SEISMIC ISOLATION OF ADVANCED REACTORS: A PATHWAY TO STANDARDIZATION AND TO CLIMATE TARGETS

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EXTENDED ABSTRACT

A range of innovative low-carbon technologies will be needed very soon to achieve the Paris Agreement and limit global temperature rise this century to below 2 degrees Celsius below pre-industrial levels, with the aspirational goal to limit the increase to 1.5 degrees Celsius. Nuclear power could play a very significant role in achieving the goals of the Paris Agreement, decarbonizing the global economy, and meeting future demands for energy (e.g., Buongiorno *et al.* (2018), Partanen *et al.* (2019), IEA (2019), ETI (2020), Ingersoll and Gogan (2020), IAEA (2020a; 2020b; 2020c)), and it is a subject of this paper. At the time of this writing, nuclear power represents about one quarter of the global low-carbon electricity production (EMBER, 2023).

ETI (2020) deconstructed the capital cost of nuclear projects in the United States and Western Europe, and elsewhere in the world. The data suggests that aside from the higher direct costs of materials, equipment, and labor in the United States and Western Europe, the long build times of First-of-a-Kind (FoaK) projects lead to substantially greater time-based indirect costs (e.g., engineering, supervision, project management, rental site infrastructure), greater interest payments, and much higher interest rates due to project risk. The high cost, budget overruns, and time delays for FoaK plants have stymied the deployment of nuclear energy at scale (i.e., Nth-of-a-Kind (NoaK) construction) in the United States. The cost and time savings associated with *learning from doing* and *standardization* have not been realized in the nuclear industry in the United States and Western Europe.

Malhotra and Schmidt (2020) described the fundamental differences in carbon-technology uptake using the typology of Fig 1. Type 1 technologies access large and growing international markets, spurring continued innovation, because they are simple, standardized, and mass produced. Type 2 technologies "…provide opportunities for national green industrial policies fostering technological adaptation, and participation in global value chains." Type 3 technologies require "…a combination of national green industrial policies and measures to promote international coordination for inter-project and inter-context learning at a regional or global scale." The authors note that the "…need for international coordination increases as one moves to the top-right of the figure." Complex, customized systems are expensive and challenging to deliver: the nuclear power experience in the United States and Western Europe. So how do we move from complex, customized (FoaK) nuclear construction (Type 3, top right in Fig 1) to simple, standardized (NoaK) standardized construction (Type 1, bottom left in Fig 1) and tackle climate change?

The advanced nuclear reactors being developed in the United States are fundamentally different from the large light water reactors in the US operating fleet, offering a range of power outputs from 1 MWe to 300 MWe, using accident tolerant fuels, coolants other than water enabling operation near atmospheric pressure, and passive safety systems. The wide range of power outputs of these advanced reactors makes possible the repowering of coal and gas plants in the US and abroad. To repower the 250 GWe (2 TWe) of coal in the US (global) will require the design, licensing, and construction, of 1000+ (10,000+) advanced reactors. Simple, standardized advanced reactors is the only nuclear-energy pathway to decarbonizing this energy sector.

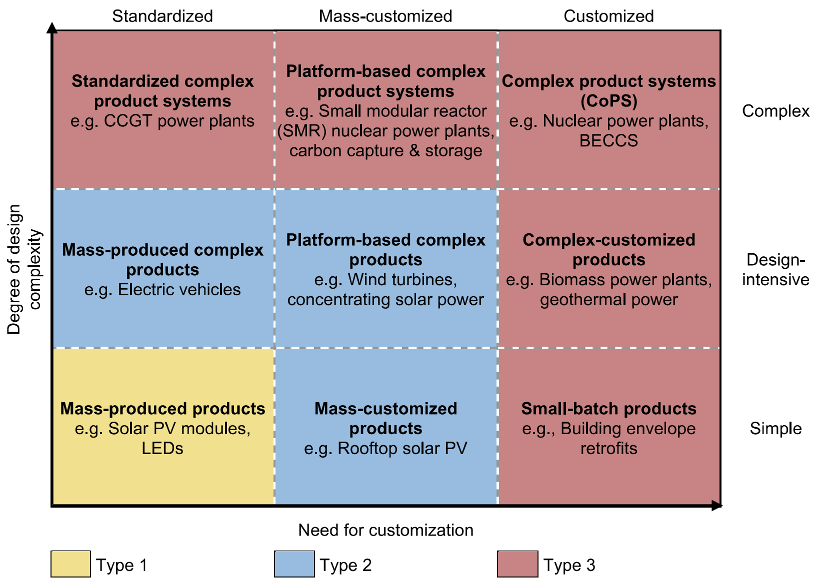


Figure 1. Binning of clean energy technologies based on design complexity and need for customization (adapted from Malhotra and Schmidt (2020)).

The seismic load case is a key contributor to the complexity and customized construction of US nuclear power plants (Parsi *et al.*, 2022). The near-surface geology and seismic hazard are different at each power plant site, requiring site-specific geotechnical investigations, probabilistic seismic hazard analyses, seismic soil-structure-interaction analysis, design, engineering, equipment qualification, and licensing: all thwarting standardization. The impact of the seismic load case on direct and indirect cost, and the standardization it thwarts, must either be substantially reduced or eliminated to deploy advanced reactors at the scale needed to support decarbonization. Seismic isolation can mitigate the impact of the seismic load case on safety-class structures, systems, and components and is, in my opinion, the pathway to standardized advanced reactors: an idea first proposed by Gluekler *et al.* (1991) but never acted upon.

The benefits of seismically isolating nuclear reactors, in terms of reduced seismic demands and risk, are well and long established (e.g., Tajirian *et al.* (1989), Tajirian (1992), Tajirian and Patel (1993), Clark *et al.* (1995), Aiken *et al.* (2002), Huang *et al.* (2008; 2009; 2011a; 2011b), Kumar *et al.* (2015; 2017a; 2017b), Yu *et al.* (2018)). (Earthquake-simulator experiments on isolated advanced reactors were undertaken by Professor Kelly at the University of California, Berkeley in the late 1980s when the author and a few others in the audience with grey hair were PhD students.) Despite the benefits of seismic isolation being well known, it has yet to be applied to a nuclear power plant in the US, in part due to a lack of new builds. (Two nuclear power plants, in Cruas, France and Koeberg, South Africa were seismically isolated in the early 1980s to enable the re-use of a French design developed for a site of lower seismic hazard: an approach indirectly pursued here.)

In the late 2000s, the two key impediments to industry's implementation of seismic isolation in NPPs were: 1) a lack of technical guidance and standards for analysis and design of seismically isolated NPPs, and its associated regulatory and financial risks, and 2) a lack of data on the financial costs and benefits of seismic isolation. Both impediments have been addressed. Tools and guidelines for base isolation of nuclear facilities have been developed through research projects funded by the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC). Consensus standards, ASCE/SEI 4-16 (ASCE, 2017) and ASCE/SEI 43-19 (ASCE, 2021), now include chapters specific to seismic isolation. Three technical reports on the analysis and design of seismically isolated nuclear power plants have been published by the NRC: 1) NUREG/CR-7253, Technical considerations for seismic isolation of nuclear facilities (Kammerer *et al.*, 2019), 2) NUREG/CR-7254, Seismic isolation of nuclear power plants using sliding bearings (Kumar *et al.*, 2019a), and 3) NUREG/CR-7255, Seismic isolation of nuclear power plants using elastomeric bearings (Kumar *et al.*, 2019b). A topical report on the seismic isolation of advanced reactors, written to enable analysis, risk-based design, and licensing, is being submitted to the NRC. Journal articles, conference papers, and technical reports support and complement the standards, with many identified in Whittaker *et al.* (2018). Studies on the seismic isolation of safety-class equipment in NPPs have been completed and published (e.g., Lal *et al*. (2023a; 2023b), Mir *et al*. (2022; 2023a; 2023b)) and outcomes will be included in future editions of ASCE/SEI 4 and ASCE/SEI 43.

The impact of seismic isolation on the cost of advanced reactors is being quantified. Studies funded by the Electric Power Research Institute and the U.S. Department of Energy (e.g., Lal *et al*. (2020; 2022)) quantified the reductions in the capital cost of key safety-class equipment, in two very different types of reactors, made possible by seismic isolation and standardization: factors of 3 to 5, depending on the site seismicity. Fig 2 presents sample results for a reactor vessel (RV) and a steam generator (SG) in a molten chloride fast reactor for sites characterized by peak horizontal ground acceleration (0.3g and 0.5g): compare the normalized FoaK conventional and NoaK isolated costs to judge the reductions in capital cost of equipment.

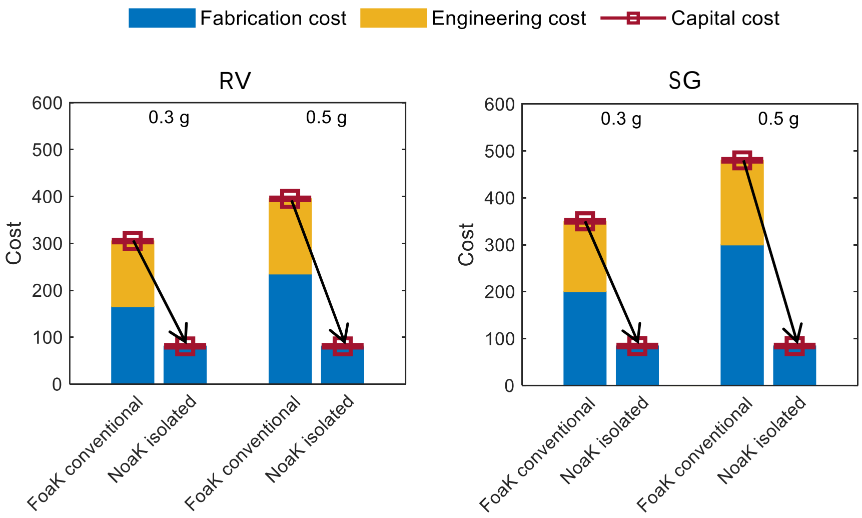
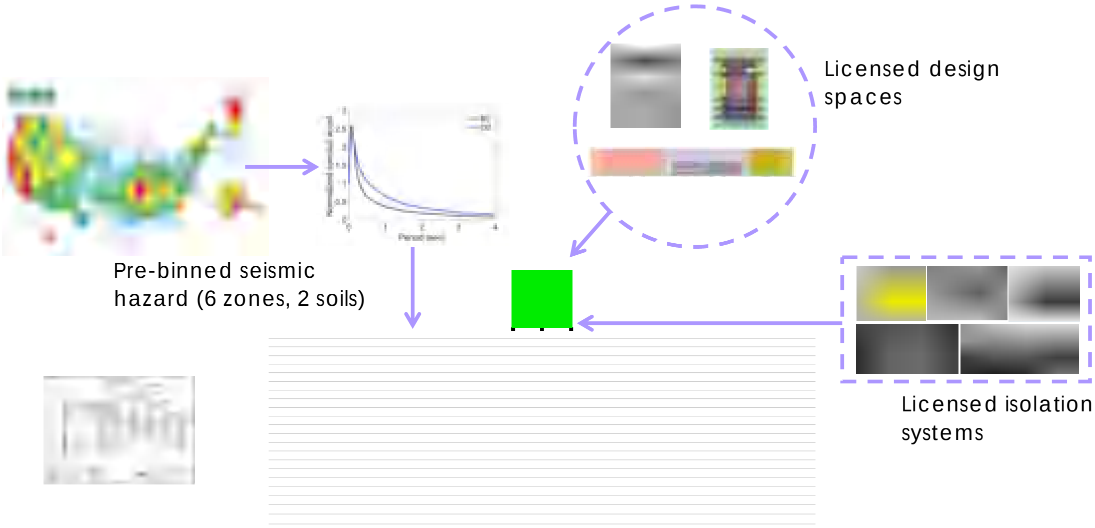


Figure 2. Capital cost of safety-class equipment in a molten chloride fast reactor, RV = reactor vessel, SG = steam generator (adapted from Lal *et al.* (2022)).

Quantifying the percentage reduction in capital cost of advanced reactors enabled by standardization and seismic isolation is a work in progress. The goal is cartooned in Fig 3: standardized reactor buildings and isolation systems, all pre-licensed by the NRC, with an adequate treatment of other external hazards, including flooding and wind-borne missile impact. The customer selects her/his site and a reactor type. Soil-structure-interaction analysis will not be needed for isolated advanced reactors, enabling the use of surface free-field United States Geological Survey (USGS) seismic hazard data requiring only location coordinates and site-specific geotechnical studies. The site and reactor type will dictate the choice of a pre-licensed isolation system.

The increment in cost attached to additional excavation (if needed), casting of a foundation and pedestals, and supply of the isolation system, is expected to be a small percentage of the building construction cost, with preliminary estimates available in Yu *et al.* (2018). The percentage reduction in the cost of the building framing will be reactor specific and may be relatively small because component thicknesses might be driven by non-seismic considerations such as shielding around the reactor vessel and protection from wind-borne missiles, affecting the building envelope. However, the standardization of the building framing will enable the use of modular construction, including precast reinforced concrete, driven by innovative design approaches used in non-nuclear construction sectors such as Design for Manufacturing and Assembly.

The greatest reductions in capital cost will accrue from the de-engineering of the project and the standardization of all components above the foundation supporting the pedestals and isolators and dampers. Eliminating the need for site-specific probabilistic seismic hazard assessment, soil-structure-interaction analysis, design of structures, systems, and components (aside from the foundation), probabilistic risk assessment and release calculations, and licensing, will cut 5+ years from the schedule for design and construction, drastically reducing interest rates, financial risk, and indirect costs. This is the plan to move from complex, customized (FoaK) nuclear construction (Type 3, top right in Fig 1) to simple, standardized (NoaK) standardized construction (Type 1, bottom left in Fig 1), tackle climate change, and do our part to achieve the Paris Agreement.



1) Site selected. 2) Pick a licensed heat source (MWe). 3) Pick a licensed isolation solution. 4) Price time and construction. 5) Evaluate alternatives and iterate on 2, 3, and 4.

Figure 3. Simple, standardized, safe, inexpensive advanced reactors.

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