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Original Article

Technological readiness, fuel cycle analysis, levelized cost evaluation, and comparative assessment of very small modular reactors (vSMRs)

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ABSTRACT

With the increasing adoption of renewable energy and energy storage technologies, even in affluent regions like the Gulf, the issue of grid connectivity for microgrids and off-grid systems remains critical. Nuclear energy, with its established track record as a primary energy source, provides an effective solution for remote and off-grid locations, particularly through the innovative concept of very small modular reactors (vSMRs). Thus, it is essential to assess the economic feasibility of these reactors, assuming technological challenges have been addressed. The initial focus of this study is on identifying technology readiness levels (TRLs) for vSMRs, outlining both their benefits and limitations. Following this, an economic assessment of a 10 MW modular reactor is conducted, taking into account various factors such as performance, fuel expenses, maintenance and operational costs, capital investment, and decommissioning expenditures. The overall levelized cost of the fuel cycle, encompassing both upstream and downstream processes, is calculated, and cumulative expenditures are illustrated using an S-curve. Additionally, the load pattern and levelized cost of electricity are estimated. Finally, a comparison between different SMR and vSMR designs is made to evaluate their cost-efficiency. Findings from this research indicate that vSMRs meet the necessary economic benchmarks, supporting their suitability for deployment.

1. Introduction

Very small modular reactor(vSMRs) have emerged as new technological source for low carbon energy source. These reactors advocate their potential capabilities to enter new energy markets in which high scale reactor technological units are not favorable. The energy production level is between 1 MW and 20 MWe using light water design or other novel reactor design. The design of these reactors are very competitive for remote regions in which geological conditions are not cumbersome or renewable energies are not feasible. Such regions are often found in remote mining or mineral processing places. Besides various potential applications of these reactors in energy sector, some limitations and hurdles should be accounted as well. The Kingdom of Saudi Arabia(KSA) is a desert like region in which national plans for low carbon emissions strategies are progressing supporting the Saudi Vision 2030. The country is strengthening to regions with less accommodates and may have intermittent supply of various resources. In this context, the deployment of nuclear reactors offers a strategic solution, with vSMRs being particularly effective for remote regions. Given the country's vast desert landscape and the presence of areas far from urban centers, vSMRs are well-suited to address these challenges. These reactors feature advanced safety systems with an inherent design approach, significantly reducing vulnerabilities. Their compact size and ability to operate in multi-unit configurations further enhance their appeal. Additionally, their versatility allows for integration with other energy sources, making them an ideal choice for stabilizing power fluctuations and optimizing energy utilization. These reactors can be installed in short time, thus reducing the cost and saving time delays. The transportation of reactors is particularly very smooth subjected to national regularity standards. Nuclear energy institute(NEI) have conducted a study on the economic assessment of these reactors by comparing with diesel generators. The assessment shows that the very small modular reactors are cost effective in terms of electricity production thus supporting the long term investment plan [1–3]. The planning and creation of vSMR has commenced in a short span following the deployment and licensing of SMRs. The development process was guided by close cooperation with reactor developers and related regulatory bodies such as the U.S. Nuclear Regulatory Commission (U.S.

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NRC) and, in Saudi Arabia, the Nuclear and Radiological Regulatory Commission (NRRC). It is evident that conventional fuels and established technologies can shorten the timeframe, given their well-established foundations. First-of-a-kind reactors (FOAK) of these types may encounter obstacles and potential delays [4]. Due to the complexity of the designs, these reactors are still in design phase and are undergoing rigorous certification and approval procedure. Therefore, the current research is focused on assessment of technological level of these reactors contingent with the cost analysis report. Several vSMRs are currently in various stages of design and development such as eVinci, Aurora, U-battery, SEALER, Holos generator, micro modular reactor (MMR). Westinghouse Electric, which has a long history of innovative reactor designs, is developing the eVinci reactor. This reactor has a rated power of 0.2–5 MWe and can operate for more than three years without refueling. The design minimizes the number of components thus enhancing the reliability and operational capability. LeadCold's SEALER reactor is a 3 MWe reactor designed for power systems in off-grid applications. It utilizes uranium nitride fuel to boost the efficiency of next-generation energy systems and is crafted for air transport. The Holos generator incorporates a simple layout that removes the need for multiple piping systems, pumps, storage tanks, heat exchangers, and valves. This reactor, using carbon dioxide as the main coolant, is configured to operate at up to 60 % efficiency and employs fuel tolerant to high temperatures for additional safety. The U-Battery has a 4 MWe capacity, utilizing multi-layered fuel particles, graphite as a moderator, and helium cooling. Designed to function for a lifespan of 30 years, this reactor can be installed underground with facilities for storing spent fuel or for energy production. However, in March 2023, Urenco ended its support for U-battery and transferred all intellectual rights to national nuclear laboratory [5]. Lastly, the Micro-Modular Reactor (MMR), developed by Ultra Safe Nuclear Corporation(USNC), is moderated with graphite, cooled by helium, and provides a 5 MWe capacity. It can use two types of fuel: tristructured and all-ceramic microencapsulated fuel. A demonstration plant for this reactor is currently being developed at Chalk River. But Seattle based USNC developer has drawn interest due to bankruptcy recently [6]. Some of the prons and cons of vSMR with enrichment levels are presented in Table 1.

vSMRs exhibit exceptional heat and mass transfer capabilities, making them highly effective for extraction and multiphase reactions. They are considered a powerful tool for process intensification. Yao et al. [13] provide a comprehensive summary of the microstructure and fluid dynamics of these reactors. The heat pipe concept is highlighted as a potentially reliable and cost-effective solution, suitable for operations in remote regions and various civilian communities. One study proposed a conceptual design for a heat pipe reactor with a power output of 3.5 MWt, demonstrating that the design meets the required shutdown margins [14]. dditionally, a detailed review of the microstructural analysis of these reactors, spanning from fabrication to applications, is available in Ref. [15].

Several innovative techniques have been developed to facilitate the commercialization of these reactors. For instance, a comparative analysis of technology readiness levels (TRLs) and levelized cost calculations for Indonesian nuclear power plants is discussed in Ref. [16]. Another study optimized the design of the heat pipe for vSMRs, ensuring sustainability without refueling, and advanced the concept as a nuclear battery [17]. Furthermore, technical and economic assessments of various vSMR types were conducted to evaluate their feasibility for Saudi Arabia's LINE city project. The findings suggest that these reactors are more cost-effective compared to other modular reactors [18].

National aeronautics and space administration(NASA) has developed a program that can help to support the management and technology and named it as Technology Readiness level(TRL). The tool is divided into nine levels with highest level depicts proven technology and lowest level means basic principle. Regarding nuclear reactor technology, TRL is used for the assessment of nuclear materials and it serves as assessment tool. Fig. 1 illustrates the progression of Technology Readiness Levels

Table 1
vSMR enrichment levels with pros and cons [7–12].

Reactor	Enrichment level(%)	Power Capacity (MWe)	Pros	Cons
Nu Scale	<20	77	- Remote facilities - Small power grids – 10years refueling - TRISO fuel	- Higher cost - Not commercial yet
U-Battery	<20	4	- Novel core - Less power – 5 years refueling	- Complex design - Under development - Helium turbine
SEALER	19.75	3–10	- Long operation - Decay heat removal - Sealed core	- Technical challenges - Lead coolant requirements
MMR	19.75	5	- High temp stability – 20 years refueling - Flexible heat transfer - TRISO fuel	- Higher operational cost - Under development stage
eVinci	5–19	0.2–5	- Compact structure - Durability - Fuel refill every 3 years - Heat pipes	- Higher initial cost - Limited operational data
Aurora	<20	1.5	– 20 years operation - Compact design - Nuclear waste burning	- Limited operational data - Safety measures - Under development
Xe-Mobile	<20	2–7	– 4 years refueling - portable - TRISO fuel	- Higher cost - Control system for autonomous operation
Kaleidos	20	1	– 6 years refueling - Portable - Compact design - Operate autonomously - TRISO fuel	- Higher cost - Regularity challenges - Under development
Holos Generators	8–15	3–13	– 60 % efficient - Simple design - Turbojet engine - Saleable power options	- Design not commercial - Potential safety requirements - Operational challenges

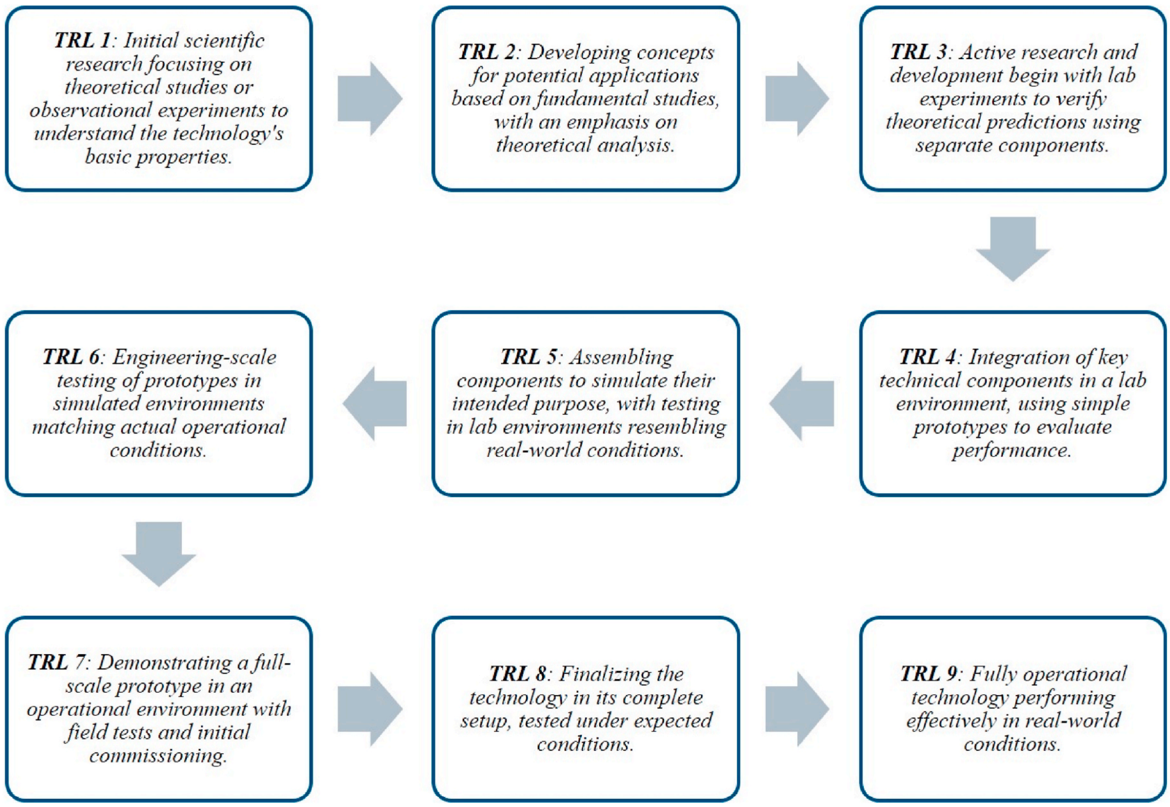

Fig. 1. Technology readiness levels (TRL) progression from initial research to full operational capability.

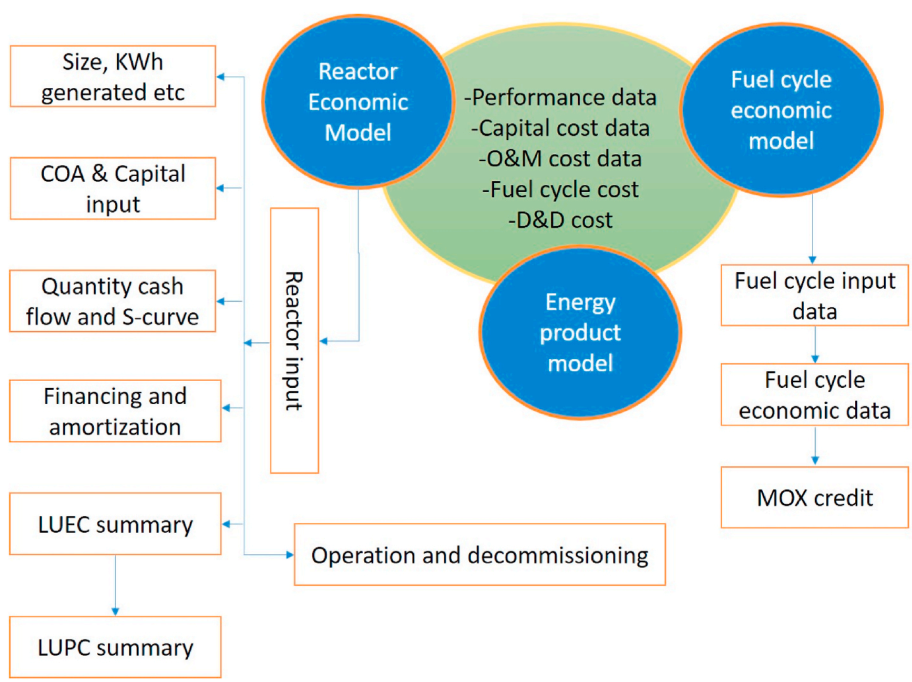

Fig. 2. G4-ECONS model.

(TRL) from initial research to full operational deployment.

The TRLs of very small and small modular nuclear reactors are shown in Table 2 below.

Among various vSMRs as discussed above, the most optimized and easy-to-implement option for the desert region was identified through a parametric assessment of various micro reactors as mentioned in Table 2. The optimization studies were carried out by considering various factors as mentioned above. The main descriptive parameters of the selected 10 MW vSMR is given in Table 3.

Table 2
TRLs level of micro reactors [19–22].

Reactor	TRL
U-Battery	1
SEALER	1
MMR	1
eVinci	2
Aurora	1
Xe-Mobile	1
Kaleidos	1
Holos Generators	1
CAREM	7
KLT-40S	8
StarCore	1
MHR-T	2
RDE	2

Table 3
Parametric analyses of vSMR.

Parameters	Values
Reactor type	vSMR
Thermal power	10 MW
Electric power	3.4 Mwe
Fuel material	UO_2
Average reactor capacity	60 years
Annual electricity production	3.154E+07 KWh/yr
Thermodynamic efficiency	34 %
Construction duration	Approx. 5 years
Quartile spending profile	S-curve
Discount rate (construction and amortization)	5 %
Decontamination and Decommissioning(D &D) cost	269 M$

2. Economic assessment model

G4-ECONS is developed by Generation IV international forum and is one of the widely used nuclear reactor system economic modeling code (see Fig. 2). The tool is based on visual basic and is extracted to MS excel. The input includes main parameters required for economic analysis, the data includes reactor design as well as specific data such as non-fuel operational annual recurring costs, fuel material, fuel assembly information, reprocessing materials data, nuclear material source unit, Intermediate and end states, Capital cost parameters etc [18,23–26]. This study utilized the G4-ECONS program, an application built on Microsoft Excel, to conduct an economic evaluation of a 10 MW vSMR. This technology functions based on four fundamental principles: simplicity, transparency, universality, and adaptability. This framework efficiently manages both estimated and actual plant data, accommodating both open and closed fuel cycles in accordance with international standards. The program examines cases pertaining to Generation III and Generation IV nuclear reactors, organized into five primary categories: design, manufacturing, fuel cycle, power products, and modularization. The lifecycle of a nuclear reactor system includes several stages: research, commercial design, commissioning, operation, fuel supply, and decommissioning. The G4-ECONS economic model is versatile, facilitating the computation of the standardized unit cost of the plant and the levelized cost of electricity generated by the reactor. The International Atomic Energy Agency (IAEA) has developed a model to calculate costs associated with capital, operations, maintenance, and the fuel cycle for each system. This adaptable method is applicable to various reactor types and project methodologies, offering significant assistance during the construction bidding phase. Investment costs include expenses related to planning, construction, commissioning, and testing of commercial operations. Core expenses encompass the design, installation, equipment, structures, and essential materials and supplies for the plant. Additional costs encompass supervision, indirect expenses, initial setup, spare parts, financing, ownership costs, contingencies, and other financial requirements. The total capital investment cost (TCIC) encompasses all financial resources necessary for the construction and operation of the plant, as illustrated in Fig. 3. The G4-ECONS fuel cycle model includes elements such as fuel materials, burnup cycle, enrichment, total fuel quantity, and a comprehensive reactor core model, as illustrated in Fig. 4. The model's input data must encompass the fuel requirements for the initial core and the enrichment levels of uranium or plutonium containing fissionable materials.The study investigated the application of vSMR from a variety of perspectives, highlighting its advantages and disadvantages, as well as the TRL scale. A small-scale vSMR with a capacity of 10 MW was selected to assess the economic feasibility. Computed values of 1.40 and 1.52 were obtained by modeling the fuel cycle's expenses to include both the front-end and back-end stages.Cumulative expenses were calculated using the S-curve and reported on a quarterly basis. The levelized costs, including operations and maintenance (O&M), decommissioning and decontamination (D&D), replacement investments, and sink factors, were computed. The levelized cost and fuel cycle costs were calculated to be $123.7 per megawatt-hour and $2.92 per megawatt, respectively. The total cost of $154.84/MWh was markedly inferior to that of analogous nuclear reactors. Nevertheless, as illustrated by the S-curve, specific stochastic uncertainties remain. It is recommended to augment and expand the uncertainty analysis for this reactor system.

Certain reactor types, like high-temperature reactors, may require specialized fuel types, while fast reactors might depend on advanced thermochemical or pyrometallurgical facilities for fuel production, recovery, processing, and recycling. In such instances, fuel cost data may not be readily accessible, so fuel cycle costs (e.g., $/kg) must be estimated using a methodology similar to that used for calculating electricity costs for each reactor type. In a particular study, the G4-ECONS tool was employed in two significant cases to demonstrate its effectiveness in conducting economic analyses of supercritical water reactors (SCWR). In the first case, an economic comparison was performed between six Generation IV reactor systems and Generation III light water reactors, following guidelines set by the Generation IV International Forum (GIF) for nuclear technology comparisons using the G4-ECONS model. Despite this, some questions remain about the approach used to estimate capital costs. The model's key advantage lies in its ability to compare different nuclear energy systems across various development stages. Results from this analysis were shared at the 2012 GIF Symposium [27,28]. In the second application, an economic evaluation was completed for the European High Power Pressurized Water Reactor (HPPWR), with findings published in 2012 [29]. This analysis underscored the importance of sensitivity analysis as a vital component.

To aid in cost estimation for Generation IV nuclear power systems, the Generation IV reactor consortium has developed standards that offer a consistent approach for evaluating costs. These standards facilitate comparisons between Gen IV reactors and other future energy systems. The framework includes a structured chart of accounts, cost assumptions, estimation guidelines, a collection of formulas, and an Excel-based cost model tailored specifically for Generation IV nuclear energy systems. Designed to be accessible, the program utilizes basic economic calculations and operates independently of country-specific factors. This approach allows users to bypass complex aspects such as cost accounting, depreciation, interest rates, discount rates, taxation, and capital cost recovery. The model is based on several key assumptions, including annual fixed dollar costs, capital and financing costs, levelized cash flow, and consistent plant operation with yearly power generation over the plant's lifetime. The Levelized Unit Electricity Cost (LUEC) serves as a central metric, calculating the average cost of electricity generation, while the Levelized Non-Electricity Unit Product Cost (LUPC) determines the levelized cost of producing other energy products. Both LUEC and LUPC consider capital cost recovery (including financing), non-fuel operations and maintenance, decommissioning and decontamination, and fuel cycle costs. The LUEC is calculated by the following expression,

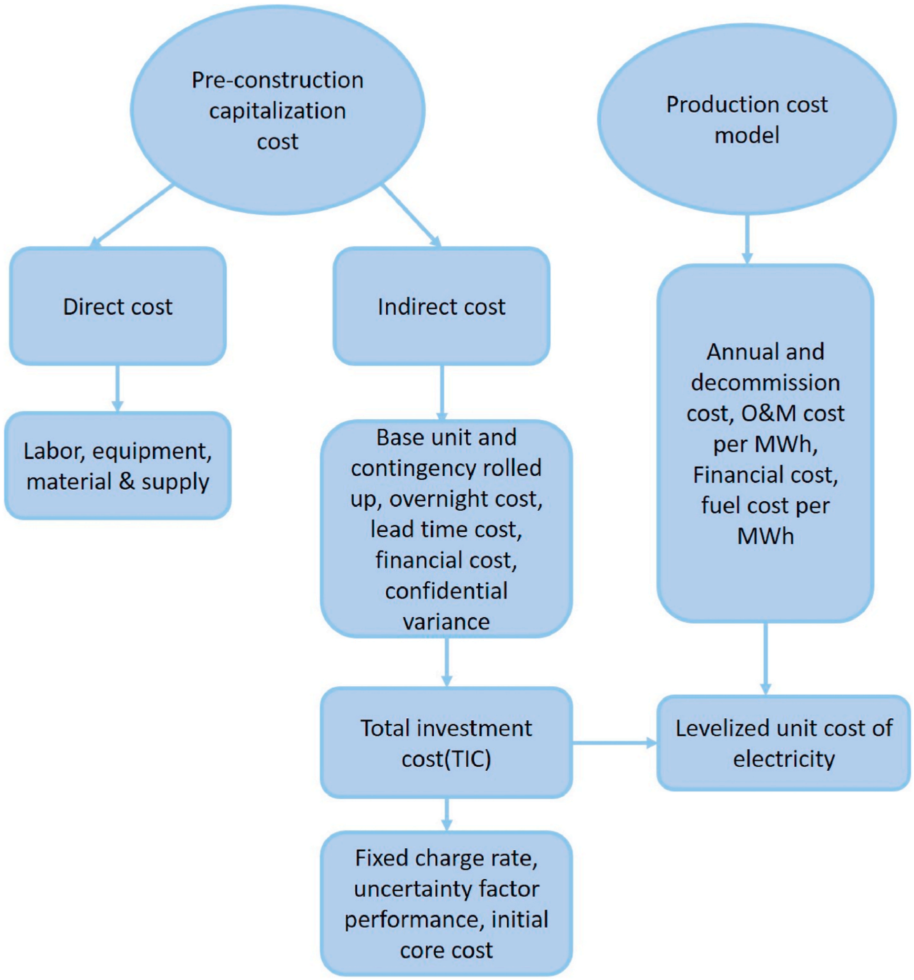

Fig. 3. Model for construction and production.

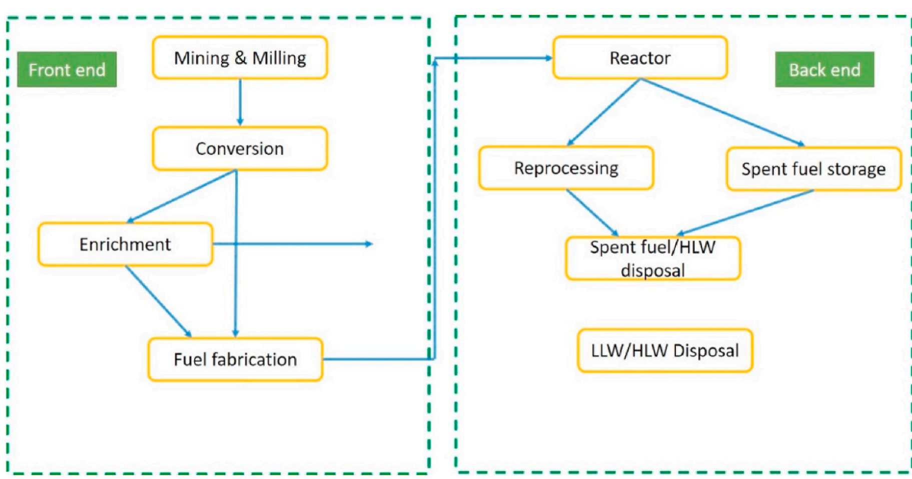

Fig. 4. Front and back end of fuel supply system.

$$LUEC = \sum \left(\frac{I_t + F_t + O\&M_t \, (1+r)^{t+1}}{E_t} \right) \tag{1}$$

Considering the constant annual expenditures and production, cost of D&D needs to be added in LUEC to obtained the levelized cost of capital, then the above equation takes the following form as,

$$LUEC = LCC + \sum \left(\frac{[D\&D + Fuel + O\&M](1+r)^{t+1}}{E_t} \right) \tag{2}$$

$$LUEC = LCC + \left[\frac{Fuel + O\&M + D\&D}{E} \right. \tag{3}$$

3. Fuel cycle modeling

A nuclear power plant generates electricity throughout its operational lifetime within the entire nuclear fuel cycle. This cycle begins with exploration, mining, milling, refining, and enrichment, then progresses to producing reactor-grade fuel elements, and concludes with the disposal of spent fuel. End-of-cycle costs cover both short-term and long-term storage at the plant site, as well as charges for handling spent fuel once it leaves the reactor. "Nuclear fuel burn-through" describes the energy output from the reactor per ton of U-235 consumed. Many advanced reactor designs or small modular reactors (SMRs) require enriched uranium levels above 5 %, often ranging between 10 % and 20 %. The cost of nuclear fuel is impacted by factors like the price of natural uranium, conversion, enrichment, and manufacturing fees. Converting one kilogram of uranium into UO_2 costs approximately USD 1.663. The Fuel Cycle simulation is based on the model developed by the Economic Modeling Working Group (EMWG) [28,29]. This economic analysis of fuel cycle options, documented in articles from 1994 to 2002, includes required materials and their costs for different reactor types [30]. These sources also detail the expenses for managing high-level radioactive waste, spent fuel, and the broader fuel cycle. Nuclear fuel costs cover uranium production, conversion, enrichment, fuel fabrication, transportation, and ultimate disposal of spent fuel. Reprocessing costs encompass chemical processing, waste management, and disposal of high-level radioactive waste, including uranium, plutonium, and other materials. Fig. 4 provides a flowchart illustrating the unit costs for each stage of the simulation process.

The cost of managing radioactive waste is a unique aspect associated with nuclear power plants (NPPs), commonly known as decommissioning and decontamination (D&D) costs. Some studies consider these costs as separate items [18,31]. The expenses can be categorized within the broader framework of the plant's operating and maintenance costs [32–34]. The capital cost of a nuclear power plant, commonly known as the overnight cost, encompasses all expenses associated with construction, while excluding any interest that may accumulate during the construction phase (IDC). The initial costs encompass the entire construction process, incorporating engineering, procurement, and construction (EPC) expenses as presented in Table 4. Additionally, they account for various owner-related costs such as land acquisition, cooling systems, auxiliary buildings, construction sites, switchgear, project management, permits, and other necessary provisions. EPC costs, encompassing physical plant equipment, labor, and materials, typically constitute approximately 70 % of the total cost. The remaining 30 % consists of indirect expenses, including supervision and staff support. About 20 % of the overall expenditure is designated for owner fees and contingencies, which includes system testing and employee training. The overnight costs for small modular reactors (SMRs) are detailed as follows: CAREM 25 is priced at $3600 per kW, KLT-40S at $3950 per kW, and HTR-PM at $1500 per kW [35,36].

4. S-curve pattern development

The S-curve values displayed in Fig. 5 demonstrate the cumulative cash flow pattern used to determine construction spending on an annual or quarterly basis. A key advantage of the S-curve model lies in its ability to create a suitable cash flow distribution over a specified number of quarters, represented by "n." The sine function illustrates both descending and ascending trends, facilitating the estimation of payment amounts needed. For analysis, the period was divided into eight quarters, with annual figures calculated for each to provide an accurate assessment of interest during the construction phase (IDC). The cumulative expenditure forms an S-shaped curve, which can be plotted across quarters if the spending is distributed evenly. The interest rate during construction is impacted by factors such as the plant construction duration, initial activities, scheduling, and discount rates. These factors utilize a quarterly sine wave function to approximate project expenditures throughout the year (in quarters). As illustrated in Fig. 5, cumulative spending reaches a peak value of 1.0 before decreasing sharply relative to the number of quarters. Values remain consistently between 0 and 1, with the sine function accurately calculating the interest rate for each quarter, as demonstrated in Table 5 for each period within the year.

During the construction phase, the interest rate for the total cost of capital is influenced by the front-end activities, the duration of the project and various discounting options. To simplify the model, a sine wave function is used that captures the interest rate peak in the middle of the capital campaign. This approach provides an acceptable mathematical estimate of interest over the entire project life. The loading parametric analysis of fuel materials are presented in Table 5.

Interest calculations can be performed with cumulative expenses represented by an S-shaped curve. To increase modeling accuracy and fidelity, interest payments can be estimated on a quarterly basis, as shown in Fig. 5. Typically, interest calculations begin in the middle of each quarter and continue until the start of commercial power generation. Consequently, the total interest accrued during construction is the sum of all these interest payments. This S-curve approach is commonly used for various projects as it allows the automatic calculation of capital cash flow data and reduces the need for manual input.

Table 4
Loading parametric study of fuel materials.

Parameters	Values
Refueling time	3 years
Average fuel assemblies	11800
Annual heat production	3.86E+03 MWd/Year
Annual electricity production	3.15E07 KWh/year
HM of an actual reload	84 of KgHM
Heavy metal mass of fuel assembly	7 % of KgHM
Average fuel burnup	46,788 MWd(th)/MTHM

5. Levelized cost model

The term known as Interest During Construction (IDC) refers to the interest charged on the funds allocated for financing the construction of a power plant, as detailed in Table 6. These costs are incurred throughout the construction phase before the plant starts generating revenue [37,38]. The International Nuclear Association suggests an IDC of approximately 30 % of capital costs for a construction duration of five years, increasing to 40 % if the construction extends to seven years. Nuclear energy provides an advantage with lower operating and maintenance (O&M) costs compared to coal, natural gas, and other power generation sources. O&M expenses cover the costs associated with the routine operation and maintenance of a nuclear power plant (NPP) and are significantly influenced by the technology and type of reactor used. These expenses are classified into two main types: fixed O&M and variable O&M. Fixed O&M costs are regular expenses, including labor, property taxes, plant insurance, and life cycle maintenance. Variable O&M costs, in contrast, fluctuate with production factors, such as fuel prices, consumables, direct equipment maintenance, building upkeep, and contractor services. Currently, the operating and fuel expenses for small modular reactors (SMRs) are 0.0141 USD/kW for CAREM-25, 0.0107 USD/kW for KLT-40S, and 0.0209 USD/kW for HTR-PM [39].

The Levelized Cost of Electricity (LCOE) is an important way to figure out how much it costs to make electricity from different sources over the life of a power plant. The total costs of building, running, and maintaining a power plant are divided by the total amount of energy it produces over its lifetime. This is usually shown in dollars per kilowatt-hour (kWh). Calculating LCOE for small modular reactors (SMRs) presents challenges due to limited commercial operation data. In NuScale Power's spring 2020 update, the LCOE for the 12-module UAMPS project was projected at $0.065/kWh, while broader estimates for SMRs range between $0.045 and $0.095/kWh. Studies that consider various capital cost factors indicate that the LCOE for nuclear power plants

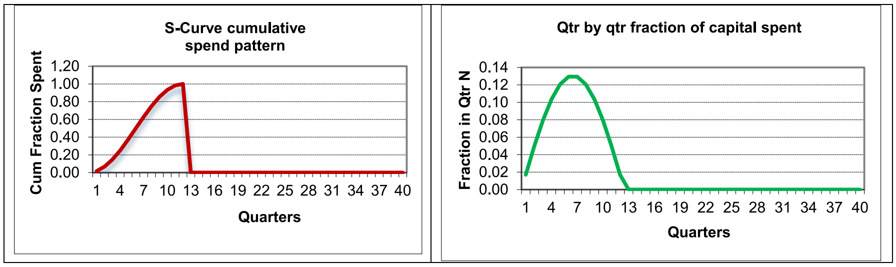

Fig. 5. S-curve pattern of vSMR.

Table 5
Cumulative spending pattern.

Possible Quarters	Calculated Quarters Qtr N	Calculated Year Number	Normalization for S-curve	x-axis for sine function	sine (x)	cumulative normalized y	S-curve fractions	Principal Amount Spent in Qtr N ($M)	Compounding Factor	Interest on amount borrowed in Qtr N to end of construction ($M)
1	1	0.25	0.0833	−1.3090	−0.9659	0.0170	0.0170	3.25	1.0145	0.05
2	2	0.50	0.1667	−1.0472	−0.8660	0.0670	0.0500	9.53	1.0132	0.13
3	3	0.75	0.2500	−0.7854	−0.7071	0.1464	0.0795	15.15	1.0120	0.18
4	4	1.00	0.3333	−0.5236	−0.5000	0.2500	0.1036	19.75	1.0107	0.21
5	5	1.25	0.4167	−0.2618	−0.2588	0.3706	0.1206	23.00	1.0094	0.22
6	6	1.50	0.5000	0.0000	0.0000	0.5000	0.1294	24.68	1.0082	0.20
7	7	1.75	0.5833	0.2618	0.2588	0.6294	0.1294	24.68	1.0069	0.17
8	8	2.00	0.6667	0.5236	0.5000	0.7500	0.1206	23.00	1.0056	0.13
9	9	2.25	0.7500	0.7854	0.7071	0.8536	0.1036	19.75	1.0044	0.09
10	10	2.50	0.8333	1.0472	0.8660	0.9330	0.0795	15.15	1.0031	0.05
11	11	2.75	0.9167	1.3090	0.9659	0.9830	0.0500	9.53	1.0019	0.02
12	12	3.00	1.0000	1.5708	1.0000	1.0000	0.0170	3.25	1.0006	0.00

Table 6
Capital cost investment of vSMR.

Parameters	Values
Capital replacements/upgrades (levelized)	0.89 $M/year
O&M cost	28.22 $/MWh
D &D cost	269 $ M
Sinking fund interest	0.50 %/year
D&D as direct reactor capital cost	302.25 %
Sinking funds factor	0.01433/year
Annualized D&D	3.86 $M/year
Annualized D&D cost	122.226 $/MWh

(NPPs) can vary from USD 0.04 to 0.14/kWh.In this study, the levelized cost of electricity is 154.84 $/MWh including the capital, operation and fuel cost as presented in Table 7. The aim of this study is to identify an vSMR technology that is commercially viable and to assess its economic performance.

6. Cost comparison between vSMR and SMRs

The main financial metrics of the very small modular reactor (vSMR) were analyzed and compared to various other small modular reactors (SMRs). The Integral Molten Salt Reactor (IMSR), an advanced design of compact molten salt reactors (MSRs), is used to calculate the Levelized Unit Electricity Cost (LUEC). L. Samalova et al. [33] employed the G4ECONS code to determine the LUEC and validated their approach by comparing it to the AP1000 from Westinghouse, a large-scale nuclear facility. Following a thorough review of available options, including other SMRs and the vSMR, this advanced reactor design was selected for further study due to its distinctive insights into cost efficiency. The G4ECONS code's comprehensive cost estimation model employs algorithms to evaluate costs related to fuel cycles, capital recovery, operations and maintenance (O&M), decontamination and decommissioning (D&D), and additional associated costs [27].

The overall LUEC is obtained by combining these components. Tables 4 and 6 provide specifics on how this assessment also examines the Levelized Unit Product Cost (LUPC), as well as O&M expenses, capital investments, and D&D reserves [33]. The findings reveal that the vSMR achieves a lower LUEC for electricity production compared to other SMRs, as illustrated in Table 8 [31,34]while its operational costs remain similar to those of alternative reactors. Additionally, D&D expenses are handled as annualized costs rather than one-time capitalized expenses, covering items such as yearly interest on the sinking fund, portions of direct capital outlays, the sinking fund rate, reserves for end-of-life expenses, and the annualized D&D costs [35]. Table .8 presents a comparison of calculated costs for various SMRs in relation to the selected vSMR. Pu-MoX exhibits the highest costs among the SMRs, while the vSMR demonstrates the lowest capital cost, distinguishing itself as one of the most cost-effective alternatives [39,40].

Table 7
Levelized cost of electricity($/MWh).

Parameters	Values($/MWh)
Capital cost	123.7
Front end fuel cycle cost	1.40
Back end fuel cycle cost	1.52
Operation & maintenance cost	28.22
Total Levelized cost	**154.84**

Table 8
Comparison of cost between vSMR and various SMRs.

Parameters ($/MWh)	vSMR	SMRs			
		Pu-MOX	MIT PBMR	PWR based	System 80+ PWR
Capital cost	123.7	–	–	–	–
O&M cost	28.22	222.66	23	34.61	116.55
Fuel cycle cost	2.92	134.45	6.51	8.88	67.86
D&D cost	3.86	59.67	13.05	8.21	57.39
Total cost	154.84	417.85	42.81	51.76	242.53

The direct cost of a nuclear power plant includes the structural components, the reactor, the turbine, the electrical equipment and other miscellaneous components, including the heat removal system of the main condenser. In contrast, indirect costs include engineering services, construction work, surveys and supervision. Supporting costs include total capital costs and owner's costs, which can be expressed as a percentage of total capital cost.

7. Conclusion

The study analyzed the application of vSMR from multiple perspectives, emphasizing its benefits and drawbacks alongside the TRL scale. The cost evaluation of viability was determined by selecting a small-scale vSMR with a capacity of 10 MW. Fuel cycle costs were modeled by considering both the front and back ends of the cycle, yielding calculations of 1.40 and 1.52, respectively. The cumulative expenditure was determined through the S-curve method and presented in quarterly intervals. The levelized costs, encompassing operations and maintenance, decommissioning and dismantling, and replacement investments, along with the sink factors, were calculated. The levelized cost and fuel cycle costs were determined to be $123.7/MWh and $2.92/MW, respectively. The total cost of $154.84/MWh is notably lower than that of other nuclear power plants within the same power class. Nonetheless, the S-curve illustrates that stochastic uncertainty persists. It is recommended to expand and correct the uncertainty analysis of the reactor system.

CRediT authorship contribution statement

Salah Ud-Din Khan: Writing – review & editing, Software, Methodology, Funding acquisition, Formal analysis, Investigation, Project administration, Conceptualization. **Zeyad Almutairi:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Redhwan Almuzaiqer:** Writing – review & editing, Writing – original draft, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

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