Accelerating Safe Small Modular Reactor Development in Southeast Asia

PLEASE CITE AS "Nian, V.; Ghori, A.; Guerra, E. M.; Locatelli, G.; Murphy, P. 2022. Accelerating safe small modular reactor development in Southeast Asia. DOI10.1016j.jup.2021.101330. pp.101330-101334. In UTILITIES POLICY - ISSN0957-1787 vol. 74"

Abstract

The emerging economies in Southeast Asia are facing challenges in achieving decarbonisation and energy resilience. Small modular reactors (SMRs) could represent a strategic option but are yet to be properly understood and communicated at the policy level, especially in terms of the favourable implications for energy security and economic and technical benefits, as well as inherent risks and mitigation strategies. With the flourishing designs and start-up companies driving potentially new business models for future nuclear power projects, we present a series of actionable recommendations for utilities and policymakers in Southeast Asia, together with an analysis on the importance of including SMRs as an option in the future energy mix.

Keywords

Small modular reactor; capacity building; independent nuclear advisory.

Background

The Association of South East Asian Nations (ASEAN) is home to about one in ten of the world's population. Their rapidly growing economies have driven the primary energy demand to 701 million tonnes of oil equivalent (Mtoe) in 2018, with such demand projected to grow at a rate of 2% per year, reaching 1110 Mtoe by 2040. The electricity demand in ASEAN is expected to double to about 730 terawatt-hours by 2040, with renewables collectively providing around a 25% share in the electricity sector fuel mix and coal stabilising to around 40% (IEA, 2019b).

Much of the economic growth of ASEAN relies heavily on a thriving industrial sector. Thus, energy consumption is characterised by high energy-intensity and continuous base-load power demand, presently provided by fossil-fuelled coal, oil, and natural gas power plants. As ASEAN Member States (AMS) look to transition from fossil fuels to clean energy, a critical question arises: how to provide reliable base-load power for growing and energy-intensive industrialised economies while transitioning to a clean energy future? Especially at the base-load level, ASEAN has limited options to diversify towards low-carbon electricity if nuclear energy were excluded from the energy mix (Nian and Chou, 2014). When large reactors were perceived as high-risk following the incident at Fukushima, debates followed about small modular reactors (SMRs) becoming a game-changer for ASEAN (Nian and Bauly, 2014).

The pre-feasibility study conducted by ASEAN Centre for Energy (ACE, 2018) in cooperation with NEC-SSN through the ACE-Canada Nuclear and Radiological Programme Administrative Support has identified Indonesia, Malaysia, the Philippines, Thailand, and Vietnam as the frontrunners to establish nuclear power programmes. The pre-feasibility study concluded:

(a) the importance of experience, sharing of best practices and capacity-building in nuclear safety, security, and safeguards, potentially through the ASEAN Network of Regulatory Bodies on Atomic Energy (ASEANTOM) as a regional platform,
(b) multi-agency cooperation in providing financial support and ensuring due diligence in nuclear power projects,
(c) establishing a Nuclear Energy Programme Implementing Organisation reporting directly to the Prime Minister's Office,
(d) building public acceptance, both within the country and around neighbouring countries,
(e) ensuring the independence of the nuclear regulator, and
(f) addressing nuclear legal and regulatory frameworks after making nuclear policy decisions.

SMRs, when deployed as serial, smaller distributed units, could represent a favourable option for ASEAN to address concerns over reliable and sustainable electricity supply (Nian and Bauly, 2014). With the pre-feasibility study further concluding that the frontrunners have established 2030-2035 as the target timeframe to "start enjoying the benefits of nuclear energy", it is time for utilities and policymakers to take a serious look into the policy implications associated with the developments in SMR technologies, to include project development and commercial/financing models, as these technologies become available to be deployed around the same timeframe.

Why is this important?

SMRs could completely disrupt the traditional concepts and approaches of nuclear power plant planning, project management, and financing.

Conventional large nuclear power plants (NPPs) present several challenging features, including lengthy development and construction schedules, multi-billion dollar total project costs and significant upfront outlays, and overall scale and complexity of project size and delivery (Locatelli and Mancini, 2012; Nian, 2017). Current reactor designs being deployed exceed 1000 MWe per unit, creating an "all or nothing" proposition for interested countries. However, SMRs are a new series of reactor designs in development, which challenge traditional notions about NPP project development. According to the International Atomic Energy Agency (IAEA, 2020), SMRs are generally smaller than conventional large reactors and are intended to be constructed in a factory setting and then shipped to the project site for final installation.

With such "beneficial" parameters, SMR projects are intended to have lower unitary costs and shorter construction periods, with factory assembly standardising the NPP offering (Mignacca and Locatelli, 2020). Such scenarios reduce the aggregate financing burden on the developer, reduce interest during construction, reduce the equity hold time between initial investment and revenue generation, and reduce the aggregate contingency needed in the financing plan (and, thus, less completion support). Smaller designs also create opportunities for scaling project development whereby demand growth can be matched more directly through the addition of additional units, as well as unlocking new deployment opportunities built around smaller grid sizes and potentially beyond electricity production (e.g., hydrogen production, desalination, and heat/steam for industrial applications).

Overall, by coupling a scaled-down product with enhanced safety features and with standardized plant designs and dedicated production facilities, SMRs can reduce project risks and financing challenges, thereby potentially making civilian nuclear technology more available and deployable to ASEAN countries.

A vendor-neutral assessment would be essential in the future, especially with SMRs, which could see a genuinely competitive market landscape with multiple companies offering a suite of different technologies and project delivery options.

The present propositions for SMRs could appear attractive to AMS (Nian, 2015), especially those constrained by land space and natural resources, to decarbonise the power sector while enhancing energy independence and self-sufficiency, all while supporting clean growth strategies. However, in order to enjoy such benefits, national-level assessments and science-based policies focused on the integration of SMRs in the national power sector must be first in place. Having those assessments and policies is especially important in the foreseeable future, where many designs, presently under development, become available for commercial deployment (IAEA, 2020).

National-level assessments would need to come from both strategic and technical perspectives. Strategically, policymakers would need to ensure that deploying SMRs or nuclear power, in general, is aligned with the country's energy priorities. With the goal of rapid industrialisation and urbanisation, ASEAN needs to evaluate the competitive low-carbon alternatives with SMRs included in the national or micro-level grids. Unlike the civilian nuclear power veterans in the world, like the USA, France, Japan, and China, ASEAN lacks a strong and qualified domestic industrial supply chain to support a civilian nuclear energy programme. As such, attention needs to be given to developing and enhancing relevant local industries, considering present and future needs for SMR development. At the same time, research and regulatory bodies, private industries, and non-governmental organisations need to work in synergy with support from the national governments to engage in public outreach and communication highlighting the true benefits and risks of nuclear power in ASEAN's context, all within a comparative context for the energy sector, which also recognizes both the attributes and shortcomings of other forms of generation.

The national technical assessment is required to assess the value of integrating SMRs in the national electrical grids. The national grid size is generally smaller for AMS than other larger countries like the USA and China. In some cases, like Indonesia, the Philippines, and Singapore, the national grids are very small and/or scattered across the territories. While SMRs, with their smaller generating capacities, could fit in well to the grid size of most ASEAN Member States (U.S. DOE, 2020a), there are issues with the load profile, quality of distribution lines, seismic stability, and other technical considerations that need to be evaluated. These evaluations could help ascertain the true cost of adopting SMRs at the central or localised grids from the perspective of infrastructure development, electricity market framework, and future planned economic activities.

If SMRs were to be offered as an "end-product", a vendor-neutral approach needs to be adopted by both utilities and national governments. "Vendor-neutral" refers to reliance on design information and technological advances generally found across a range of advanced reactors rather than relying on a particular vendor design. The IAEA's milestones approach "splits the activities necessary to establish the infrastructure for a nuclear power programme into three progressive phases of development", with the completion of each phase marked by a "milestone" (IAEA, 2015). This approach might become insufficient. For instance, it is critical for government entities and policymakers to conduct due diligence efforts in order to assess the capacity of the vendor to deliver the product, the maturity of its supply chain, the industrial partners supporting the supplier, the financiers (both debt and equity), and the project developer (if applicable). All of these considerations would need to be integrated into the national-level assessment and built upon science- and evidence-based policymaking approaches.

Applications-focused projects can open up new opportunities for hydrogen production, desalination, and industrial processes, as well as provide power to more remote communities.

Industrial heat application and nuclear cogeneration are ideas explored since the early days of nuclear power. These ideas are appealing because, for light water reactors, the most common nuclear power technology, the average efficiency is 33% for electricity production; therefore, two-thirds of all the thermal energy produced is wasted. With the SMRs and advanced Generation IV reactor technologies (GIF, 2014), the proposition is for the nuclear reactors to produce high temperature heat that can be used for industrial processes, such as hydrogen production and desalination (Locatelli et al., 2015). Because of the small size, there is potential for SMRs to co-locate with industrial facilities, subject to adjustments in nuclear safety regulations to account for such siting (Nian, 2017).

Cogeneration options to achieve load following (Locatelli et al., 2017) could be considered an economically viable option for AMS like Singapore (Nian and Zhong, 2020) to balance the demand for heat and electricity in industrial clusters. In the case of Singapore, due to scarcity of freshwater supply, desalination is relevant given the high household potable water price of approximately 2-2.7 $\$/m^3$ depending on usage (PUB, 2020). Hydrogen production is also potentially attractive, and the model of cogeneration to produce hydrogen can be further developed, especially with a view of future advanced SMR technologies (Locatelli et al., 2018).

Applications like desalination can be run off the electricity source itself; consequently, these applications-driven models can examine both the heat and electricity aspects of an SMR, to include off-peak applications under a constant-run model (whereby the SMR sends electricity into the grid during high demand / economically favourable conditions, and then uses the electricity in other cases (to include load following models with renewable generation) to run the cogeneration applications.

SMRs could represent a proposition for powering remote communities that currently rely on diesel generation, especially in the context of the Indonesian archipelago and off-grid villages in Malaysia, Thailand, Cambodia, and others. However, the commercial viability of such an application remains to be ascertained with the demonstration project such as the KLT-40S floating NPP dubbed Akademik Lomonosov (Nian, 2018).

What should policymakers do?

There are varied developments among AMS in nuclear research programmes and experience with nuclear research reactors, and there is no operating NPP in the region. While frontrunners in ASEAN have conducted work under the IAEA's milestone approach, there is a general lack of practical experience in commissioning and operating NPP, despite the existence of the Bataan nuclear plant in the Philippines.

Build strong domestic technical and regulatory competence in safety, security, and safeguards

The development of a domestic technical and regulatory competence in safety, security, and safeguards is a prerequisite for all nuclear programmes and projects. These are uncompromisable requirements expected by the international community and need to be considered at programme inception. With the emergence of SMR and advanced reactor technologies, additional focused considerations should be given to ensure an efficient and inclusive licensing approach as presented in (Sainati et al., 2015). In particular, licensing obstacles that have held back the introduction of advanced non-light water reactor technologies might include the lack of reference cases for novel technologies, the long duration and lack of predictability of the licensing progress, the national nature of the licensing process, and the need for internationally recognised standards. However, approaches are under development and can be promising to optimise the design and minimise the cost for introducing these promising technologies (NEI, 2019; U.S. NRC, 2020).

In addition, ASEAN should also give attention to effective long-term management of spent fuel and radioactive waste as recommended and detailed in the IAEA's milestone approach (IAEA, 2015).

Develop a programme based on standardisation and harmonisation

While in the early days of nuclear history, countries like the United States, then Soviet Union, and the UK, developed mostly independently, their own technical and regulatory standards, such an approach is no longer advisable for newcomer countries, especially in the context of SMRs, where standardization and regulatory harmonization will facilitate more rapid deployment of the technology. Such rapid deployment is essential if ASEAN countries intend to employ clean growth strategies to address development needs and climate change considerations.

Develop a "knowledgeable customer" capability

Becoming a "knowledgeable customer" (IAEA, 2015) is essential for a newcomer country to manage the NPP as an owner/operator and to have a competent regulatory authority to oversee the NPP from a safety perspective. The experience of the United Arab Emirates in building up domestic nuclear competence (WNA, 2020) shows how newcomer countries can efficiently and effectively embark on a nuclear programme by leveraging international experience from both organizations such as the IAEA and other countries with established nuclear programmes and vendors. Such knowledgeable customer capability is a significant human resources endeavour for the newcomer country. Particularly during the early stages of the nuclear power programme development, a newcomer country can enhance its capabilities more rapidly by employing external subject matter experts as the country develops its own personnel capacity over time.

Ensure transparency and diligence in project assessment

Commitment to international nuclear regimes, covering the areas of safety, security, and safeguards, and nuclear liability, establishes the intent of a nation's nuclear power programme to adhere and be guided by the internationally recognised system for the nuclear power industry. This commitment to international best practices enhances the reputation of a country's nuclear power programme. In addition, cooperation and coordination with international organisations like the IAEA ensure transparency vis-à-vis the international community and facilitate external diligence of the programme (and any NPP thereunder) by both the international community and project participants (e.g., financiers).

Collaborate both regionally and globally; learn from the experiences of others

The global nuclear power industry has a unique level of interdependency. Information exchange and standardisation serve to facilitate prudent industry practices. For newcomers in ASEAN, sharing information is essential when importing technologies and experiences from established vendors. Despite the differences in national circumstances, AMS face common challenges at both individual country-level and the regional level when developing domestic nuclear industries. Due to AMS' proximity and the regional geopolitical landscape, information sharing at a regional level also offers a form of assurance as a "good neighbour". In the context of the ASEAN Power Grid Integration Project (IEA, 2019a), leveraging resources and standardising project development efforts can facilitate more rapid deployment of technologies to meet the needs of the countries in question. Furthermore, undertaking a robust "lessons learned" analysis – both positive and negative – can mutually benefit all AMS.

Leverage an independent advisory panel for added assurance on technology and project assessment, coupled with collaborative development among interested countries

The early stages of programme and project development are critical to project success (Babaei et al., 2021). However, for newcomer countries, these early stages are the most challenging, as experiential knowledge is lacking within the country and financial resources are hard to justify (given that commercial operation of the unit is so far into the future). Further, newcomer countries are at an information deficit relative to nuclear reactor vendors, making it difficult to carry out a robust assessment of technology choices, cost parameters, and project schedules (Mignacca et al., 2020).

Given barriers to entry, there is the opportunity for regional cooperation, whereby interested newcomer countries pool their resources to engage an independent advisory panel (IAP). The IAP could be comprised of a small group of subject matter experts across various disciplines (technical, commercial, financial, and legal) and international backgrounds, with the IAP not being tied to any particular technology or representing the interests or perspectives of any particular foreign country. ASEAN members would be able to leverage the IAP to produce work on matters of common interest and to serve as a resource for technology and project assessments, particularly in the development of "lessons learned" analysis and project risk registers. Given the international nature of the nuclear industry and the sourcing of technology and project delivery services that are necessary for successful NPP development, having an available, shared resource for interested ASEAN countries will create both cost and schedule efficiencies, as well as provide a resource for training and knowledge sharing at the country level. The IAP can also serve as an agent for standardisation and harmonisation, which will enhance the deployment of SMRs within the ASEAN region.

Develop project models that demonstrate commercial and financial viability

Ongoing examples in other jurisdictions, such as Canada, China, Russia, the United Kingdom, and the United States, continue to confirm the vital and multiple roles the government needs to play in providing financial and other support to advance design and development to deliver First-of-a-Kind SMRs. These governments have either developed SMRs as national programmes (Russia and China) or are crafting financing models that integrate multiple roles for the government -- ranging from co-investor, debt guarantor, debt provider, and off-taker of electricity generated.

In the example of Russia and China, the KLT-40S and HTR-PM respectively are national SMR projects enjoying the full regulatory, policy, and financial support from each government. In the USA and Canada, federal, provincial, and municipal agencies support the deployment of SMRs (the NuScale-UAMPS project at Idaho National Laboratory is one example). Following the Energy White Paper published by the UK Department of Business, Energy, and Industrial Strategy (BEIS, 2020a, b), Rolls-Royce has received funding from both the UK government and private investors (WNA, 2021). The Advanced Reactor Demonstration Programme provided a total of USD 2.5 billion in funding to X-energy and TerraPower to develop high temperature gas-cooled reactor and Natrium reactor technology, respectively (U.S. DOE, 2020b). The floating nuclear reactor space saw Seaborg Technologies supported by private sector investment (Starn, 2020) and Core Power with both private and public sector funding (Cision, 2021) in developing molten chloride reactor technologies independently.

In the ASEAN context, national governments should stand ready to support an already commercially viable SMR technology by taking an equity stake in the project and/or directly providing debt or guarantees to mobilise private sector co-investment and co-financing. In fully or partially liberalised electricity markets, utilities and relevant government departments need to cooperate in deciding the right "go-to-market" frameworks for nuclear electricity to ensure maximum economic benefits from SMRs. This need is especially apparent when a "fleet" of reactors is deployed to maximize cost savings and optimize the levelized cost of electricity generation from the fleet. In addition, the host government could also consider incorporating initial SMR projects into their regulatory asset base with clearly defined investment return metrics to attract private sector institutional equity and debt financing.

Develop stakeholder engagement strategies to position nuclear power within clean growth strategies.

The only way for SMRs to enter into the national energy mix is for policymakers from ASEAN countries to include SMRs as part of national energy and decarbonisation strategies. This policy will allow developers and investors to evaluate SMRs as a low-carbon energy source. Including SMRs as part of the national energy strategy can be done in four key steps.

- First, perform a nationwide market assessment which will serve as a first screen to address the need and market readiness for SMRs. The market assessment will address critical aspects of programme development relative to energy needs, such as the condition and necessary investments for grid infrastructure (decommissioning timeline of existing fossil plants and demand growth) a study of public perception and the plan to improve acceptability and an evaluation of the existing legal and regulatory energy framework. This initial market assessment will provide a sense of timing and legislative effort to develop SMR projects.
- Next, once a positive outlook is obtained from the market assessment, a nationwide safety assessment would follow, considering the life cycle of an SMR project through all phases and aspects, including construction, operation, fuel transport and disposition, emergency planning, and decommissioning. This evaluation will provide an in-depth understanding of how SMR safety features would address the nation's natural and human-made hazards.
- Then, a national strategy can be established that considers energy needs for industrial and economic development, along with follow-up actions for site-specific safety assessments conducted in accordance with well-established international standards.
- Finally, an analysis of economic and financial viability would be done, including the development of a project risk register and project development plan (and timeline).

This 4-step process towards a national energy strategy should be developed in collaboration with international energy experts and relevant government departments of AMS. A national strategy should include SMRs as "zero carbon energy", which can unlock fiscal and financing tools, such as tax credits, carbon credits, and green financing (such as bonds and portfolio allocations requiring green investments). These tools will, in turn, facilitate SMR development, as they have the potential to enhance both project economics and financing techniques.

What is next for SMRs?

A national energy strategy with the inclusion of SMRs as a clean zero-carbon energy option will allow investors and developers the freedom to consider SMRs as part of the site- and application-specific evaluations along with other energy sources. Policymakers have the power to take this initial leadership step in developing a national energy strategy inclusive of SMRs and, thereby, paving the way for industrial growth and a transition to a sustainable and clean energy future.

Given the ASEAN regional geographical and geopolitical landscape, regional cooperation in nuclear safety and security is as important as it is difficult. The establishment of an IAP can help facilitate regional cooperation by providing independent and vendor-neutral recommendations that consider the collective good of the ASEAN region. Regional groupings, such as the ASEAN Network of Regulatory Bodies on Atomic Energy dubbed ASEANTOM and ACE, can be potential proponents of the IAP, further building credibility and facilitating sharing of experiences in NPP project development and financing.

Acknowledgement

This policy note is produced from a virtual workshop on the “Opportunities and Challenges in Deploying Small Modular Reactors in ASEAN” organised by the Energy Studies Institute, National University of Singapore, on 3 September 2020.

References

ACE, 2018. Pre-Feasibility Study on the Establishment of Nuclear Power Plant in ASEAN. ASEAN Centre for Energy, Jakarta, Indonesia.
Babaei, A., Locatelli, G., Sainati, T., 2021. What is wrong with the front-end of infrastructure megaprojects and how to fix it: A systematic literature review. Project Leadership and Society 2, 100032.
BEIS, 2020a. The Energy White Paper: Powering our Net Zero Future, in: Department for Business, E.I.S. (Ed.). UK National Archives, London, UK.
BEIS, 2020b. The Ten Point Plan for a Green Industrial Revolution, in: Department for Business, E.I.S. (Ed.). UK National Archives, London, UK.
Cision, 2021. Southern Company signs agreement with U.S. Department of Energy to demonstrate world's first fast-spectrum salt reactor in collaboration with TerraPower and Idaho National Laboratory, PR Newswire. Cision US Inc., Chicago, Illinois, USA.
GIF, 2014. Technology Roadmap Update for Generation IV Nuclear Energy Systems. Generation IV International Forum, p. 66.
IAEA, 2015. Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series. International Atomic Energy Agency, Vienna, Austria, p. 79.
IAEA, 2020. Advances in Small Modular Reactor Technology Developments, A Supplement to IAEA Advanced Reactors Information System (ARIS), 220 ed. International Atomic Energy Agency, Vienna, Austria, p. 354.
IEA, 2019a. Establishing Multilateral Power Trade in ASEAN, Paris, IEA. International Energy Agency, Paris.
IEA, 2019b. Southeast Asia Energy Outlook 2019, Paris, IEA. International Energy Agency, Paris.
Locatelli, G., Boarin, S., Fiordaliso, A., Ricotti, M.E., 2018. Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: A techno-economic analysis. Energy 148, 494-505.
Locatelli, G., Boarin, S., Pellegrino, F., Ricotti, M.E., 2015. Load following with Small Modular Reactors (SMR): A real options analysis. Energy 80, 41-54.
Locatelli, G., Fiordaliso, A., Boarin, S., Ricotti, M.E., 2017. Cogeneration: An option to facilitate load following in Small Modular Reactors. Progress in Nuclear Energy 97, 153-161.
Locatelli, G., Mancini, M., 2012. Looking back to see the future: building nuclear power plants in Europe. Construction Management and Economics 30, 623-637.
Mignacca, B., Locatelli, G., 2020. Economics and finance of Small Modular Reactors: A systematic review and research agenda. Renewable and Sustainable Energy Reviews 118, 109519.
Mignacca, B., Locatelli, G., Sainati, T., 2020. Deeds not words: Barriers and remedies for Small Modular Nuclear Reactors. Energy 206, 118137.
NEI, 2019. Risk-Informed Performance-Based Technology Inclusive Guidance for Advanced Reactor Licensing Basis Development. Nuclear Energy Institute, Washington, D.C., USA.
Nian, V., 2015. Progress in Nuclear Power Technologies and Implications for ASEAN. Energy Procedia 75, 2852-2858.
Nian, V., 2017. The prospects of small modular reactors in Southeast Asia. Progress in Nuclear Energy 98, 131-142.
Nian, V., 2018. Nuclear Power Becomes Critical to Arctic Dominance, Oilprice.com. OilPrice.com, USA.

Nian, V., Bauly, J., 2014. Nuclear Power Developments: Could Small Modular Reactor Power Plants be a “Game Changer”? – The ASEAN Perspective. Energy Procedia 61, 17-20.
Nian, V., Chou, S.K., 2014. The state of nuclear power two years after Fukushima – The ASEAN perspective. Applied Energy 136, 838-848.
Nian, V., Zhong, S., 2020. Economic feasibility of flexible energy productions by small modular reactors from the perspective of integrated planning. Progress in Nuclear Energy 118, 103106.
PUB, 2020. Water Price. Public Utilities Board, Singapore.
Sainati, T., Locatelli, G., Brookes, N., 2015. Small Modular Reactors: Licensing constraints and the way forward. Energy 82, 1092-1095.
Starn, J., 2020. Danish Nuclear Startup Taps Billionaire for Asian Reactor, Bloomberg. Bloomberg L.P., New York City, USA.
U.S. DOE, 2020a. 4 Key Benefits of Advanced Small Modular Reactors. United States Department of Energy, Washington DC, USA.
U.S. DOE, 2020b. INFOGRAPHIC: Advanced Reactor Development. United States Department of Energy, Washington DC, USA.
U.S. NRC, 2020. Guidance for a Technology-Inclusive, Risk-Informed, and Performance Based Approach to Inform the Content of Applications for Licenses, Certifications, and Approvals For Non-Light-Water Reactors, Regulatory Guide 1.233. United States Nuclear Regulatory Commission, USA.
WNA, 2020. Nuclear Power in the United Arab Emirates. World Nuclear Association, London, UK.
WNA, 2021. Rolls-Royce secures funding for SMR deployment, World Nuclear news. World Nuclear Association, London, UK.