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Original Article

Techno-economic assessment of a very small modular reactor (vSMR): A case study for the LINE city in Saudi Arabia

Salah Ud-Din Khan [a, b, *], Rawaiz Khan [c]

[a] Sustainable Energy Center Technologies, College of Engineering, King Saud University, P.O.Box 800, Riyadh 11421, Saudi Arabia
[b] KA.CARE Energy Research and Innovation Center, King Saud University, Riyadh, Saudi Arabia
[c] Engineer Abdullah Bugshan Research Chair for Dental and Oral Rehabilitation, College of Dentistry, King Saud University, Riyadh, 11545, Saudi Arabia

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A B S T R A C T

Recently, the Kingdom of Saudi Arabia (KSA) announced the development of first-of-a-kind(FOAK) and most advanced futuristic vertical city and named as 'The LINE'. The project will have zero carbon dioxide emissions and will be powered by clean energy sources. Therefore, a study was designed to understand which clean energy sources might be a better choice. Because of its nearly carbon-free footprint, nuclear energy may be a good choice. Nowadays, the development of very small modular reactors (vSMRs) is gaining attention due to many salient features such as cost efficiency and zero carbon emissions. These reactors are one step down to actual small modular reactors (SMRs) in terms of power and size. SMRs typically have a power range of 20 MWe to 300 MWe, while vSMRs have a power range of 1–20 MWe. Therefore, a study was conducted to discuss different vSMRs in terms of design, technology types, safety features, capabilities, potential, and economics. After conducting the comparative test and analysis, the fuel cycle modeling of optimal and suitable reactor was calculated. Furthermore, the levelized unit cost of electricity for each reactor was compared to determine the most suitable vSMR, which is then compared other generation SMRs to evaluate the cost variations per MWe in terms of size and operation. The main objective of the research was to identify the most cost effective and simple vSMR that can be easily installed and deployed.

1. Introduction

In the past, fossil fuels played an important role in the development of nations when technological possibilities were limited. Currently, sustainable fuels with all their variants dominate the energy sector and they are inevitably increasing, leading to massive technological progress in the energy industry [1]. These alternative energy sources solar, wind, geothermal, hydropower, nuclear, etc. [2,3]. Nowadays, with the modern civilization and development, nuclear energy takes its role as the base load capacity (rely on technology with low variable costs and high fixed costs) for the new era of evolution with safe and sustainable energy for the future generation.

On July 25, 2022, the Kingdom of Saudi Arabia(KSA) unveiled the "LINE" city which will be a civilizational revolution. The city offers an unprecedented urban living experience by developing a city of the future with pure clean energy resources (zero carbon footprint). The city LINE can accommodate 9.0 million people and will be built on a footprint of only 34 km^2. It will be a vertical city up to 170 km long, 200 m wide, and only 500 m above sea level, as shown in Fig. 1. The city will consist of three layers including pedestrians track, underground infrastructure and underground transportation. The building cost of estimated to be 400–700 Billion SAR. The city will lead the concept of urban development with unprecedented experience while keeping the clean energy atmosphere. There will be no roads, vehicles and carbon emission and will run entirely on renewable energy. The clean environment is a part of 100% sustainable transport system which could only be possible with sustainable energy sources.

It is said that the entire city will run on 100% renewable energy, including all industries and residential areas [4]. Since the project is based on pure clean energy resources, therefore, solar, nuclear, wind, geothermal and hydroelectric power plants can be an attractive alternative [5]. Nuclear energy is inherently carbon-free compared to conventional fossil fuels, which have pollution to

* Corresponding author. Sustainable Energy Center Technologies, College of Engineering, King Saud University, Riyadh, Saudi Arabia.
E-mail address: drskhan@ksu.edu.sa (S.U.-D. Khan).

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Fig. 1. Sketch of Saudi Arabia's NEOM LINE city [4].

the environment and other water resources [6]. Accordingly, the development of nuclear energy technology as a sustainable energy has become a constant topic in many energy discussions and dominates research in academia to explore the feasibility and prove that this promising technology can meet the projected demand for electrical and thermal applications. The use of nuclear energy is now becoming a dominant flux in any energy dialogue, challenging research in many areas of research and development (R&D) to find ways to make it more lucrative and attractive, and to minimise dependence on fossil fuels as the main energy supplier. Therefore, small modular reactors (SMRs) may be a good option, capable of generating up to 300 MWe energy, while very small modular reactors (vSMRs) can generate up to 20 MWe energy. Fig. 2 illustrates the differences in development and operation of SMRs and vSMRs. It can be observed that SMRs can be factory-built with all components integrated into a capsule-like structure that is exactly like vSMR. However, for small-scale applications, vSMRs can be a good choice because they can be easily manufactured and transported [7]. These vSMR can be placed underground providing more protection from natural disasters and can have multiple units on same site. Therefore, these reactors can be placed in lower layer with acute safety in a futuristic vertical city of LINE. There should be complete feasibility studies of these vSMRs for installation in LINE and since the output power range is are not large therefore many vSMRs should be installed but it may increase the cost very much. Hence, the hybrid energy system can serve the purpose consisted of renewable energy and nuclear together. Further, to consider a large nuclear power plant cannot be possible as huge space is needed for this purpose and also cannot be feasible in such vertical city. The main objective of the study was to investigate the cost effective clean energy sources (renewable, SMR, vSMR) particularly for vSMR as this type of reactor can be fixed and transported easily. For instance, if combine with any renewable energy sources in hybrid mode, it can also be a cost-effective.

Table 1
Classification of fossils and clean energy sources according to cost [9].

Reactor types	Size	Capital cost($/kWe)	Electric cost($/kWh)
Fossils based	small	200–2000	0.15–0.60
Renewable based	>small	3000–5000	0.15–0.30
vSMR	small	5000-20,000	0.14–0.41

These vSMR is ideal for remote locations where power grids are not available, as in the case of the LINE project, where transportation and other resources may impose higher costs. In this case, vSMR can be a good choice for meeting energy needs. This is because mining, oil and gas facilities, isolated resources, parks, public facilities, and more, require electricity. This energy can be on perpetual basis using a combination of power plants and other existing infrastructure. Since, nuclear power does not need to add fuels for longer time as compared to other sources and it can run on perpetual basis. Existing infrastructure includes the type of fuel used, loading pattern, shutdown, de-commissioning etc. The decommission stage of these vSMR takes longer time as compared to other SMRs and large nuclear power plants which makes them operational for longer time.

The fuel cycle of these plants is up to 20 years and can be done online (while the reactor is operating). These vSMRs have not yet been developed by any country to-date, but conceptual designs have been developed and work on them continues. For different market options, including stationary and portable devices, the concept of microreactors is presented by Caponiti et al. [8]. Modularization of microreactors in factories, including manufacturing methods, is explained by Moe et al. [9]. Table 1 shows the comparison between fossil, renewable and nuclear energy. Since, LINE project includes a development to vertical city and it is important to

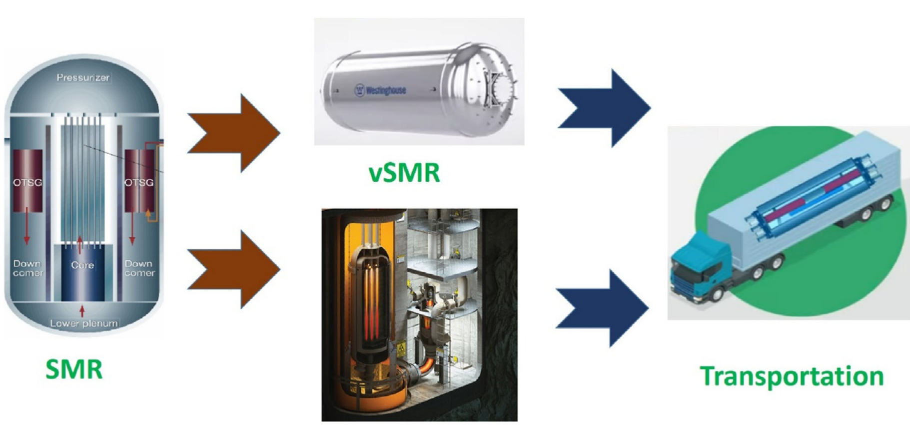

Fig. 2. General schematic diagram of SMR and vSMR [7].

understand the economic assessment of available energy sources which can be installed in such vertical city and being in remote site. Therefore, vSMR have been compared with small scale diesel generator(fossil) and solar rooftop (renewable energy). It can be seen that, if combine with any renewable energy sources in hybrid mode, it can also be a cost-effective as well. The vSMR can be a dual purpose producing both electricity and heat and if integrated to become hybrid system, it can serve purposes like heat or energy carriers effectively if multiple units are installed depending upon the requirement of the LINE city. Table .1 presented a critical details of costs.

In Table 1, fossil based reactor types for example, diesel generator which seems to be attractive as well in comparison with vSMR but while considering the fuel supply, the vSMR cost is expected to be competitive on the long term. The lower band of both entities are approximately same (0.15 $/KWh for fossil and 0.14 $/KWh for vSMR) but the upper band for fossil is quite higher due to the cost of fuel added with transportation charges. Thus, concluding vSMR as economical competitive. The same ideology applied to renewable energy as well as presented in Table 1, if we consider the capital cost of vSMR, it shows the lower bound as 5000 $/KWe while renewable sources is 3000 $/KWe [10,11] because like large nuclear power plants, vSMR also have higher initial capital cost. However, the current renewable energy market particularly for micro grids are more than 0.40 $/KWh. It is expected that this cost will gets lower to 0.15 to 0.30 $/KWh by 2035 and same is the case with vSMR according to IRENA, 2020 report [12–14]. It is important to understand that the comparison shown in Table 1 is for microgrid technology and it can be observed that these vSMRs can be competitive and even by the time of their commercialization.

2. Very small modular reactors(vSMR)

The design of vSMR was initiated immediately after the development of the small modular reactors in close consultation with many reactor designers and the regulatory authority like United states nuclear regularity commission(U.S.NRC). This results in the fact that the first-of-a-kind (FOAK) reactor is expected to be in service by 2027, neglecting the uniqueness of the technology. Those concepts that use conventional fuels and coolants may have a shorter timeline because they are already proven. In the case of the FOAK reactor, the challenges and risks may largely affect the duration of the schedule, as liquid metal, molten salt, and high-temperature gas reactors require greater efforts in development and certification. Since these reactors are in conceptual design phase having complicated geometries that makes them innovative (not proven yet) and ultimately needs to go through tough certification and licensing procedure. There are several vSMRs in the design and in conceptual stages, including Aurora, eVinci, SEALER, Holos generator, U-battery, and micromodule reactor (MMR). Aurora was developed by Oklo Inc. and is named Aurora and produces about 1.5 MWe. This reactor can operate autonomously for 20 years and consists of a metal block with metallic fuel in a heat pipe. Many parts of the design have not yet been decided or made public, but the design is said to be simple and safe. The beauty of this reactor is that it can also burn nuclear waste [15]. The developer of the eVinci reactor is Westinghous Electric, which has a proven track record with reactors of innovative design, including space reactors, and has been operating reactors for about 50 years. The reactor is based on a high-temperature heat pipe reactor with a power range of 0.2–5 MWe and an operating life of more than 3 years without refueling. The reactor is designed to use few components to increase reliability and operational stability [9]. SEALER is a lead-cooled microreactor developed by LeadCold to replace diesel propulsion in off-grid applications with an electrical output of 3 MWe. The reactor is designed to use uranium ni-tride so to improve the performance of future energy generations. The design also allows for transportation by air [16]. The design of the Holos generator is simple enough to eliminate the use of multiple pipelines, pumps, tanks, heat exchangers, and valves. Carbon dioxide is used as the primary coolant and the reactor is designed for the organic Rankine cycle (ORC). The efficiency is up to 60% and follows safer, melt-tolerant fuels [17]. The U-battery is actually a high-temperature gas-cooled reactor. This reactor uses three-stage fuel particles with graphite moderation and helium cooling. The maximum power of this reactor is 4 MWe, and the expected lifetime of the plant is 30 years. The reactor cavity can be fixed underground and has a spent core storage and power conversion facility [18]. Ul-tra-safe nuclear corporation has developed a micro-modular reactor (MMR) moderated with graphite and cooled with helium. The power range of this reactor is 5 MWe and two types of fuels can be used, namely three-structured and all-ceramic micro-encapsulated fuels. The demonstration plant of this reactor is located in Chalk River [19]. A summary of the main parameters of the above reactors is shown in Table 2. It is noted that SEALER and NuScale use conventional fuels used in various PWR and BWR, or all proven and practiced designs. TRISO fuel (TRi-structural ISOtropic particle fuel) is considered the most robust fuel and is used in various III + and IV generation reactor systems. The remaining vSMR uses TRISO fuel to achieve maximum fuel efficiency. The Aurora reactor, on the other hand, is designed for low power with a uranium-zirconium mixed fuel and sodium as coolant.

The LINE project of Saudi Arabia is by now a futuristic city which should have clean energy sources and nuclear can be a good choice. There are numerous studies published on SMRs and modular reactors but none of the study was performed to calculate the cost of vSMR in comparison with other SMRs. This will help the policy makers to think about this vSMR to integrate with any renewable energy (out power of vSMR is maximum 20 MWe). There is big difference between commissioning and decommissioning, design and other associated parameters between SMRs and vSMRs, but unfortunately, both SMR and vSMR are being considered as single entity which affects the cost and ultimately gives wrong indications. The reason to add selected vSMRs is to know which one and why eVinci was selected. The research pave the way to explore and integrated eVinci with any renewable energy based reactor for multiple applications in cost effective manner.

3. Fuel cycle modeling of vSMR

The fuel cycle modeling was performed using the EMWG (Economic Modeling Working Group) model [20,21]. It is based on the microsoft excel model having the capability of calculating the levelized unit cost of electricity(LUEC) for various types of Generation IV reactor systems. This combine model is called G4-ECONS which is then extended to calculate fuel cycling cost, hydrogen production and desalination cost besides energy cost. The same modeling approach described in the National Energy Agency (NEA) were used to estimate incremental costs. The economic evaluation of fuel cycle decisions, which includes core materials and fuel cycle costs for different reactor types, is presented in the 1994 and 2002 reports from NEA [19,21]. These reports include fuel cycle costs, spent fuel management costs, and high-level radioactive waste management costs. In general, nuclear fuel costs include the costs of uranium, conversion, enrichment, fuel fabrication, transportation, and final disposal of spent fuel. Reprocessing costs, on the other hand, include chemical processing, waste management, disposal of high-level radioactive waste, uranium, plutonium, or other materials. A flowchart is shown in Fig. 3, which also includes conversion unit of cost for each step required for the simulation. It gives the main

Table 2
Parametric analysis of vSMR [15].

Name of reactor	Power(MWe)	Fuel	Coolant	Designer
SEALER	3.0	UO_2	Lead	Lead cold(Sweden)
U-Battery	4.0	TRISO	Helium	Urenco(UK)
NuScale	1–10	UO_2	Light water	NuScale Power(USA)
Xe-Mobile	1.0	TRISO	Helium	X-energy(USA)
MMR	5.0	TRISO/FCM	Helium	Ultra-Safe Nuclear Corporation(USA)
eVinci	0.2–5.0	TRISO	Sodium(liquid)	Westinghouse Electric company (USA)
Holos generators	3.0–100	TRISO	Helium/carbon dioxide	HolosGen(USA)
Aurora	1.5	U–Zr(Metallic)	Sodium(liquid)	Oklo Inc. (USA)

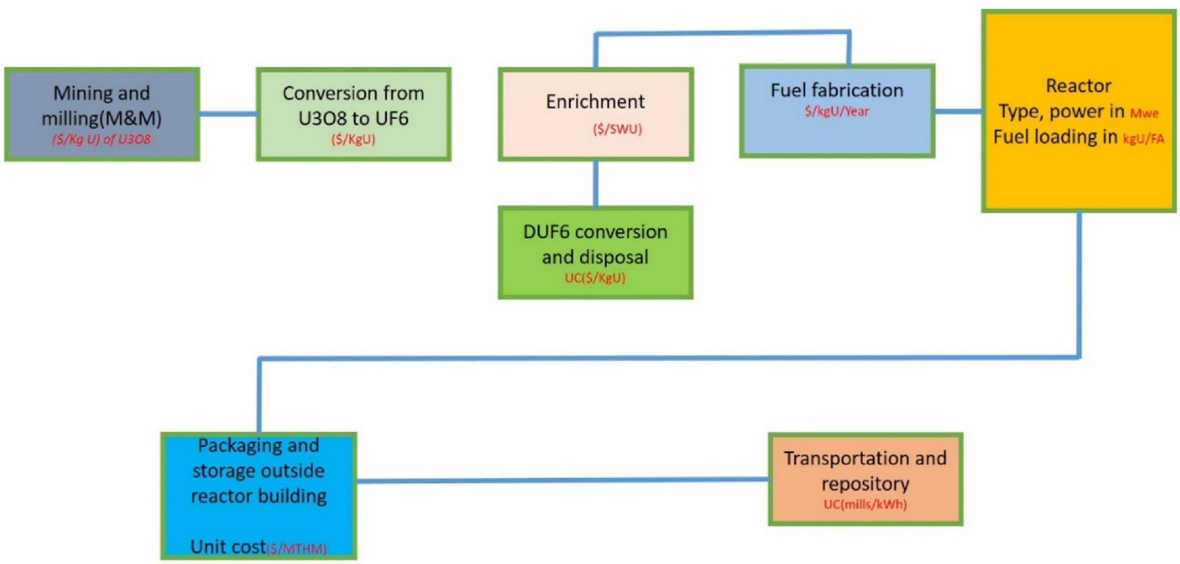

Fig. 3. Fuel cycle conversion cycle.

methodology used in the computational program for calculating costs which not only includes the electricity cost but also IDC interlinked with interest rate per quarter of the year, construction duration rate, front end activities etc.

However, operation and maintenance costs include costs other than fuel, such as labor, supplies and equipment, and other services. Government fees and taxes, decommissioning fees, and other miscellaneous costs may also be included. Table 3 shows various parameters for the fuel cycle costs of 1 MWe vSMR. It is important to understand that the total capital cost during construction is referred to as IDC (interest during construction). The discount rate and cash flow rate are directly linked to IDC, which is then associated with the design, construction, and overnight capital costs which is given by the following relation,

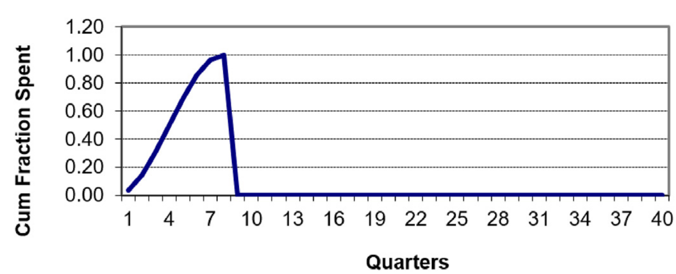

Fig. 4. S-curve terms in terms of quarters.

Table 3
Analysis of fuel cycle supply system for vSMR.

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	0.25	0.1250	−1.1781	−0.9239	0.0381	0.0381	5.71	1.0094	0.05
2	0.50	0.2500	−0.7854	−0.7071	0.1464	0.1084	16.26	1.0082	0.13
3	0.75	0.3750	−0.3927	−0.3827	0.3087	0.1622	24.33	1.0069	0.17
4	1.00	0.5000	0.0000	0.0000	0.5000	0.1913	28.70	1.0056	0.16
5	1.25	0.6250	0.3927	0.3827	0.6913	0.1913	28.70	1.0044	0.13
6	1.50	0.7500	0.7854	0.7071	0.8536	0.1622	24.33	1.0031	0.08
7	1.75	0.8750	1.1781	0.9239	0.9619	0.1084	16.26	1.0019	0.03
8	2.00	1.0000	1.5708	1.0000	1.0000	0.0381	5.71	1.0006	0.00

Table 4
Levelized and annualized cost components.

Parameters	Values ($/MWh)				
	vSMR *(This work)*	SMART [16]	IMSR600 [17]	IMSR300 [17]	IMSR80 [17]
Capital cost	2.9	19.02	21.92	28.60	70.48
Operation	21.5	21.03	13.85	17.15	44.73
D&D cost	0.2	0.16	0.15	0.17	0.35
TOTAL LUEC	**24.6**	**53.77**	**44.13**	**54.58**	**126.05**

$$\mathrm{IDC} = \sum_{i}^{i=1} C_f\left[(1+r)^{t-i} - 1\right]$$

Where, 'Cf' denotes cash flow, 'r' is the real discount rate,'t' is the quarter and 'i' is the period.

The S-curve values given in Table 3 indicate the pattern for cumulative cash flow that determines annual or quarterly construction expenditures. The advantage of the S-curve model is that it can generate a suitable cash flow pattern for a number of "n" quarters. Sine value function determines the lower and upward trends which ultimately estimates the amount need to pay. The analysis period was divided into eight quarters, and the annual number was calculated for each quarter to accurately estimate the IDC. The normalized sine wave curve is generated in the form of the S-curve function, as shown in Table 3.

Cumulative expenditures are represented by an S-shaped curve, and if all expenditures are made in quarters, they can be represented accordingly. For instance, interest rate during construction depends upon the plant construction duration, front end activities, time line and discount rate. All these factors used a quarter base sine wave function which approximate project expenditure over the project year (in quarter). In Fig. 4, it can be observed that cumulative spending increases up to a value of 1.0 and then drops sharply as a function of the number of quarters. The values always lie between 0 and 1 and sine function exactly figure out the interest rate for each quarter as given in Table 3 for each quarter of the year.

The core financial parameters of this vSMR were studied and compared with other different SMRs. Integral molten salt reactor (IMSR) is an advanced compact design of MSR allows to calculate the levelized unit of electricity cost (LUEC). L. Samalova et al. [22] developed a methodology and used the G4ECONS code to calculate the LUEC in comparison with the large nuclear power plant named as AP1000 developed by Westinghouse. The comparison provides information on the cost efficiency and since it is an advanced reactor design, this reactor was selected for analysis in comparison to SMART and vSMR. The cost estimation model was used in the G4ECONS code, including the levelized algorithms required for the calculations with the fuel cycle component factor, capital recovery, operation and maintenance costs, and decontamination and decommissioning cost(D&D) were calculated. The summation of these components yields the total LUEC. The comparison between levelized unit product cost (LUPC), operation and maintenance (O&M) cost, capital and D&D funds was investigated and is shown in Table 4. For this purpose, different power ranges of IMSR, system modular advanced reactor (SMART) and a generation reactor system III +, were compared with vSMR. It can be found that the total power generation unit (LUEC) of vSMR is lower than that of the other SMRs, as shown in Table 4. The capital cost of vSMR is 2.9 $/MWh which is far less than SMART and IMSR (with 300,600 and 80) but operational cost is nearly equal to other reactor options. Similarly, D&D cost which is annualized cost rather than capitalized includes the sinking fund interest (per year), fraction of direct capital cost, sinking fund factor, funds at the end of plant life and annualized D&D. All these parameters were calculated under fuel cycle cost estimation model.

As concluded from the study, the cost of vSMR is less as compared to other reactors that makes them suitable as long as economy is concerned. But a proper regulatory framework is required and IAEA has already developed guidelines for regularity framework. KSA is following all the regulations through Saudi Arabian Atomic Regulatory Authority (SAARA) and in November 2016, an agreement with South Korea's nuclear safety and security commission protection was held to promote cooperation in regulating nuclear safety, safeguards and physical protection. SAARA in coordination with KA.CARE and IAEA regulates the government utilities and makes decisions accordingly which includes many factors as describe in IAEA handbooks [23,24].

4. Conclusion

KSA's NEOM LINE city and the drive to advance the entire project through clean energy resources make this research possible. It was found that among the various vSMR designs, Westinghouse's eVinci has the lowest possible cost along with other features. The breakdown of each quarter for fuel cycle analysis predicts the normalized S-curve values. This indicates that the total capital cost and fuel cost must be identified as deterministic. Comparison of the levelized cost between the lowest cost SMRs (IMSR and SMART) with vSMR shows that the cost of vSMR is half that of the other SMRs. The concluded value for vSMR is 24.6 $/MWh which gives an indication that multiple units of this reactor if installed in similar capacity as per the LINE project requirement, it can provide both heat and electricity. The study shows that uncertainty calculations should be performed prior to the deployment of any research technology. The study paved the way for policy makers and investigators to consider the option of vSMR.

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.

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