 8**.

Table 8. MCDA Weighting Scenarios Used for Sensitivity Testing.

Scenario	Technology	Techno-economics	Site	Water–Energy	Safety/Licensing	Strategic Fit	Principal emphasis
Base case	20%	20%	20%	15%	15%	10%	Coastal industrial
Safety-focused	15%	15%	15%	15%	30%	10%	Technical–regulatory pilot
Economic-focused	15%	30%	15%	15%	15%	10%	Industrial offtake
Site-risk-focused	15%	15%	30%	10%	20%	10%	Reference/coastal screened sites
Geopolitical-risk-focused	15%	15%	15%	10%	15%	30%	Supply-chain resilience, localization, and reduced external dependency

The sensitivity assessment examines whether changes in criterion importance produce material changes in option scores, pathway priorities, or technology–site preferences. The corresponding results and their strategic interpretation are presented in the Results and Discussion section. Accordingly, robustness is assessed on the basis of score and ranking stability rather than inferred solely from the alternative weight distributions.

2.6. SWOT/TOWS Analysis

The seventh analytical layer applies SWOT/TOWS analysis to translate the technical, economic, site-related, water–energy, safety, licensing, geopolitical, and supply-chain findings into strategic deployment responses. SWOT analysis identifies the internal strengths and weaknesses of the proposed SMR programme and the external opportunities and threats affecting its implementation. TOWS analysis extends this diagnosis by systematically connecting internal and external factors and converting them into actionable strategies. As emphasized by Weihrich, the value of the TOWS matrix lies not merely in listing strategic factors, but in combining them to formulate implementable responses [14].

In this study, four strategic categories are considered:

- SO strategies use national strengths to exploit deployment opportunities;
- WO strategies use external opportunities to address domestic capability gaps;
- ST strategies use existing strengths to mitigate geopolitical, financial, regulatory, and supply-chain threats;
- WT strategies reduce exposure by postponing or restructuring deployment until critical safety, licensing, environmental, institutional, and financing conditions have been satisfied.

The detailed SWOT matrix and the resulting TOWS-based strategies are reported in the Results and Discussion section. Keeping the strategic outputs in the results section avoids duplication between the methodological procedure and the study findings.

2.7. Methodological Output

The output of the proposed methodology is not a simple ranking of reactor technologies or candidate sites. Rather, it is a structured and staged decision pathway in which technology characteristics, site suitability, economic performance, multipurpose value, safety readiness, licensing feasibility, geopolitical exposure, and strategic objectives are assessed jointly. The integrated framework assigns candidate technology–site combinations to three broad implementation pathways:

- A technical–regulatory pilot focused on risk reduction, licensing learning, preliminary safety analysis, environmental assessment, and institutional capacity building;
- Coastal industrial deployment focused on economic value creation through integrated electricity, desalinated water, and industrial heat production;
- Phased multi-unit development focused on design standardization, transition from FOAK to NOAK economics, localization, supply-chain development, and establishment of a national SMR technology platform.

The detailed deployment phases and their expected outputs are presented in the Results and Discussion section. Overall, the methodology shifts the decision question from whether SMRs are generally suitable for Iran to a more operational question: Which SMR technology–site combination, under which business model, risk conditions, licensing pathway, and implementation stage, should be pursued within Iran's future energy system?

3. Results and Discussion

This section presents the principal findings obtained from applying the proposed feasibility-to-deployment framework to the assessment of SMRs in Iran's future energy mix. The results indicate that SMR deployment should not be interpreted solely as an electricity-generation initiative. Rather, it should be evaluated as a broader energy–water–industry programme whose strategic value depends on the interaction of technical readiness, site suitability, financial performance, water and heat applications, safety and licensing preparedness, supply-chain resilience, and national capability development. Within this context, the potential contribution of SMRs extends beyond firm electricity generation. It includes diversification of the national energy mix, reduction of exposure to seasonal fossil-fuel constraints, support for freshwater production in coastal and water-stressed regions, provision of process heat and steam to energy-intensive industries, enhancement of critical-infrastructure resilience, and development of domestic engineering and nuclear-grade supply-chain capabilities. The findings further demonstrate that SMR decision-making should move beyond the isolated selection of a reactor design. The more relevant deployment-oriented question is which technology–site combination, under which business model, financing structure, licensing pathway, risk conditions, and implementation stage, can realistically contribute to Iran's long-term energy development. This interpretation is consistent with international SMR deployment approaches, which emphasize the combined importance of technology maturity, regulatory readiness, site and infrastructure suitability, financing conditions, fuel availability, supply-chain capability, stakeholder engagement, and phased implementation [3, 4, 7, 8].

3.1. Technology Screening and Strategic Roles of Candidate Options

The technology-screening results indicate that the suitability of an SMR option for Iran cannot be determined on the basis of reactor type, nominal capacity, or vendor information alone. A multidimensional assessment is required that considers design maturity, operating or construction experience, fuel type and fuel-cycle requirements, safety characteristics, licensing readiness, cogeneration capability, compatibility with coastal and industrial sites, capital exposure, supply-chain dependency, vendor-support requirements, and the potential for technology transfer and progressive localization. Four candidate technologies—RITM-200N, ACP100, KLT-40S, and VBER-300—were examined within differentiated deployment scenarios. As summarized in **Table 9**, each option presents a distinct combination of potential strategic roles, technical advantages, and implementation constraints. The screening is therefore intended to identify appropriate functional roles for the technologies rather than to establish a definitive vendor or reactor ranking. RITM-200N may be considered a reference option for early-stage coastal and industrial assessment because of its compact configuration, multipurpose potential, and technological heritage from the RITM-200 marine reactor family. Its deployment in Iran would nevertheless require clear arrangements for fuel supply, refuelling, and spent-fuel management, safeguards, technology transfer, contractual responsibilities, localization, long-term vendor support, and national licensing. ACP100 represents a land-based integral pressurized-water-reactor option that may support phased capacity additions, grid-connected electricity generation, and desalination applications. Its potential advantages include land-based deployment, modular capacity expansion, and compatibility with multipurpose energy applications. However, first-of-a-kind project risk, commercial replication, financing conditions, vendor dependency, and licensing adaptation to the Iranian regulatory framework require further assessment. KLT-40S benefits from operating experience associated with floating nuclear power applications and may therefore be relevant to pilot, floating, remote, islanded, or specialized coastal scenarios. Nevertheless, its comparatively smaller unit capacity, dependence on external fuel-cycle services, marine infrastructure requirements, and specialized operational model may limit its suitability for conventional large-scale grid deployment. VBER-300 offers a larger unit capacity and may be suitable for industrial baseload, grid-support, and higher-demand cogeneration applications. Its scale may provide advantages in unit capital cost and electricity-generation economics, but it also increases absolute capital requirements. In addition, limited commercial deployment experience and uncertainties related to detailed engineering, financing, licensing, fuel-cycle services, and vendor support must be resolved before project-level selection. The comparative technology-screening results are presented in **Table 9**.

Table 9. Strategic Screening of Candidate SMR Technologies for Deployment in Iran.

Technology	Potential strategic role in Iran	Principal advantage	Principal limitation
RITM-200N	Reference option for coastal and early industrial assessment	Compact configuration, multipurpose potential, and operational heritage of the RITM-200 reactor family	Fuel-cycle, contractual, licensing, localization, and long-term vendor-support requirements
ACP100	Land-based option for phased and multipurpose deployment	Integral PWR configuration, modular expansion potential, and compatibility with electricity and desalination applications	FOAK, financing, commercial replication, and licensing uncertainty
KLT-40S	Pilot, floating, remote, or specialized coastal option	Operating experience in floating nuclear power applications	Lower unit capacity, specialized marine infrastructure, and external fuel-cycle dependency
VBER-300	Medium-scale industrial, cogeneration, or grid-support option	Higher capacity and potential economies of scale for industrial baseload demand	Higher absolute capital exposure and limited commercial deployment experience

As shown in **Table 9**, no single candidate technology provides the strongest performance across all technical, economic, site-related, licensing, and strategic dimensions. RITM-200N appears particularly relevant to coastal and multipurpose applications; ACP100 offers comparatively broad flexibility for land-based phased deployment; KLT-40S is more closely aligned with pilot and specialized floating or remote applications; and VBER-300 may be better suited to larger industrial or grid-support requirements.

Accordingly, the results support a scenario-based technology portfolio rather than early dependence on a single reactor design or vendor. Under this approach, technology selection is subsequently refined through technology–site matching, quantitative techno-economic analysis, MCDA, and risk-adjusted assessment of fuel-cycle, geopolitical, licensing, and supply-chain constraints.

3.2. Site Prioritization and Functional Roles of Candidate Regions

The site-assessment results indicate that SMR siting in Iran should not be based solely on a single composite ranking or one dominant criterion. Within a national SMR programme, candidate regions may perform different functional roles depending on their engineering characteristics, infrastructure readiness, regulatory value, industrial demand, and long-term development potential. Some locations may be more appropriate for technical learning, site-characterization methodology, preliminary safety documentation, environmental assessment, and regulatory-risk reduction, whereas others may have greater relevance for industrial or commercial deployment because of stronger grid connections, port infrastructure, seawater access, industrial demand, and potential for stable project revenues. Within this functional approach, Bandar Khajeh-Nafas may be positioned primarily as a technical–regulatory reference site. Its principal value lies in supporting site-specific investigations, development and testing of the safety and licensing framework, preparation of preliminary environmental and safety documentation, and reduction of institutional and regulatory uncertainty. This designation does not imply final site acceptance; rather, it reflects the potential role of the region within an early-stage national learning pathway. In contrast, the southern coastal industrial corridor—particularly Asaluyeh, Bandar Abbas, and the Chabahar–Makran region—shows greater potential for industrial, multipurpose, and revenue-oriented deployment. These areas may benefit from combinations of seawater availability, port and heavy-transport access, industrial electricity and process-heat demand, desalination requirements, transmission infrastructure, and potential long-term industrial offtakers. However, their suitability remains subject to detailed evaluation of seismic, coastal, environmental, industrial, NaTech, emergency-planning, and licensing constraints. The functional classification of the candidate regions is summarized in **Table 10**.

Table 10. Functional Classification of Candidate Regions for SMR Deployment in Iran.

Region / Site type	Functional role	Main value	Main concern
Bandar Khajeh-Nafas	Technical–regulatory reference site	Licensing learning, site-specific studies, EIA development	Environmental and site-specific uncertainties
Southern coastal industrial corridor	Main industrial deployment corridor	Electricity–water–heat integration and bankability	Industrial/NaTech hazards and licensing complexity
Chabahar/Makran	Long-term strategic option	Regional development and water–energy infrastructure	Infrastructure readiness
Central industrial regions	Selective deployment option	Grid support and industrial baseload	Water scarcity and cooling constraints
Northern coastal regions	Limited local option	Local grid support	Environmental and social constraints

As shown in **Table 10**, the candidate regions should not be interpreted as directly competing for a single national ranking. Rather, they may contribute to the SMR programme through differentiated functions, including technical–regulatory learning, coastal industrial cogeneration, selective grid support, and long-term regional development.

Accordingly, SMR siting in Iran should move from a “single best site” approach toward a functional site-role framework. This enables site selection to be aligned with the phased deployment pathway while preserving the requirement for detailed site-specific engineering investigations and regulatory review before any investment or licensing decision.

3.3. Technology–Site Matching

A central finding of the assessment is that reactor-technology selection and site selection should be conducted simultaneously rather than as independent sequential decisions. Each SMR design has specific requirements related to unit capacity, cooling configuration, fuel and refuelling strategy, deployment mode, equipment dimensions, heavy-component transportation, grid connection, cogeneration capability, licensing maturity, safeguards, spent-fuel management, and long-term vendor support. Consequently, no single technology can be assumed to be equally suitable for all candidate regions or deployment functions.

Based on the qualitative technology–site matching assessment, RITM-200N appears particularly relevant to coastal and industrial applications in which firm electricity generation is integrated with desalinated-water production and industrial heat or steam supply. Its compact configuration and technological heritage from the RITM-200 marine reactor family may support such applications, although practical deployment remains conditional on fuel-cycle arrangements, licensing, contractual responsibilities, localization, safeguards, and sustained vendor support.

ACP100 exhibits comparatively broad flexibility because of its land-based integral PWR configuration, modular capacity, and potential compatibility with grid-connected, industrial, and desalination applications. It may therefore be considered across technical–regulatory, coastal industrial, grid-support, and longer-term deployment scenarios. Nevertheless, its suitability remains dependent on the resolution of FOAK, financing, licensing, commercialization, and technology-transfer uncertainties.

KLT-40S is more closely aligned with pilot, floating, remote, islanded, or specialized coastal applications. Its floating-nuclear operating heritage provides a relevant reference for such deployment models, but its comparatively smaller unit capacity, specialized marine infrastructure requirements, and external fuel-cycle dependency may limit its suitability for conventional large-scale grid applications.

VBER-300 may be more appropriate for regions with larger industrial loads, greater baseload requirements, or stronger grid-support needs. Its higher capacity may improve unit-cost performance and support substantial industrial demand, although higher absolute capital exposure and limited commercial deployment experience increase the importance of financing, implementation, licensing, and vendor-risk assessment.

The resulting qualitative compatibility matrix is presented in **Table 11**.

Table 11. Qualitative Technology–Site Compatibility Matrix for Candidate SMR Options.

Technology / Site role	Technical–regulatory pilot	Coastal industrial deployment	Grid-support deployment	Long-term fleet development
RITM-200N	High	Very high	Medium	High
ACP100		High	High	
KLT-40S		Medium	Low	Medium
VBER-300	Medium	High	High	

Note: The qualitative categories represent relative strategic compatibility at the pre-feasibility level. They do not constitute final site-acceptance, licensing, safety, or investment decisions.

As shown in **Table 11**, ACP100 provides the broadest qualitative flexibility across the four deployment functions, whereas RITM-200N shows particular relevance to coastal industrial and multipurpose applications. KLT-40S is more closely associated with pilot-scale, floating, and specialized coastal deployment, while VBER-300 may offer advantages for larger industrial and grid-support applications.

These results do not establish a definitive reactor ranking. Rather, they support the development of a phased and scenario-based technology portfolio in which different reactor designs may be assigned to different functional roles. Such a strategy can reduce premature dependence on a single technology or vendor while improving flexibility, learning opportunities, supply-chain resilience, and alignment between reactor characteristics and regional requirements.

The qualitative matching results provide the strategic basis for the quantitative financial comparison presented in the following section. The next stage therefore, evaluates whether the candidate configurations remain attractive when capital requirements, electricity-generation costs, multi-product revenues, investment returns, and financing conditions are considered explicitly.

3.4. Quantitative Techno-Economic Scenario Analysis

To complement the qualitative technology and site assessments, a scenario-based quantitative financial screening was conducted for the four candidate SMR project configurations considered in this study. The purpose of the analysis is to compare the relative financial performance of the technologies under a consistent investor-oriented base case, rather than to provide vendor-certified construction prices or definitive project-finance forecasts.

The base-case financial model assumes a three-year construction period, a weighted average cost of capital (WACC) of 10%, a debt-to-equity ratio of 70:30, a debt interest rate of 6%, a 15-year debt tenor, and a corporate tax rate of 20%. Technology-specific assumptions were applied for capacity factor, project lifetime, electricity purchase price, refuelling cycle, capital expenditure, and annual revenues from electricity, industrial steam, desalinated water, and capacity services. The capacity factors range from 85% to 92%, while the project lifetimes are 60 years for RITM-200, ACP100, and VBER-300 and 40 years for KLT-40S.

The principal base-case results are presented in **Table 12**. Power LCOE represents the discounted cost of electricity generation before crediting non-electric revenue streams. Revenue-adjusted effective LCOE represents the corresponding net cost after accounting for the modelled revenues from industrial steam, desalinated water, and capacity services.

Table 12. Base-Case Quantitative Techno-Economic Results for Candidate SMR Project Configurations in Iran.

Technology	Modelled Project Capacity (MWe)	Capacity Factor (%)	Total CAPEX ($ million)	CAPEX Intensity ($/kW)	power LCOE ($/MWh)	effective LCOE ($/MWh)	Project IRR (%)	Project NPV ($ million)
RITM-200	165	92	858	5,200	120.1	60.7	15.74	517.7
ACP100	125	90	675	5,400	130.3	69.4	15.13	361.4
KLT-40S	70	85	455	6,500	166.4	80.1	15.52	252.3
VBER-300	300	92	1,470	4,900	112.2	54.2	15.4	831.0

Notes: All monetary values are expressed in nominal US dollars according to the financial model. The capacities represent the project configurations modelled in the workbook and should not necessarily be interpreted as the capacity of a single reactor module. Effective LCOE is a revenue-adjusted metric that credits the non-electric revenue streams included in the multipurpose business model. The results are preliminary feasibility-level estimates and do not constitute vendor quotations, guaranteed EPC prices, or final investment estimates.

As shown in **Table 12**, the electricity-only power LCOE ranges from approximately 112.2 to 166.4 *USD/MWh*. VBER-300 exhibits the lowest power LCOE and the lowest CAPEX intensity because of its larger modelled capacity, whereas KLT-40S exhibits the highest power LCOE and CAPEX intensity. However, VBER-300 also requires the highest absolute capital commitment, amounting to approximately USD 1.47 billion, which may increase financing, construction, and exposure risks despite its favourable unit-cost performance.

When revenues from desalinated water, industrial steam, and capacity services are credited, the revenue-adjusted effective LCOE decreases to approximately 54.2–80.1 *USD/MWh*. This represents a reduction of approximately 47–52% relative to the corresponding electricity-only power LCOE values. The result quantitatively supports the central argument of this study that the economic rationale for SMR deployment in Iran is significantly strengthened when the reactors are configured as multipurpose electricity–water–heat assets rather than as electricity-only generating units.

The modelled project IRRs range from 15.13% to 15.74%, marginally exceeding the 15% project hurdle rate used in the base case. The corresponding equity IRRs range from approximately 27.11% to 28.70%. All four configurations exhibit a modelled payback period of approximately eight years and minimum debt-service coverage ratios ranging from 2.45 to 2.57, indicating adequate debt-servicing capacity under the assumed industrial offtake and multipurpose revenue conditions.

Among the evaluated configurations, VBER-300 generates the highest project NPV, approximately USD 831.0 million, largely because of its greater generation capacity and industrial revenue potential. RITM-200 provides an intermediate capital requirement together with a project NPV of approximately USD 517.7 million and the highest project IRR in the base case. ACP100 shows comparatively balanced capital exposure, project return, and deployment flexibility. KLT-40S has the highest electricity-generation cost and the lowest absolute project NPV; therefore, its economic justification is stronger for pilot, floating, remote, or specialized coastal applications than for large-scale bulk electricity generation.

Nevertheless, the narrow distribution of project IRRs should be interpreted carefully. The technology-specific electricity purchase prices and non-electric revenue assumptions in the financial screening model were structured to assess whether each configuration could meet an approximate 15% project hurdle rate. Consequently, the results should not be interpreted as evidence that all four technologies possess identical intrinsic profitability. Rather, they demonstrate the revenue and contractual conditions required for the respective project configurations to achieve comparable investment performance.

Overall, the quantitative analysis indicates that no single SMR design dominates all financial and deployment dimensions. Larger configurations benefit from lower unit capital costs and LCOE, whereas smaller configurations may reduce absolute investment exposure and provide greater flexibility for phased implementation. Technology selection should therefore be based on the combined consideration of capital affordability, site requirements, industrial demand, licensing maturity, vendor and fuel-cycle risks, and the availability of credible long-term electricity, water, steam, and capacity-payment contracts.

3.5. Comparative Techno-Economic Assessment with Fossil-Fuel and Renewable Alternatives

To place the quantitative techno-economic results into a broader energy-planning perspective, the representative performance of candidate SMR technologies was compared with conventional fossil-fuel-based generation and renewable energy options. This comparison extends beyond electricity generation costs and incorporates dispatchability, carbon intensity, and the capability to provide integrated energy services. The results are summarized in **Table 13**.

It should be noted that direct economic comparisons in the Iranian context are influenced by the presence of substantial fossil-fuel subsidies and regulated electricity tariffs. Consequently, short-term market competitiveness may differ from long-term strategic competitiveness. Under subsidized fuel-price conditions, conventional gas-fired generation can exhibit lower apparent electricity costs. However, when fuel opportunity costs, long-term energy security, supply resilience, environmental considerations, and multipurpose applications are taken into account, the relative attractiveness of SMR deployment increases significantly.

As presented in **Table 13**, renewable technologies such as utility-scale solar photovoltaics and onshore wind offer competitive electricity costs but are inherently variable and require complementary storage systems or flexible backup generation to ensure a reliable supply. In contrast, SMRs provide firm low-carbon baseload electricity and can simultaneously support desalinated water production and industrial heat supply through cogeneration schemes. This multipurpose capability enhances the overall economic and strategic value of SMRs, particularly for coastal industrial regions where electricity, freshwater, and process heat demands coexist.

Accordingly, the findings suggest that the competitiveness of SMRs in Iran should not be evaluated solely on the basis of electricity-only LCOE. Instead, assessment should consider their broader contribution to energy security, water security, industrial development, infrastructure resilience, and diversification of long-term revenue streams.

Table 13. Comparative Techno-Economic Characteristics of SMRs, Fossil-Fuel-Based Generation, and Renewable Energy Options.

Energy Source	**Indicative LCOE (*USD/MWh*)**	**Dispatchability**	**CO_2 Emissions**	**Strategic Value**
Gas-fired generation (subsidized fuel)	Low	High	High	Short-term economic advantage
Utility-scale Solar PV	Low–Moderate	Variable	Very Low	Requires storage/grid support
Onshore Wind	Moderate			Site dependent
SMR (electricity only)		Firm baseload		High reliability
SMR (electricity + water + heat)	Moderate–High	Firm multipurpose		Highest long-term strategic value

As shown in **Table 13**, SMRs may not always provide the lowest electricity cost under subsidized fossil-fuel conditions; however, their ability to deliver firm low-carbon power together with desalinated water and industrial heat substantially improves their long-term strategic and techno-economic value within Iran's future energy system.

3.6. Business Model Implications and Bankability of Multipurpose SMR Deployment

The quantitative and comparative results indicate that the economic case for SMR deployment in Iran should not be assessed through an electricity-only model. Under subsidized fossil-fuel and regulated electricity-tariff conditions, electricity-only SMR deployment may face limited short-term market competitiveness. However, its investment attractiveness can improve when the project is structured as a multipurpose asset combining electricity sales, desalinated water production, and industrial heat or steam supply.

Accordingly, several business models were considered for SMR deployment in Iran, as summarized in **Table 14**. These include an electricity-only model, an industrial offtake model, a nuclear desalination model, and an integrated multipurpose electricity–water–heat model. Among these options, the multipurpose model provides the strongest long-term strategic and economic value because it diversifies revenue streams, reduces dependence on electricity-market revenues alone, and aligns SMR deployment with the simultaneous energy, water, and industrial needs of southern coastal regions.

From a bankability perspective, long-term power purchase agreements (PPAs), water purchase agreements, industrial steam contracts, capacity payments, and financing structures such as Engineering, Procurement and Construction plus Financing (EPC+F) or Public–Private Partnership (PPP) can reduce revenue uncertainty and improve project-finance defensibility. Therefore, the bankability of SMR deployment in Iran depends less on electricity LCOE alone and more on the ability to create a stable, multi-product revenue structure supported by credible industrial offtakers [9, 10].

Table 14. Preferred Business Models for SMR Deployment in Iran.

Business model	Revenue source	Suitability for Iran	Key requirement
Electricity-only model	Grid electricity sales	Moderate	Stable tariff or PPA
Industrial offtake model	Direct electricity/steam sales	High	Long-term industrial contracts
Nuclear desalination model	Water and electricity sales	High in coastal regions	Water purchase agreement and desalination infrastructure
Multipurpose model	Electricity + water + heat	Very high	Integrated project structure and multi-product contracts

3.7. Water–Energy Nexus and Economic Competitiveness of Nuclear Desalination

The water–energy nexus is one of the most important strategic drivers for SMR assessment in Iran. The results show that the value of SMRs is not limited to electricity generation. Rather, their strategic relevance lies in the ability to provide firm electricity, desalinated water, and industrial heat simultaneously. This is particularly important for southern coastal regions, where water scarcity, energy-intensive industrial demand, and access to seawater coexist.

Under such conditions, SMRs can function as an integrated water–energy infrastructure. In addition to providing stable electricity, they can support industrial development, coastal settlement sustainability, and infrastructure resilience. The strategic contribution of SMRs to the water–energy nexus is summarized in **Table 15**.

Table 15. Strategic value of the water–energy nexus in SMR deployment.

Dimension	Role of SMRs	Strategic implication
Electricity	Firm low-carbon baseload generation	Energy security and grid stability
Freshwater	Support for RO/MED/MSF desalination	Water security in coastal regions
Industrial heat	Steam and process heat supply	Improved industrial productivity
Fuel substitution	Reduced fossil fuel consumption	Lower vulnerability to gas shortages
Regional development	Support for coastal industries and cities	Infrastructure resilience

As shown in **Table 15**, the integration of electricity generation, freshwater production, and industrial heat supply significantly enhance the overall value proposition of SMR deployment in water-stressed coastal and industrial regions. However, the economic competitiveness of nuclear desalination in Iran must be interpreted carefully because domestic natural gas and electricity prices are strongly influenced by subsidies. Therefore, a direct comparison based only on short-term fuel prices may underestimate the long-term strategic value of SMR-based desalination.

To address this issue, **Table 16** compares conventional gas-powered desalination pathways with SMR-powered desalination and integrated SMR electricity–water–heat cogeneration. Under subsidized domestic gas prices, gas-powered desalination may remain economically dominant in the short term. However, when fuel opportunity cost, gas-supply constraints, emissions exposure, long-term water security, and industrial heat integration are considered, SMR-based desalination becomes a strategic rather than merely tariff-based option.

Table 16. Comparative assessment of SMR-powered and gas-powered desalination pathways.

Desalination option	Energy source	Main cost driver	CO_2 exposure	Suitability for southern Iran	Key limitation
Gas-powered RO	Electricity from gas	Subsidized gas/electricity	High	High under subsidized fuel	Vulnerable to gas shortage and emissions
Gas-powered MED/MSF	Thermal energy from gas	Gas price and heat efficiency	High	Technically mature	High fuel dependence
SMR-powered RO	Nuclear electricity	CAPEX and WACC	Low	Suitable with stable baseload	High initial cost
SMR-powered MED/MSF	Nuclear heat	Heat integration and coupling design	Low	Suitable for cogeneration	Requires licensing and nuclear safety case
SMR electricity–water–heat	Nuclear cogeneration	Integrated project structure	Low	Strong strategic value	Needs multi-product contracts

The comparison in **Table 16** indicates that SMR-powered desalination should not be justified solely on the basis of near-term cost competition with subsidized gas. Its stronger rationale lies in system-level benefits, including reduced fossil-fuel dependence, lower emissions exposure, improved water security, and the ability to integrate desalination with industrial heat and firm low-carbon electricity generation.

3.8. Safety, Licensing, and Environmental Readiness

The results indicate that the SMR deployment pathway must be linked from the outset to safety requirements, licensing, EIA, waste management, spent fuel strategy, and engagement with local communities. This is particularly important for the first SMR project because the initial deployment experience will influence the national regulatory pathway, public acceptance, licensing cost, and future replication model.

Accordingly, an SMR project should not first be selected solely on the basis of technical or economic attractiveness and only afterwards be subjected to safety and licensing considerations. Instead, safety compliance, EIA, Preliminary Safety Analysis Report (PSAR) development, waste management, physical protection, and stakeholder engagement should be incorporated at the feasibility stage. This approach is consistent with nuclear power plant design safety requirements, SMR-specific EIA considerations, and the IAEA phased approach to nuclear infrastructure development [5, 6, 12].

The minimum readiness requirements that should be satisfied prior to deployment are summarized in **Table 17**. The results indicate that licensing readiness and safety compliance are not independent activities but integral components of the feasibility-to-deployment pathway.

Table 17. Key readiness requirements for SMR deployment.

Area	Required output before deployment
Design safety	Safety case aligned with IAEA SSR-2/1 principles
Licensing	Defined pathway for site, construction, commissioning, and operation
EIA	Environmental baseline, impact assessment, and mitigation plan
Waste and fuel	Fuel supply, spent fuel, and waste management strategy
Emergency preparedness	Site-specific emergency planning framework
Public engagement	Stakeholder communication and local acceptance plan
Quality assurance	QA/QC, requirement traceability, and nuclear-grade documentation

3.9. Geopolitical and Supply-Chain Risk Considerations

The feasibility of SMR deployment in Iran is influenced not only by technical, economic, and safety-related factors, but also by geopolitical and supply-chain constraints. International sanctions, export-control restrictions, technology-transfer limitations, fuel-cycle dependencies, and vendor concentration may affect project implementation schedules, financing arrangements, equipment procurement, localization pathways, and long-term operational support. Therefore, these risks should be explicitly incorporated into technology selection and deployment planning rather than treated only as external threats within the SWOT framework. In the revised assessment, geopolitical and supply-chain exposure is treated as a cross-cutting constraint that can modify the practical suitability of each technology–site option. For example, a reactor design may show strong technical compatibility with coastal industrial regions, but its risk-adjusted suitability may be reduced if fuel-cycle services, spare parts, digital control systems, licensing support, or technology transfer depend heavily on a single foreign vendor. **Table 18** summarizes the main geopolitical and supply-chain risks considered in this study and the corresponding mitigation measures.

The inclusion of these constraints modifies the interpretation of technology–site matching results. In particular, technologies with strong technical suitability for coastal or industrial sites should still be evaluated against fuel-cycle exposure, procurement vulnerability, sanctions-related uncertainty, and the feasibility of gradual localization. This risk-adjusted view supports a phased deployment strategy in which technical–regulatory learning, supply-chain development, and localization progress are achieved before large-scale commercial implementation.

Table 18. Geopolitical and supply-chain risk considerations for SMR deployment in Iran.

Risk category	Potential impact on SMR deployment	Suggested mitigation measure
Technology-transfer restrictions	Delayed localization and reduced design autonomy	Phased technology transfer and multi-stage localization plan
Fuel-cycle dependency	Operational uncertainty and long-term vendor dependence	Long-term fuel agreements and spent-fuel management framework
Supply-chain disruption	Construction delay and cost escalation	Domestic nuclear-grade supply-chain development
International sanctions	Financing, procurement, and insurance constraints	Phased deployment and diversified partnership models
Vendor concentration	Reduced flexibility and negotiation power	Multi-vendor evaluation and modular procurement strategy
Licensing-support dependency	Delay in PSAR, EIA, and safety documentation	Early regulatory engagement and domestic safety-analysis capability

3.10. SWOT/TOWS-Based Strategic Interpretation: The SWOT analysis provides a strategic synthesis of the internal capabilities and external conditions influencing the potential deployment of SMRs in Iran. As illustrated in **Fig. 2**, the analysis identifies a combination of enabling factors—including the country's existing nuclear infrastructure, operational experience from the Bushehr Nuclear Power Plant, modular deployment flexibility, multipurpose energy applications, and the growing need for reliable low-carbon baseload generation—as well as important constraints such as first-of FOAK costs, limited domestic SMR-specific experience, licensing gaps, financing challenges, and the current maturity level of the nuclear-grade supply chain.

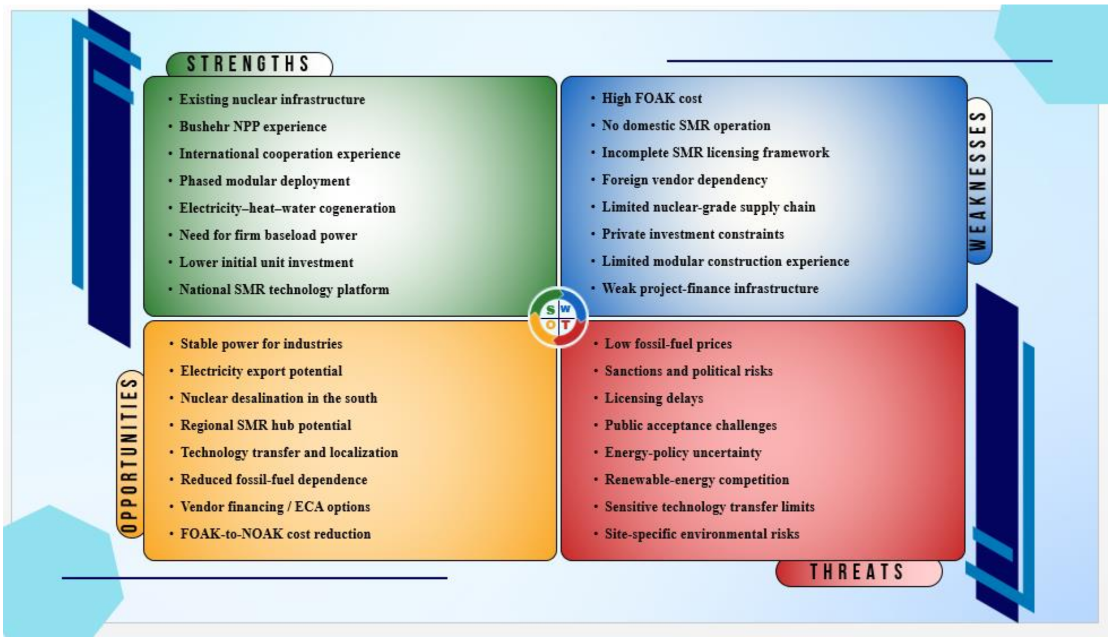
The external environment presents both significant opportunities and substantial risks. Opportunities include the development of nuclear-powered desalination, provision of reliable electricity and process heat for energy-intensive industries, technology transfer, progressive localization, and the transition from FOAK to NOAK deployment. Conversely, geopolitical uncertainties, sanctions-related restrictions, licensing delays, public acceptance issues, and site-specific engineering constraints may adversely affect project implementation. These strategic factors complement the quantitative risk assessment presented in the previous sections and highlight the importance of phased deployment and adaptive planning [14].

Building upon the SWOT findings, the corresponding TOWS-based deployment strategies are summarized in **Table 19**. Rather than serving as a descriptive exercise, the TOWS framework translates strategic observations into practical implementation pathways by linking internal capabilities with external opportunities and threats.

Table 19. TOWS-Based Strategic Pathways.

Strategy	Interpretation	Proposed action
SO	Use strengths to exploit opportunities	Develop coastal industrial SMR projects integrating electricity, desalinated water, and industrial heat
WO	Use opportunities to reduce weaknesses	Initiate a technical–regulatory pilot project to strengthen licensing capability and operational experience
ST	Use strengths to mitigate threats	Expand domestic supply chains, workforce development, and regulatory capacity while reducing external dependencies
WT	Reduce weaknesses and avoid threats	Postpone large-scale commercial deployment until licensing, EIA, PSAR, financing arrangements, and institutional preparedness are sufficiently mature

The strategic interpretation of **Table 19** indicates that an incremental deployment pathway is more appropriate than immediate commercialization. In particular, the analysis supports beginning with a technical–regulatory pilot to reduce institutional and licensing uncertainties, followed by coastal industrial projects that exploit cogeneration opportunities and stable industrial demand. Such a phased approach also facilitates technology localization, strengthens domestic capabilities, and improves the long-term resilience of the national SMR program.



STRENGTHS

- Existing nuclear infrastructure
- Bushehr NPP experience
- International cooperation experience
- Phased modular deployment
- Electricity–heat–water cogeneration
- Need for firm baseload power
- Lower initial unit investment
- National SMR technology platform

WEAKNESSES

- High FOAK cost
- No domestic SMR operation
- Incomplete SMR licensing framework
- Foreign vendor dependency
- Limited nuclear-grade supply chain
- Private investment constraints
- Limited modular construction experience
- Weak project-finance infrastructure

OPPORTUNITIES

- Stable power for industries
- Electricity export potential
- Nuclear desalination in the south
- Regional SMR hub potential
- Technology transfer and localization
- Reduced fossil-fuel dependence
- Vendor financing / ECA options
- FOAK-to-NOAK cost reduction

THREATS

- Low fossil-fuel prices
- Sanctions and political risks
- Licensing delays
- Public acceptance challenges
- Energy-policy uncertainty
- Renewable-energy competition
- Sensitive technology transfer limits
- Site-specific environmental risks

Fig. 2. Strategic SWOT Matrix for SMR Development in Iran.

3.11. Proposed Deployment Pathway

Based on the integrated technical, economic, safety, strategic, and risk assessments, the results suggest that SMR deployment in Iran should follow a phased, adaptive, and reviewable implementation pathway structured around clearly defined decision gates. The proposed roadmap seeks to achieve three parallel objectives: reducing deployment risk, maximizing long-term economic value, and strengthening national technological capabilities. The recommended implementation sequence is summarized in **Table 20**.

Table 20. Proposed Phased Deployment Pathway for SMR Development in Iran.

Phase	Main objective	Expected output
Phase 1: Strategic preparation	Complete technology screening, site evaluation, licensing planning, and financial assessment	National SMR decision framework
Phase 2: Technical–regulatory pilot	Reduce licensing, EIA, and operational uncertainty	Reference site, preliminary safety case, and regulatory learning
Phase 3: Coastal industrial project	Create value through integrated electricity–water–heat production	Bankable project supported by long-term industrial offtake
Phase 4: Multi-unit deployment	Achieve cost reduction and design standardization through repeated deployment	Transition from FOAK to NOAK deployment
Phase 5: National SMR platform	Develop domestic supply chains, human resources, and localization capability	Sustainable national SMR ecosystem and long-term fleet development

As shown in **Table 20,** the proposed roadmap establishes a progressive transition from strategic planning and regulatory preparation toward commercial deployment and fleet-scale expansion. Rather than focusing exclusively on reactor selection, the framework emphasizes the coordinated evolution of technology, site readiness, financing, licensing, infrastructure, and institutional capacity.

Overall, the findings indicate that SMRs can become a complementary component of Iran's future energy portfolio if implemented as a phased and multipurpose programme. Their principal value extends beyond electricity generation to include freshwater production, industrial heat supply, enhanced energy and water security, reduced dependence on fossil fuels, improved infrastructure resilience, and long-term technological development. Consequently, decision-making should shift from selecting a single reactor technology to designing an integrated deployment pathway that simultaneously addresses engineering, economic, environmental, regulatory, and strategic considerations.

3.12. Limitations and Future Work

The findings of this study should be interpreted within the scope of a strategic pre-feasibility assessment. The reported techno-economic values are scenario-based estimates rather than vendor-certified quotations or project-specific investment costs. The MCDA weights represent planning assumptions informed by literature review and engineering judgment and have not been derived from a formal national expert-elicitation campaign. Likewise, the site-risk assessment constitutes regional engineering screening and does not replace site-specific seismic, geotechnical, hydrological, environmental, grid-integration, and emergency-planning investigations. Future work should therefore incorporate verified vendor data, probabilistic cost and schedule risk analysis, expert-based AHP elicitation, detailed levelized cost of water modelling, site-specific field investigations, and the development of PSAR, EIA, and licensing documentation for the preferred technology–site combinations.

4. Conclusion

This study developed an integrated feasibility-to-deployment framework for assessing small modular reactors (SMRs) in Iran’s future energy system. The findings indicate that SMRs should not be evaluated merely as smaller nuclear power plants or electricity-only assets. Their principal strategic value lies in their potential to function as multipurpose infrastructure combining firm low-carbon electricity, freshwater production, industrial heat supply, energy-security enhancement, and national technological development. The assessment demonstrates that no single reactor design is optimal for all applications. ACP100 offers relatively broad flexibility for land-based and phased deployment; RITM-200N appears particularly relevant to coastal industrial and cogeneration applications; KLT-40S is more closely aligned with pilot, floating, remote, or specialized coastal scenarios; and VBER-300 may be suitable for larger industrial and grid-support requirements. However, final technology selection must also consider licensing maturity, fuel-cycle arrangements, vendor support, safeguards, localization potential, contractual responsibilities, and geopolitical exposure. The site analysis further shows that candidate regions should be assigned functional roles rather than ranked through a single “best-site” criterion. Bandar Khajeh-Nafas may serve as a technical–regulatory reference location for site investigations, environmental assessment, preliminary safety documentation, and regulatory learning. In contrast, southern coastal industrial regions with seawater access, port infrastructure, grid connectivity, and concentrated industrial demand offer stronger potential for revenue-oriented electricity–water–heat projects. Nevertheless, seismic, coastal, environmental, industrial, NaTech, logistical, and emergency-planning constraints must be resolved through detailed site-specific investigations. The quantitative assessment indicates that the electricity-only LCOE of the evaluated configurations ranges from approximately 112.2 to 166.4 *USD/MWh*, while project IRRs range from 15.1% to 15.7% under the stated base-case assumptions. When revenues from desalinated water, industrial heat, and capacity services are included, the revenue-adjusted effective LCOE decreases to approximately 54.2–80.1 *USD/MWh*. These results support the conclusion that the economic case for SMRs in Iran is considerably stronger under a multipurpose business model than under electricity-only generation. Although subsidized gas-fired generation and gas-powered desalination may retain a short-term cost advantage, SMR-based cogeneration offers broader system-level benefits related to fuel diversification, water security, industrial resilience, and reduced exposure to gas-supply constraints. Safety, licensing, environmental readiness, and geopolitical resilience remain essential conditions for implementation. Design safety, EIA, preliminary safety analysis, fuel and waste management, physical protection, emergency preparedness, quality assurance, and stakeholder engagement should be incorporated from the feasibility stage. In parallel, sanctions, export controls, technology-transfer restrictions, vendor concentration, fuel-cycle dependence, and procurement uncertainty should be treated as cross-cutting factors in technology and site selection. The recommended pathway is therefore phased, adaptive, and reviewable. It begins with strategic preparation and a technical–regulatory pilot, proceeds to a coastal industrial project based on integrated electricity–water–heat production, and subsequently advances toward multi-unit deployment, FOAK-to-NOAK cost reduction, localization, workforce development, and establishment of a national SMR platform. Overall, SMRs can become a complementary and strategic component of Iran's future energy system, provided that deployment decisions integrate technology, site, economics, safety, licensing, environment, financing, supply chain, and national policy within a unified program.

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Author contributions

A.K. conceived the main research idea, developed the system-level assessment framework, performed the comparative analysis, interpreted the results, and prepared the initial draft of the manuscript. **P.P.**, **N.M.S.**, and **A.B.S.** supervised the research process, provided scientific and technical guidance, contributed to the critical review of the manuscript, and supported the improvement and finalization of the paper.

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

The numerical inputs and scenario outputs reported in this study were derived from the authors' feasibility-study models and publicly available scientific literature, technical reports, international guidance documents, and other published sources cited in the manuscript. The aggregated assumptions and results required to interpret and reproduce the principal findings are presented in the article. The underlying financial spreadsheets and detailed project-level inputs may be made available by the corresponding author upon reasonable request, subject to institutional approval and applicable confidentiality restrictions.

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