Proceedings of the INMM & ESARDA Joint Annual Meeting
May 22-26, 2023, Vienna (Austria)

ASSESSING PROLIFERATION RISKS IN NEW NUCLEAR ENERGY COUNTRIES: THE CASE OF SMALL MODULAR REACTORS

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ABSTRACT

Several nuclear energy newcomer countries have become interested in small modular reactors (SMRs) as a nuclear energy source to meet growing electricity demand, given the heightened concerns about greenhouse gas emissions. While SMR technology lowers the threshold for newcomer countries, it can generate new uncertainties about future nuclear proliferation risks. Therefore, this study seeks to determine whether future SMR nuclear trade will contribute to nuclear proliferation, and how the risks can be mitigated. This research uses the Bayesian network (BN) approach in conjunction with surveys of experts to assess nuclear proliferation risks when newcomer countries deploy SMRs. In this study, we perform a comprehensive assessment of the general nuclear energy newcomer country in terms of non-proliferation infrastructure, the country's economic and commercial electric grid capacity, the unique characteristics of SMRs, enrichment and spent nuclear fuel management plans. By modeling the risks for future SMR deployment and clarifying the solutions, the findings of this research will provide recommendations for policymakers in the United States and abroad seeking to promote peaceful nuclear cooperation while reducing nuclear proliferation risks.

1. INTRODUCTION

With heightened electricity demand and energy security, more countries have become interested in nuclear energy to reduce greenhouse gas emissions. Specifically, the Russian invasion of Ukraine in 2022 has made European countries return to energy security as their main concern. Germany has extended the decommissioning schedule of two of its remaining three nuclear power plants (Reuters, 2022), and France has declared that it will open a renaissance era for the nuclear power industry (World Nuclear News, 2022). These announcements by Germany and France also aligns with the countries that have not been interested in nuclear energy but are now considering it as an alternative option to improve energy security.

In particular, the nuclear energy newcomer (NEN) countries[1] and major nuclear exporter countries recently have a growing interest in SMRs because SMRs have advantages than large commercial reactors in terms of governance, public perception, safety, and financial risk. SMRs can fundamentally be marketed as a cheaper, safer, and faster construction alternative to the large commercial reactors, and ideally complement intermittent renewable sources of zero-carbon

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[1] Nuclear energy newcomer countries in this study refer to countries that have not yet deployed a commercial nuclear power plant, but are currently interested in doing so and have contacted the International Atomic Energy Agency (IAEA) or other countries for assistance in launching a nuclear energy program.

electricity in the future. SMRs are also known to enhance nuclear security and safety by reducing the amount of plant area, implementing a passive safety system, and having a long refueling cycle in most core designs.

However, there are concerns on SMRs in terms of nuclear proliferation risk. Nuclear technology and materials inherently have "dual use" purposes. This implies that it can be used for civilian as well as military purposes. One area of potential concern regarding the NEN countries is their governance characteristics and political environment, which can have significant implications for nuclear safety, security, and spent fuel management. Many of these NEN countries scored low on regulatory quality, government effectiveness, control of corruption, and political stability (Nguyen and Yim, 2019; Lin, Bae and Bega, 2020). These scores imply vulnerabilities from the mismanagement and misuse of the technology. Although previous studies (Sagan, 2011; Fuhrmann, 2012) have pointed out that the evidence for obtaining civilian nuclear power to build a national nuclear weapons program is uncertain, such vulnerabilities of newcomer countries may introduce new uncertainties in non-proliferation compliance in the future. This could result in growing pressure on the international community to ensure the peaceful uses of nuclear technology. Lastly, the risks due to the external security threat cannot be ignored of the NEN countries, which are potential SMR clients.

Since SMRs are innovative and lower the barrier to adopting nuclear power programs in many countries, it is difficult to project the impacts of these reactors on the non-proliferation regime that will be adopted by the NEN countries. To address vulnerabilities and pressures of nuclear proliferation in the future nuclear trade and find solutions to mitigate those issues, this research offers a comprehensive assessment for proliferation risks under the future SMR era.

This study estimates the nuclear proliferation risks of the NEN countries with different perspectives of SMR types, domestic environments, and nuclear fuel cycle options. This study specifically uses the Bayesian network (BN), in conjunction with expert surveys since this study focuses on future prediction. This study aims to integrate the experts' opinions and guidance on nuclear proliferation issues from various perspectives, ranging from regions, experiences, and affiliated institutions. Additionally, this study strives to find solutions for mitigating the future risks arising from SMRs through the expert elicitation process. Therefore, the following two questions will be addressed in this study:

- ✓ How to estimate the nuclear proliferation risks associated with the deployment of different types of SMRs and nuclear fuel cycle options to the general NEN countries?
- ✓ What will be the solution for the nuclear proliferation risk?

2. METHODOLOGY

2.1 Bayesian network (BN)

This study uses the BN as a statistical method for assessing proliferation risks in conjunction with the expert surveys. The BN is one of the statistical methods to calculate probabilities for certain events occurring, given some evidence or historical dataset. It offers a method for utilizing causal understanding and representing knowledge in unknown domains. Previous studies have evaluated whether the BN could quantitatively model the proliferation timelines of some countries, using social, geopolitical, technological, political, and economic factors (Holcombe, 2008; Coles *et al.*, 2011).

The BN consists of two main parts: qualitative and quantitative. The qualitative part uses a directed acyclic graph, and the quantitative part uses probability distribution to specify stochastic relationships. The directed acyclic graph is composed of nodes and directed arcs (edges). Each node represents random variables, and each directed arc indicates statistical (informative) or causal dependencies between the random variables. Arcs are used to define kinship relationships or parent-child relationships. For example, as shown in Figure 1, the arc from X_1 to X_2 indicates that X_1 is the parent node of X_2 and X_2 is the child node (child). The edge therefore represents the cause (X_1) and consequences (X_2) between the nodes.

The BNs are generally used in analyzing low probability-high consequence events. Three types of probability data/evidence are used in the BNs: 1) prior probability, 2) conditional probability, and 3) posterior probability. Since the direction of the arcs in a BN determines the parent-child relationship between the nodes, the network is used to represent the joint probability distribution. The dependencies between the nodes are quantified by obtaining a conditional probability table (CPT) for each node, given its parent node, in a directed acyclic graph. When fully specified, BNs concisely represent the joint probability distribution using equation (1). For example, if the network is depicted as in Figure 1, a BN defines a joint distribution over X as a product of local conditional distributions, with each node being calculated using equation (2).

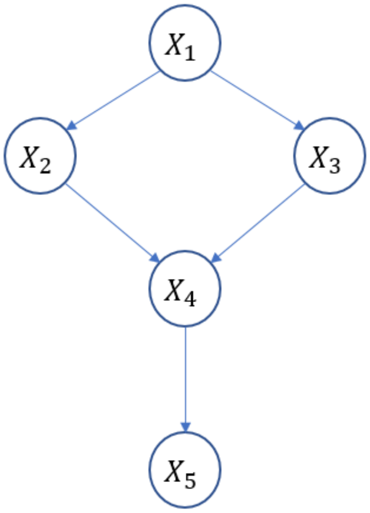

Figure 1 Example of the Bayesian network graph

$$\mathrm{P}(X_1 = x_1, \dots, X_n = x_n) = \prod_{i=1}^{n} p(x_i | x_{parents(i)}) \tag{1}$$

$$\mathrm{P}(X_1, X_2, X_3, X_4, X_5) = \mathrm{P}(X_1)\mathrm{P}(X_2|X_1)\mathrm{P}(X_3|X_1)\mathrm{P}(X_4|X_2, X_3)\mathrm{P}(X_5|X_4) \quad (2)$$

In addition, the BNs can be used to compute the posterior probabilities of subsets of nodes for which evidence is established on other subsets. The posterior probability refers to the probability of a particular event or node given the observed evidence or information. For example, if V and N are two random variables and there is clear evidence that V has occurred, the posterior probability of N can be determined from the occurrence of V and the evidence of the occurrence of V by following equation (3).

$$\mathrm{P}(\mathrm{N}|\mathrm{V}) = \frac{\mathrm{P}(\mathrm{N}) \times \mathrm{P}(\mathrm{V}|\mathrm{N})}{\mathrm{P}(\mathrm{V})} \quad (3)$$

In this study, we compare the relative proliferation risks of a general NEN country with those of the United Arab Emirates (UAE) when deploying small modular reactors (SMRs) or large reactors with different reactor types, and enrichment/spent fuel options in the BNs. We plan to assess which factors the experts think have the highest impact on the nuclear proliferation risks of the general NEN country by using posterior probability.

2.2 Construction of Bayesian network: Nodes

Our objective is to develop a comprehensive assessment tool for evaluating the NEN countries when deploying SMRs. In previous literature, Carless et al. (2021) employed the BN to assess risks associated with nuclear power plant deployment in specific NEN countries and compared these risks among selected countries. They designed the BNs to estimate nuclear weapons proliferation and nuclear security risks when deploying a Generation III+ reactor (VVER-1200) or SMR (HTR-PM) in 12 NEN countries. The nodes in their study include responsible user of nuclear power, energy needs, nuclear technological capabilities, reactor technology, type of ownership framework, nuclear fuel cycle, and enrichment.

Due to the flexibility and ease of updating additional nodes, we refine and add nodes to the previous study's BN model to better evaluate risks of nuclear weapons proliferation for a general NEN country deploying various types of SMRs or a large commercial light water reactor.

To assess the prior probability of a NEN country's capability to deploy SMRs or large commercial nuclear reactors, we set the following prior nodes: economic and commercial electric grid capacity, nuclear non-proliferation infrastructure and stability of risk environment, and available uranium reserves. These prior nodes are either renamed, newly added, or slightly modified from those used by Carless et al. (2021). This is done to make the prior nodes more appropriate for assessing comprehensive NEN countries.

The economic and commercial electric grid capacity node is designed with the understanding that countries with lower economic capacity face higher financial risks when building large commercial reactors. Therefore, it may be more advantageous to deploy SMRs. In terms of commercial electric grid capacity, a grid must have a capacity of at least 10 GWe to accommodate the addition of a single large commercial reactor with a capacity of 1 GWe. This is necessary to ensure that the grid does not collapse in case of a shutdown (equivalent to a typical large commercial reactor). As a result, deploying SMRs in the NEN countries with low electric grid capacity can be more practical than deploying large commercial reactors.

The non-proliferation infrastructure and stability of risk environment node is also included. Previous literature has demonstrated that the stability of external threats (i.e., enduring rivalry, frequency of militarized interstate disputes, and political stability) and high adherence to non-proliferation norms could reduce the proliferation risks (Singh and Way, 2004). For uranium reserves, a high amount of uranium reserves in a country is more likely to lead to the adoption of an open nuclear fuel cycle and enrichment capacity to maximize the use of a country's uranium reserves, which could indirectly affect the nuclear proliferation risks.

In these prior nodes, UAE is set as a baseline country to evaluate the relative capacities of deploying nuclear power plants in the NEN countries. This method is the same as Carless et al. (2021). The UAE is considered one of the most successful cases of nuclear power development in recent years, which has a high economic (i.e., gross domestic product, foreign direct investment) and grid capacity, and stable risk environment and high non-proliferation norms adherence (i.e., additional protocol) compared to the other NEN countries.

In this study, we include various intermediate nodes for nuclear power plant deployment, such as reactor type, ownership framework, spent nuclear fuel management plan, and enrichment option. To assess the impact of each type on nuclear proliferation risks, we consider three types of SMRs: light water reactor (LWR), high-temperature gas-cooled reactor (HTGR), and sodium fast reactor (SFR). We select different types of reactors for each country, such as Nuscale (United States) for LWR, HTR-PM (China) for HTGR, and ARC-100 (Canada), which is still under development, for SFR. To reflect concerns over the possibility of nuclear export sanctions against Russia following the Ukraine invasion, we choose the United States-designed AP1000 type as the large commercial reactor for our study, instead of Russia's VVER-1200 used in the previous study. By adding one type of large commercial reactor, we could see the experts' opinions on how they think the NEN countries will deploy SMRs compared to a large commercial reactor based on their capacities captured by the prior nodes. The details of the nuclear reactor types considered in this study are shown in Table 1. For the nuclear spent nuclear fuel management plan node, we include three categories: spent nuclear fuel retrieval, direct disposal (domestic open nuclear fuel cycle), and reprocessing (domestic closed nuclear fuel cycle). For enrichment node, we include two categories: domestic and international suppliers. A detailed explanation of each intermediate node value is provided in Table 2.

For the final output node, also known as the leaf node, nuclear proliferation risks are included as the aim of this study is to assess the relative proliferation risks posed by the NEN countries. The UAE is used as a baseline country in this node, as in the prior nodes. The UAE has implemented domestic legislation to permanently forgo the acquisition of uranium enrichment and plutonium reprocessing capabilities for nuclear power plant deployment. Additionally, the UAE has signed 123 Agreement with the United States, demonstrating high nuclear transparency (Guzanksy, 2015). This makes the UAE a benchmark as a nuclear energy-established country to evaluate the relative proliferation risks of newcomer countries. The relationships among nodes are based on Carless et al.

(2021), with a few modifications. The summary of BN nodes, values, and arcs used in this study is described in Figure 2.

Table 1 Information on SMRs and large commercial reactor used in this study (Data source: (IAEA, 2020)*)*

Reactor	**Type**	**Model**	**MWth**	**Uranium Enrichment in ^{235}U (%)**	**Fuel refueling interval (year)**
SMR	Light Water Reactor (LWR)	Nuscale	160	5 (Low enriched uranium)	6 (2 year/ cycle, and 3 cycles/assembly)
	High Temperature Gas Cooled Reactor (HTGR)	HTR-PM	500	8.5 (Low level of High Assay Low Enriched Uranium)	2.89 (1057 days- online refueling system)
	Sodium Fast Reactor (SFR)	ARC-100	286	10-17 (Average: 13.1) (High level of High Assay Low Enriched Uranium)	20
Large commercial reactor	LWR	AP1000	3400	4.8	4.5 (1.5year/cycle, 3cycle/assembly)

Table 2 Summary of the Bayesian network components for proliferation risks assessments

Category	Nodes	Node values and description
Prior nodes	Available uranium reserves	• High amount • Low or no amount
	Nuclear non-proliferation infrastructure and stability of risk environment	• Lower than the UAE • Same or higher than the UAE
	Economic and commercial electric grid capacity	• Less stable than the UAE • Same or more stable than the UAE
Intermediate nodes	Reactor	• Large commercial reactors: Large commercial reactors have a power output >700 MWe. In this study, I consider AP1000 (light water reactor) as a

		large commercial reactor. • SMR: SMRs have a power capacity of up to 300 ~ 500 MW(e) per unit. SMRs usually have attractive characteristics of simplicity, modularity, modularization, and enhanced safety and require limited financial resources
	Ownership framework	• Turnkey: The term "turnkey" means that the vendor will construct the entire nuclear power plant and ultimately give the client the "key," and the vendor is responsible for the design, construction, testing and meeting regulatory requirements. Historically, turnkey frameworks have been used in nuclear reactor markets. • Build-Own-Operate (BOO): The vendor is responsible for not only design and construction, but also maintenance, operation, fuel supply, and decommissioning. BOO models bring long-term sustainability and investment returns to stakeholders in the project. In this model, the vendor can earn investment returns during the operation of the power plant by selling electricity at the negotiated price. A representative example of this framework is the Akkuyu nuclear power plant currently under construction by Russia in Turkey through the BOO framework.
	Reactor type	• LWR (AP1000, Nuscale) • HTGR (HTR-PM) • SFR (ARC-100)
	Spent nuclear fuel management plan	• Spent nuclear fuel retrieval: Supplier/vendor countries retrieve the spent nuclear fuel from the client countries after it has cooled down in interim storage. The fuel is then reprocessed, and the separated highly toxic wastes (without fissile materials) are returned to the NEN countries. • Direct disposal (Open nuclear fuel cycle): NEN countries manage spent fuel by themselves. The spent fuel is not reprocessed and sent to interim storage near the reactor. After interim storage, the fuel will be in a permanent storage repository. • Reprocessing (Closed nuclear fuel cycle): NEN countries in this category can reprocess and recycle their spent nuclear fuel.
	Enrichment	• Domestic: NEN countries will have a nuclear enrichment facility.

		• International: The enriched uranium fuel will be supplied through international suppliers.
Leaf nodes	Nuclear weapons proliferation risks	• Lower than the UAE • Same or higher than the UAE

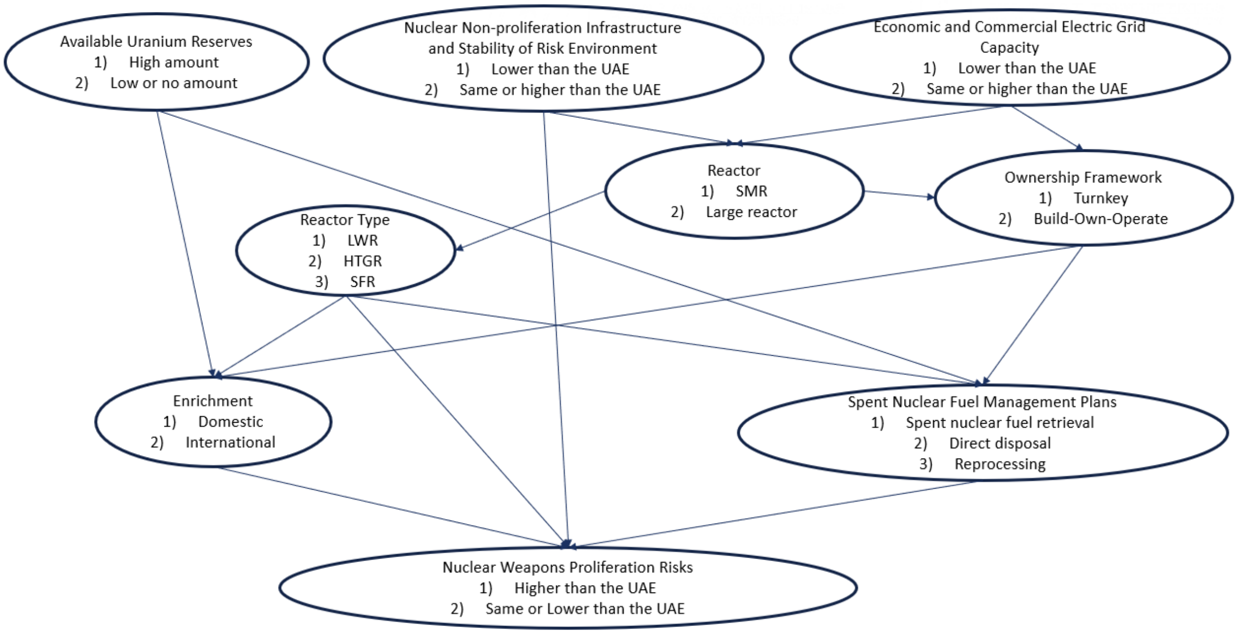

Figure 2 Bayesian network model in this study

2.3 Data acquisition: Expert survey

The calculation of predicted inference using BN depends on obtaining the CPT, which can be derived through historical data, expert knowledge, or a combination of both. Calculating the CPT using historical data is an effective option when a significant amount of data is available. However, in situations where historical data is absent or scarce, expert judgement can serve as a valuable tool for developing the CPT. Previous studies have demonstrated that expert judgement is a reliable approach for establishing the BN structure and node conditional probabilities in events where statistical data is unavailable. Expert judgement on CPT using the BN has been widely used in various fields for uncertain risk analysis and future predictions (Pollino *et al.*, 2007; Trucco *et al.*, 2008; Zhao, Wang and Qian, 2012; Christophersen *et al.*, 2018).

Given the limited incidents of nuclear weapons proliferation in the NEN countries and the limited experience with SMR deployments, developing CPTs using expert knowledge elicitation process is a suitable approach for this study. The BN with expert surveys have also been used in estimating the future proliferation and security risks associated with the deployment of nuclear power plants in newcomer countries (Carless, Redus and Dryden, 2021), as well as evaluating the physical protection capabilities of hypothetical SMRs (Prawira, 2019).

For the survey in this study, a larger sample size will help to ensure statistically robust results. The study sample will be selected based on experts' qualifications, expertise, and experience in the field of nuclear policy and/or nuclear technology. The experts must hold at least a B.S. in nuclear engineering, political science, or related fields and currently work on related issues. The minimum targeted sample size for this study is 30 experts, with at least 15 experts from established nuclear energy countries (countries with operational nuclear power plants) and 15 experts from newcomer nuclear energy countries. This stratified sampling approach will enable us to compare the perspectives of experts from different backgrounds and countries, ensuring that our results are representative of the global landscape.

It may be challenging for experts to evaluate the probability assessment of each node without explanation during the CPT assessment. Therefore, we will provide a reference table in this survey to facilitate the assessment of each intermediate node.

3. FUTURE WORK

Our study will utilize the BN model as the foundation of our data analysis strategy. Through the expert opinions collected via survey, we will calculate the conditional probabilities of proliferation risks. This BN model will also enable us to identify the most significant and sensitive factors that experts believe contribute to proliferation risks. In addition, we will assess which specific scenarios, combined with 1) the level of available uranium reserves in a country, 2) nuclear non-proliferation infrastructure and stability of risk environment, and 3) economic and commercial electric grid capacity (see Table 3) that can be correlated to proliferation risk for nuclear energy newcomer countries.

Table 3 Cases considered for this study with different categories of prior nodes

Case	Uranium reserves	Nuclear non-proliferation infrastructure and stability of risk environment	Economic and commercial electric grid capacity
1	High amount	Lower than the UAE	Lower than the UAE
2	High amount	Lower than the UAE	Same or higher than the UAE
3	High amount	Same or higher than the UAE	Lower than the UAE
4	High amount	Same or higher than the UAE	Same or higher than the UAE
5	Low or no amount	Lower than the UAE	Lower than the UAE

6	Low or no amount	Lower than the UAE	Same or higher than the UAE
7	Low or no amount	Same or higher than the UAE	Lower than the UAE
8	Low or no amount	Same or higher than the UAE	Same or higher than the UAE

Furthermore, we aim to identify disparities in perceptions of nuclear proliferation risk across different aspects, including experts from established and the NEN countries, as well as nuclear policy and technology professionals.

ACKNOWLEDGEMENT

This study is performed as part of Stanton Nuclear Security Fellow Program funded by the Stanton Foundation.

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