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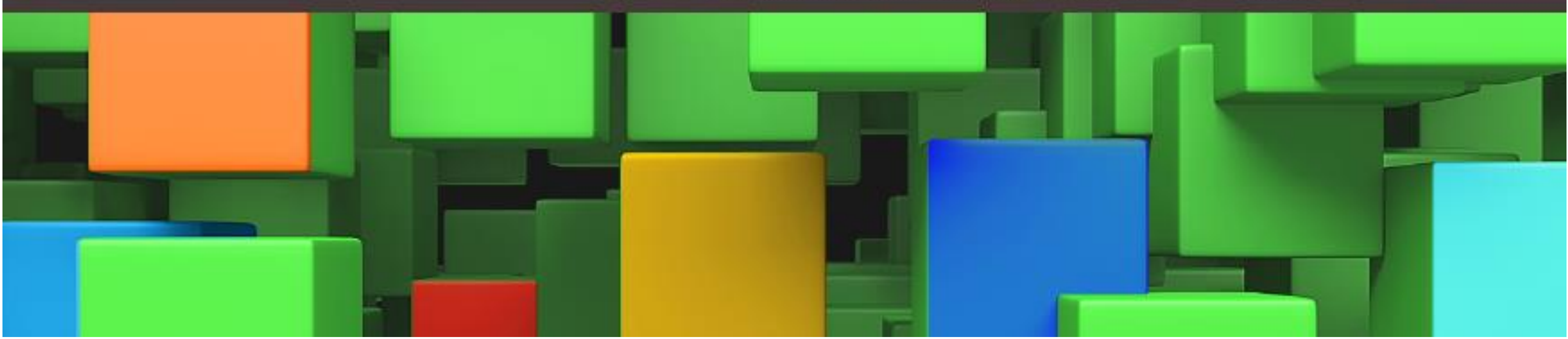
ADVANCED NUCLEAR TECHNOLOGY COST REDUCTION STRATEGIES AND SYSTEMATIC ECONOMIC REVIEW

COST REDUCTION STRATEGY #2: DESIGN – MODULARITY AT SCALE

September 2022



Foreword and acknowledgements

The present study was written by Efe G. Kurt and David E. Shropshire from the Idaho National Laboratory in the United States under the guidance of the Generation IV International Forum (GIF) Economic Modelling Working Group (EMWG) chaired by Fiona Reilly (United Kingdom), Megan Moore (Canada) and David Shropshire (USA). The authors wish to thank Megan Moore, Sergey Panov and KyungSoo Yoon for their insightful reviews and comments, which improved the quality of the report.

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List of abbreviations and acronyms

ANTSER	Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review
BOP	balance of plant
CF	cost factor
CPI	cost performance index
D&D	decommissioning and demolition
DoM	degree of modularization
EMWG	Economic Modelling Working Group (GIF)
FOAK	first of a kind
Gen-IV	Generation IV (reactor)
GIF	Generation IV International Forum
HTGR	high-temperature gas reactor
LWR	light water reactor
MWe	megawatt electric
NASA	National Aeronautics and Space Administration
NOAK	n^{th} of a kind
NPP	nuclear power plant
OCC	overnight construction cost
O&M	operation and maintenance
PWR	pressurized water reactor
RD&D	research, development and demonstration
SC	steel-plate composite
SCFR	sodium-cooled fast reactor
SFR	sodium-cooled fast reactors
SMR	small modular reactor
SSC	structure, system, component
TRISO	tristructural isotropic (fuel)
TRL	technology readiness level
USDOE	United States Department of Energy
USNRC	United States Nuclear Regulatory Commission

Executive summary

Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review (ANTSER) uses a methodological framework for evaluating nuclear cost reduction strategies. ANTSER has been described and implemented in detail, with an initial study related to the design of advanced nuclear power plants that addresses functional containment.

The present study adds to the ANTSER framework through an investigation of modularity for nuclear energy applications at different scales. Modularity can include the incorporation of all major safety-significant systems – within one module, standardized modules and factory fabricated modules – the capacity to add modules to increase power output and the consolidation of components resulting in less on-site construction. Modularity is a topic of interest in the commercial nuclear energy sector with the emergence of small modular reactors. However, the economic viability of these reactors has not been not proven to date. Focusing on reactor modularity alone is insufficient to improve the cost competitiveness of nuclear energy technologies. Historically, modularity has been limited to the balance of plant for large-scale nuclear plants, such as steel-plate composite walls. These technologies have achieved limited success because of the need for extensive on-site capabilities. Modularity applications for small- to medium- and micro-scale plants are less well-known given their limited deployment.

Modularity options for traditional nuclear energy deployment have been limited as a result of conventional light water reactor safety requirements, such as those related to high-pressure retaining, heavy and robust containment structures. However, a relatively new regulatory approach called "functional containment" – the focus of ANTSER Cost Reduction Strategy No. 1 – has the potential to allow less expensive and more flexible designs. Functional containment provides flexibility in design and deployment based on risk-informed and performance-based criteria so that reactors are not over designed. The non-nuclear industry has successfully used modular design approaches in automotive, aerospace, chemical processing, building construction and ship building. These industries have shown that modular construction reduces construction time by around 30%-50% compared to the conventional stick-built approach. Using a similar approach, through functional containment balanced with safety requirements, the nuclear industry could also reduce construction times and costs.

This study produces ANTSER cost reduction strategy no. 2, focusing on the use of modularity approaches to reduce the cost of Generation IV nuclear technologies. The study surveys the literature on modularity and describes the different ways that modularity has been used or considered for nuclear plants. Lessons learned from previous uses of modularity in the nuclear industry are used to inform readers on challenges and opportunities involved in extending uses to advanced nuclear technologies. Modularity approaches are surveyed for the highest potential to reduce costs for large-, small-, medium- and micro-scale nuclear reactors. Successful modularization approaches from other industries are considered from the perspective of their potential transferability to the nuclear sector. The functional containment design approach is explored as a means for designers to rethink how modularity is used in advanced nuclear technologies. Modular approaches, from large to very small scales, and balance-of-plant options are described in terms of their cost reduction potential; their technical readiness and their research, development and demonstration needs.

Introduction

The Generation IV International Forum (GIF) Economic Modelling Work Group (EMWG) has developed a systematic economic review process called Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review (ANTSER). The anticipated outcomes of efforts under ANTSER include making GIF reactor developers aware of cost reduction opportunities for nuclear designs, construction, operation and maintenance; identifying and conducting specific research activities to reduce advanced nuclear reactor costs; and sharing the results with the nuclear energy community.

Additionally, the results and developed methodologies under ANTSER can inform the design and selection of future cost reduction demonstration projects. Different areas of interest have been determined for potential cost reduction strategies, including design, manufacturing, construction and project management. A report (see Shropshire et al., 2021b) was published on the key area of functional containment as the initial ANTSER cost reduction strategy (see Table 1).

Functional containment refers to the set of barriers designed to prevent any release of radioactive material to the environment. The functional containment approach provides an opportunity for innovative alternatives to the traditional containment structure while maintaining (or ideally improving upon) safety and performance. Such a gain in design and cost reduction is enabled by the inherent advantages of advanced nuclear reactor and fuel designs. The approach also combines innovative alternatives to prevent the release of radioactive materials, protecting against external hazards and producing site-independent designs, such as seismic isolators, underground embedment, accident-tolerant fuels and passive safety systems. Functional containment can thus shift the nuclear plant design from satisfying rigid prescriptive requirements towards one that considers multiple possible solutions in a risk-informed and technology-inclusive manner. This flexibility can lead to significant cost reductions for nuclear plants, as discussed in the report.

The purpose of this study is to apply the ANTSER methodology in an effort to help identify efficient modularity strategies for advanced nuclear energy technologies at different scales. Modularity is considered as a cost-efficient means to deploy nuclear energy. Various modularity approaches are applied in nuclear energy designs, such as those for modular reactors and for modular balance of plant (BOP). These different modularity approaches are described in this study as the basis for further evaluation. The literature on modularity was reviewed to identify potential advancements in modularization for large-, medium-, small- and micro-scale nuclear reactors. Modularization applications in non-nuclear industries were also studied from the perspective of their potential to be adopted by the nuclear energy sector. Lessons learned from the use of modularity in nuclear are used to identify past challenges as well as future improvements that may be applied to advanced nuclear reactors. New regulatory approaches, such as the functional containment design, are assessed for their potential to enable new modularity approaches. The compatibility of these approaches at different scales of reactors and BOP options are also considered.

Table 1 presents the key parameters for ANTSER cost reduction strategies no. 1 and no. 2 in terms of their applicability to nuclear plant categories, potential cost reductions, technology readiness levels (TRL), and needs for further research, development and demonstration (RD&D). In addition to design improvements, ANTSER cost reduction strategies may also include improvements in manufacturing, construction and project management (omitted for brevity in Table 1). Further details on the cost reduction potential of modularity concepts are provided in Tables 3 and 5.

Table 1. Summary table for cost reduction assessments

Strategies	Applicability	Cost reductions	Technical readiness	Further RD&D	Additional metrics
Design					
Strategy 1: functional containment	Applicable to most Gen-IV reactor designs including reactors with a low-pressure salt coolant and gas-cooled reactors, with tristructural isotropic fuel (TRISO) fuel.	Flexibility in design through non-prescriptive engineering approaches could result in a net ~5-15% cost savings in the overall design, implementation and construction of the plants.	Most of the technologies discussed have high technology readiness levels (TRLs 6-8).	Individual cases require further RD&D, such as seismic isolators and their performance for component isolation, as well as their performance under high-temperature environments.	Design strategies may be cross-referenced to impacts on construction and project management.
Strategy 2: modularity at scale	Applicable to most reactor types, including light water, sodium-cooled and gas-cooled reactors. Non-nuclear BOP modularity approaches are mostly applicable to non-LWRs and low-pressure reactors.	Provides cost savings through standardization, quality control and minimal on-site work.	Restricted modular approaches for non-LWRs given their safety requirements. Non-LWRs are more flexible in modularity, for example in their use of precast concrete. Additional R&D is required on the use of precast concrete for safety related structures. Otherwise, the technologies discussed for modular reactors and BOP have high readiness levels (TRLs 6-8).	Safety assessment of modular non-LWRs need to be finalized. TRISO fuel needs further RD&D to provide robustness and manufacturing reliability. Connections of precast concrete panels need to be verified for use in non-light water reactor (LWR) applications. Performance of modular BOP applications under high-temperature environments need to be assessed.	–

Source: (Shropshire et al., 2021b).

ANSTER cost reduction strategy no. 2: Modularity at scale

Modularity in nuclear energy

The ANTSER analysis begins with a literature review on modularity in nuclear energy. Modularity has been defined from different perspectives in the literature. The attempts of the nuclear industry to use modularization, with the intention of high impact cost reductions, are usually discussed around the question of the modularity of reactor technologies or construction practices. The definition of modular design used by the United States Nuclear Regulatory Commission (USNRC) focuses on the modularity of reactors, which consists of two or more essentially identical and independently operable nuclear reactor modules, with or without some shared systems or structures (USNRC, n.d.). This kind of definition excludes modularity for BOP, such as the modularity of structures or components.

The literature and practical use of modularity in nuclear energy highlights three dominant types of modularity:

- Scale modularity, which is defined as a large nuclear power plant (NPP) composed of multiple identical small capacity NPPs. The small NPPs, or reactor modules, are manufactured and assembled in factories and are then transported to the project site, positioned and connected to make a large capacity NPP (Upadhyay et al., 2016). The Generation IV International Forum (GIF) Economic Modelling Working Group (EMWG) refers to this concept in the guidance document as the "modularity effect" (GIF, 2007).
- Scope modularity is defined as a modular design and construction strategy where a large capacity NPP is divided into a number of matching units, called modules, for installation. These modules could be related to the structure, system or component (SSC) or to composite modules (e.g. buildings, turbine-generators, auxiliary systems, service systems, refueling systems, safety and security systems) that are manufactured in factories or workshops. After manufacturing, the modules are transported, positioned appropriately and connected with other matching modules at the project site to cover the complete scope of the project (Upadhyay et al., 2016). The GIF EMWG refers to this concept in the guidance document as "modularization" (GIF, 2007).
- Comprehensive modularity combines scale and scope modularity. Multiple, identical, small capacity reactors are combined into one large NPP along with common SSCs, which are built and assembled in factories or workshops and then installed at the project site (Upadhyay et al., 2016).

Advantages of modularization (see Lloyd et al., 2021; and Stewart and Shirvan, 2021) include shorter construction schedules resulting from increased productivity and better-quality control, reduced costs through higher on-site efficiency, repeatability and learning by standardization of the design and re-use of equipment, as well as broader availability of skilled laborers working in nuclear projects at remote locations. From an investment perspective, increased construction efficiency through modularity enables robust mitigation against uncertain market conditions. It has been argued that modularity may be preferred over non-modular approaches, even if the cost is higher for the former (Gollier et al., 2005). Such a preference can also be attributed to the ability to defer investment costs for future reactor modules and enable self-financing of future deployment with revenues produced by the earlier units. This statement becomes more valuable in the case of uncertainties in the market and at the deployment stages, if the project is one large-sized plant with high capital requirements. The GIF EMWG (GIF, 2007) credits the benefits of modularization for large Gen-IV reactor concepts to learning effects, parallel production, parallel construction, site productivity, the cost of money, capital at risk and future technology benefits.

Other studies have also emphasized the benefits of modularity for nuclear energy projects and their impact on the economic competitiveness of nuclear energy. For example, building in sequence using just-in-time modules (Planview, n.d.) and performing less on-site work have been highly encouraged as a means to compete with natural gas plants (Duffey, 2019). Adding power in increments using modular reactors may also increase the competitiveness of nuclear in the energy market. These kinds of approaches would result in more efficient deployment, and hence cost savings in the long run. Another important way of increasing efficiency during nuclear energy deployment is lean thinking and manufacturing. Combined with the effectiveness of modular approaches at the reactor and BOP levels (Hussein, 2021), lean approaches have the potential to improve the competitiveness of nuclear energy in the global energy markets. The Toyota production system, originally called just-in-time production, is a working example of lean manufacturing that is used to achieve global market competitiveness (Toyota, n.d.).

Modularity for large NPPs

The ANTSER analysis shows that historically the application of modularity to large NPPs has been challenging because of the large structural elements and weight of an NPP. Depending upon the structure and systems included in the modularization scheme, the extent of modularization may be categorized as none (stick built), low, medium or full. Low modularization includes only equipment and piping, which are relatively easy to modularize, in the modularization scheme. Medium modularization includes equipment, piping, structures and liners. Most containment liner modules cannot be transported by road, regardless of the reactor size (Lloyd, 2020).

The ability to break down SSCs into transportable modules to be assembled on-site is an important parameter of modularity. Road transportability is constrained by the weight and size of modules, and depends upon the final deployment location. Large NPPs have a disadvantage over smaller sized plants due to limits on module transportability, e.g. power plants above 600 megawatt electric (Mwe) may become too large to be transported by road. From a constructability perspective, Lloyd (2020) recommends a maximum of three modules for each component and structural element. Increasing the number of modules also starts to increase the number of connections to construct the equipment or structural elements. This results in: i) time spent connecting the modules; ii) increased workmanship; and iii) increased complexity of the work. As an example, a structural module can be assembled much quicker than the same unit divided into 20 modules, which would require assembling. Module subdivision may not be feasible for all machinery and equipment; for instance, the moisture-separator-reheater units in a turbine building cannot be subdivided.

Table 2 compares cost reduction opportunities for the modularization of advanced nuclear reactor construction to stick-built plants. The EMWG reports that modularization of large-capacity plant construction (nominal plant size of 1 000 MWe) can reduce total direct overnight construction and labor costs of the nuclear island. Cost reductions focus on the following areas:

- Reducing the share of the reactor built on-site (i.e. independently built) versus fabricated in a shop (possibly in series with other units), and reducing the management and complexity of site work.
- Improving learning by building a large number of smaller modular plants that can benefit from additional n^{th} of a kind (NOAK) learning effects and reduced per-unit module costs.
- Gaining direct labor work efficiencies, including optimized labor use and coordination of trades, by building modules in controlled environments using equipment that can accurately duplicate operations, and using standardized shop and quality processes.
- Shortening construction schedules through parallel construction that allows field work to progress on-site while modules are factory built and then delivered to the site when needed; reducing indirect and management costs, direct cost contingencies and owners' costs.
- Reducing finance costs by lowering capital requirements, allowing quicker plant start-ups and revenue generation. Modularity can also reduce project risks and related finance premiums.

- Achieving cost savings from robotics and automation, which allows computer-aided manufacturing that integrates design changes with manufacturing processes to minimize the design cycle and creates tooling to produce modules faster with increased product quality.
- Reducing annualized costs though modules designed to reduce operational and maintenance requirements by simplifying and standardizing service requirements and allowing quick replacement of modular components with a minimum of operational downtime.

Table 2. Comparison of stick-built and modular plant features

Consideration	Stick-built plant	Modularized plant	Reduction percentage
Direct construction cost	All field construction	With shop fabrication	0-5
First of a kind (FOAK) through the NOAK learning effect	Larger plants, less doubling of experience (eight each)	Smaller plants, larger number of plants for same capacity (32 each)	0-10
Direct labor	All field construction	Transfer to shop	30-50
Direct labor hours (productivity)	Direct hours	Reduced field work, lower worker densities, improved access	10-25
Construction/installation schedule	Regular work schedule	Parallel construction, early start fabrication, reduced field work	30-50
Indirect field cost	Regular work schedule	Reduced field work, reduced construction schedule	30-50
Field management costs	All field construction	Reduced field work, reduced construction schedule	15-25
Direct cost contingency	All field construction	Shop safety, security, environment, seasons, support, interference, logistics, controls, etc.	10-20
Owner's costs	Regular work schedule	Early plant start-up, factory and site	0-10
Supplementary costs	All field construction	Provisions for decontamination and decommissioning	0
Capitalized finance cost	Regular work schedule, all field construction	Parallel construction, early start fabrication, early start operations	30-50
Robotics and automation	Minimum utilization	Future potential	30-50
Annualized costs	Regular work schedule	Designed for operations and maintenance	0-5

Source: (GIF, 2007).

However, further studies are needed to understand the impacts of modularization on small modular reactors (SMRs) and microreactors. The extent of modularization affects the economics of the power plant. Likewise, the capital cost of modular power plants depends on the degree of modularization (DoM). DoM is the fraction of tasks in terms of the weight, time or cost that can be done at a dedicated fabrication facility or an on-site assembly area, rather than the construction site. The DoM parameter can range from zero, representing zero modularity in the plant, to a DoM$_{max}$ value, representing a practical upper limit based on transportation constraints and modularization. In general, the cost-DoM relationship for structures and components can be generalized as shown in the equation below. The value of a cost factor (CF) <1, can change for the scope of the work done at an off-site location, for example for material handling and direct labor. Additional costs include overhead costs or freight costs. Recommendations on the cost factor, labor wages and additional costs can be found in GIF (2007).

$$Total\ cost = field\ cost \times [(1 - DoM) + DoM \times CF] + additional\ costs$$

Learning (Bertram et al., 2019) in factory production and construction will improve if identical modules can be used over different projects, independent of site location and associated hazards. To realize the full economic benefits of modularization, the design of the SMR must be standardized, regardless of differences in site hazard and regulatory requirements (Collins et al., 2008).

Lloyd (2020) expresses savings in capital cost and construction time from modular construction in nuclear industry as a function of the reactor power of the plant. To evaluate reduction in construction time, a 1:3:8 rule of modularization (Barry, 2009) was assumed for units that can feasibly be subdivided into smaller modules and transported from the factory to the site based on weight and road transportation dimension limits in the United Kingdom. The 1:3:8 rule of thumb (i.e. 1=factory production, 3=on-site shop, 8=construct in place) assumes that tasks performed at an on-site shop and in place are 3 times and 8 times slower than off-site factory production, respectively. High-quality off-site production (baseline) provides the opportunity for highly effective deployment by minimizing the work done at the site, which is a slower process than optimized manufacturing and production procedures in factory-controlled environments. Although on-site shops cannot produce as effectively as full off-site production, they still increase the effectiveness of manufacturing, assembling and deployment compared to relying solely on in-place activities. Lloyd (2020) reports that for a fully modularized (to the degree possible) 1 200 Mwe large reactor, the construction schedule can be compressed by 10%, whereas for a fully modularized 300 MWe SMR, it can be compressed by 31%. The difference stems from the evaluation that only 20% of on-site tasks can be moved off-site for reactors above 750 Mwe, compared to 80% to 90% for SMRs (Lloyd et al., 2021). Lloyd (2020) reaches the conclusion that full modularization reduces overnight capital costs. This was calculated by comparing overnight capital costs between a stick-built and a modularized NPP at different levels of reactor power. Lloyd took into account a reduction in staff hours, lower hourly factory wages compared to site wages, requirements regarding in-situ construction of certain units due to transportation constraints, adjustments for transportation costs (2% of module cost) and adjustments for installation cost (5% of module cost). The reduction in capital costs varies according to reactor power. Lloyd (2020) concludes that overnight capital costs would be reduced by 30% for a 1 200 MWe large reactor, and by 45% for a 300 MWe SMR.

Stone & Webster Engineering Corporation (1977) developed a detailed modularization scheme for a generic 950 MWe pressurized water reactor (PWR) that was never implemented. They listed more than 1 400 modules, along with weight, dimensions and contributions to cost reduction. Those modules could feasibly be fabricated at an on-site shop and lifted in place. The study paved the way for other plants with modular construction, such as the Westinghouse AP1000. The process was also limited to the fabrication of modules at a separate location near the nuclear site, which allowed for parallel construction, where module fabrication can be performed at the same time as site work, but without developing standardized modules in a factory. The modular approach in the case of large reactors has instead been implemented to resolve particular problems in construction, for instance ensuring parallel construction of complex tasks and combating concerns about working at height. The extension of a modularization scheme to large reactors brings rise to challenges concerning the development of transport-feasible modules. SMRs are geared more towards gaining the full benefits of modular construction. It was calculated that adopting full modularization can reduce the total capital investment cost by ~30% for SMRs when compared to stick-built construction (Maronati, 2018).

Large size plants have not benefited from modular approaches, either at the reactor or construction stages. Scalability has been constrained by an increase in power outputs. For example, AP1000 designs have a higher output than the former AP600 reactor. Modularity discussions on large scale plants are usually restricted to BOP, particularly for construction. In the early 2000s, a US company attempted to modularize the construction of a large-scale nuclear plant using steel-plate composite (SC) walls. SC walls are concrete walls sandwiched between steel plates. The modular steel portions of the SC walls would be built in fabrication shops, transported to the reactor site, where the modules are welded together, and then concrete would be poured inside the modules. A ICONE 9 conference paper (Winters et al., 2001) describes this approach as follows:

> "Its designers made a concerted effort to simplify systems and components to facilitate construction, operation, and maintenance."
>
> "It has been designed to make use of modern modular construction techniques. To the maximum extent possible, the design is based upon parallel construction activity paths. This is done through the extensive use of modules."
>
> "...concrete to fuel load is 36 months. This duration has been verified by experienced construction managers through 4D (3D models and time) reviews of the construction sequence."

Unfortunately, the advantages of modular construction were not realized in actual practice. Difficulties in maintaining the quality of the on-site nuclear grade welding and discrepancies in the tolerances between approved engineering drawings and on-site implementation resulted in cascading effects on the cost and schedule of the projects. However, this does not imply that modular construction is not suitable for the nuclear energy sector. It does, nonetheless, demonstrate the importance of decision making at early stages to align with the potential challenges of nuclear-grade construction. Although SC modular systems were promising, the technology's high reliance on on-site work, including high volumes of nuclear grade welding or on-site concrete pouring, quality control and inspection, decreased the effectiveness of the modular approach. If the AP1000 did not face such issues and had been successfully deployed in series, the costs could have been expected to be below USD 3000 per kilowatt (Shirvan, 2022).

Modularity for SMRs

The ANTSER analysis considered various modularity approaches, including for modular reactors. Contrary to conventional large size NPPs, which are typically monolithic plants, the integral layout and reduced size of SMRs (Carelli et al., 2010) may benefit from the factory fabrication of components, which are transported to and assembled into super modules in an on-site assembly area, and eventually lifted and installed in the designated location. This construction strategy is called modularization. The nuclear industry is still in its early stages to fully understand the merits and challenges in modularization given the lack of experience in production scale deployment of SMRs.

Mignacca et al. (2018) suggests that the transition from stick-built to modular construction in the nuclear industry requires further research to realize the benefits experienced by other industries. Based on experience from other sectors (e.g. oil, gas, high rise buildings), modular construction results in schedule compression because of simultaneous design and procurement, higher productivity off-site and parallel production (De La Torre, 1994), and because of cost savings that are achieved through economies of scale in production (Lawson et al., 2012), the lower cost of labor, tools, supervision, training and quality control in a shop environment, compared to on-site and increased competition among potential fabricators. Conversely, there is an increase in cost associated with engineering design, project management and the transportation of fabricated units. In the case of a new modular technology, for instance Westinghouse's SC modular construction, the cost of building a specific factory or finding appropriate factory layouts can potentially increase the cost of the modular units. It is therefore important to rely on existing, established and proven supply chain and production environments to realize the effectiveness benefits of modular construction. Considering all factors, past studies based on the chemical process industry, high-rise buildings (Lawson et al., 2012), modular power plants (Ondrey, 2009) and shipbuilding industries (Garver et al., 2014) have shown that modular construction reduces construction time by around 30 to 50% compared to the conventional stick-built approach.

Modularity for microreactors

As an extension to the ANSTER analysis of SMRs, microreactors were considered as a unique class given their unique and compact design, transportability and potential for mass factory production, which makes their deployment inherently effective and modular. The characteristics of microreactors include: i) modular and rapid deployment capabilities; ii) the ability to provisionally add adjacent reactor units to scale up in size; iii) the lower capital overnight costs compared to large reactors; and iv) the self-contained, minimized transportation of separate auxiliary systems (Shropshire et al., 2021a). The current financial premise for microreactors is different than that for large size NPPs, since initial estimates and business cases for microreactors focus on competing with diesel generators and serving as energy sources at remote locations, such as remote communities and mines. There are several developers of microreactors for commercial use (MMR®, n.d.), defense purposes (US Department of Defense, 2021), and also for demonstration and research (Office of Nuclear Energy, 2021).

One of the biggest advantages of microreactors is their size, which enables the manufacturing of the complete unit in a controlled factory environment and repeat-and-iterate production procedures in future deployments to increase efficiency and reduce costs. A United States Department of Energy (USDOE) study (Abou-Jaoude et al., 2021) on the economics of heat pipe microreactors identified that modularity could provide cost savings through rapid installation and deployments, as well as simplified decommissioning. Modularity further enables economies of multiples when vendors are able to scale their production units to reap the efficiencies from learning and streamlining. Learning rates for capital-related expenses were assumed to benefit from learning rates estimated at 15%, resulting in cost reductions in the range of 20-60% during the build of 100-200 units (Abou-Jaoude et al., 2021).

Table 3 outlines the potential cost reductions provided by modularization of the reactor and/or BOP, based on evaluation of the referenced literature. The DoM increases as the power source shifts from a large-scale plant to a microreactor, primarily because the sizes of relatively smaller nuclear energy sources are more suitable for factory fabrication (Lloyd et al., 2021, Buongiorno, 2018). However, in order to make smaller units profitable large orders and sufficient demands to mass manufacture would be needed to reduce the overnight construction cost (OCC) of the individual units. The US Microreactor Program's global market study on microreactors shows that to be competitive in future profile markets, costs need to decrease from USD 0.50-0.60/kWh for initial deployments (2020-2030) to USD 0.20-0.35/kWh (2035-2050) through factory scale-ups and producibility improvements in designs (Shropshire et al., 2021a).

Table 3. Potential cost reductions related to reactor and BOP modularization

Reactor size	Modularity options	DoM possible	Expected cost benefit on OCC	Limitations
Conventional large NPP (reactor only)	NA	NA	NA	Conventional reactors have not been modularized mainly for reasons of economies of scale
Conventional large NPP (BOP, and common structures)	Multiple similar modules for foundation, shielding and containment structures	<10%	<10%	Given the safety requirements of conventional large reactors, the modules need to be thick and heavy, limiting transportability
SMR (reactor)	Super modules	<50%	20–30%	Initial need for satisfactory orders for the scaling of manufacturing for modular reactors
Gen-IV – SMR BOP	Multiple similar modules for foundation, shielding and containment structures	<20%	20–25%	Construction and operation of the entire plant with a limited number of reactor modules may impact expected profitability
Microreactors	Entire unit being modular and ready to be operational	100%	20–60%	Initial need for satisfactory orders for the scaling of manufacturing for modular reactors

Source: (GIF, 2022).

Modularity experience outside the nuclear industry

The ANTSER analysis includes novel modular designs and applications from non-nuclear industries. Energy, the aerospace industry, construction, data centers, and software development are among the businesses that are using modular approaches to achieve scalability, cost savings, quality control and rapid iterations of future products. Google LLC developed modular data centers housed inside standardized shipping containers for rapid and cost-competitive deployment (Google, 2009). Sun Microsystems also developed turn-key modular data centers that are reported to be operational for 1% of the cost of building traditional data centers (Wikipedia, n.d.).

Tesla, the largest electric vehicle company in terms of sales, has applied modular and efficient methods to build and expand their lithium-ion battery factory, the Gigafactory (Bent Flyvbjerg, 2021). The methods used in constructing the Gigafactory differ from conventional construction practices, where the facility is composed of minimum viable units of product that are operational and functional as soon as they are deployed. Such an approach allows revenue generation and satisfies the supply need of businesses, even before the facility is 100% complete. An additional advantage of the modular approach is that the company could rapidly expand its factories around the world, such as in China and Germany.

The modular applications in the non-nuclear construction industry can be categorized under three headings: i) conventional non-modular construction (in-place construction); ii) SC modular construction; and iii) precast concrete modular construction. Table 3 on the previous page shows a comparison of these different approaches. As mentioned earlier, AP1000 construction was planned to be achieved through a SC-type modular design. SC-type of construction is being used in non-nuclear construction, for example in the structural core design and construction of Rainer Tower in Seattle, Washington, USA. This construction method thus provided fast-paced deployment of the second tallest structure in the Pacific Northwest of the United States.

Precast concrete was used during the construction of Tesla's Gigafactory and Apple Park Office to speed up the deployment process and compress schedules. Precast concrete structural elements are produced in factories and transported to the construction site for assembly. Precast concrete elements have been recognized as a competitive alternative to other methods of construction for use in both simple and complex structures (National Precast Concrete Association, 2010). Three main reasons for this cost competitiveness are: i) the ability to repetitively use molds for concrete casting, thus reducing material cost; (ii) the high quality of workmanship, thus reducing iteration time at the construction site; and iii) factory fabrication, which thus reduces workmanship, schedules and costs for the construction site operations. A conventional nuclear energy option has not benefited from precast modular construction at the critical paths of projects, such as during the construction of large safety-critical containment structures, mainly as a result of the safety requirements for conventional high-pressure light water reactors (LWRs).

Aeronautics and space industries have historically been challenged with budget overruns and schedule delays on multiple projects for many reasons, although this trend may be changing. A new company, called Planet, formed by former employees of NASA, has developed a relatively compact and modular satellite unit, called Dove, which is easy to iterate based on previous designs. The company has successfully launched several of its satellites faster than any company or government in the past (Planet, n.d.). Innovative construction systems are also being deployed by SpaceX for the Falcon 9 reusable rocket (Shira Teitel, n.d). The Falcon 9 pieces are assembled in SpaceX's custom-built Horizontal Integration Facility, a large hangar in Florida, with most of the rocket's modular components, including fuselages and engines, being shipped from a factory in California and from other locales to various test stands before final assembly. After use, Falcon 9's first stage is returned to the Horizontal Integration Facility where it undergoes a verification process, is refurbished and is then readied for another launch. Reusing the stage is much cheaper than building a new one for every launch (Abou-Jaoude, 2021).

Lessons learned from modularity attempts in nuclear energy

The ANTSER analysis has also evaluated lessons learned from the use of modularity. The nuclear energy industry has been pursuing modular approaches for decades. These modularity attempts have mainly focused on reducing schedules and costs at the balance of plant (BOP), with the most potential for positive financial impacts determined to be at the relatively large safety-critical containment buildings. Modular reactors have been discussed and pursued in a few cases (Ramana, 2015), but none have reached maturity or have been sustained in the industry. However, small modular reactors (SMRs) have gained substantial attention (IAEA, 2020) in the last decade, given their promise to reduce initial capital costs and their ability to expand capacity by adding a series of modular reactors based on customer needs. SMRs are also viewed as a new entry point to revive the nuclear energy industry.

As summarized in earlier chapters, the challenges observed for the steel-plate composite (SC)-type of modular construction cannot be directly attributed to modularity as a whole. These challenges are more related to selecting a suitable modular technology that adheres to nuclear energy and regulatory standards. More specifically, it could be argued that the SC-type of modular construction was not the optimal choice for the nuclear energy sector because of the extensive list of requirements concerning nuclear grade on-site activities, including: i) attaching plates with tight tolerances at the site; ii) conducting nuclear grade welding for connections under various site and geometric conditions; iii) pouring considerable amounts of high-quality controlled concrete at the site; and iv) lacking visibility on the amount of time required for regulatory inspections and approval of concrete surfaces. It is important to emphasize that when the choice of modular technology is combined with a lack of experience and capabilities in manufacturing modular steel plates, the work at the site is continuously delayed and the supply chain is adversely affected.

Because SMRs and microreactors are still in the early stages of their development, it is not possible to have an in-depth discussion on how modularity has affected associated nuclear energy deployments. However, modularity at the reactor level for SMRs has been an ongoing discussion. One of the most prominent proposals to build an SMR-based NPP was that related to the construction of an entire plant with a limited number of reactor modules, having a single reactor capacity of around 50 MWe. In the case that the customer would need additional capacity over time, it could add more reactor modules and produce more electricity with the existing BOP.

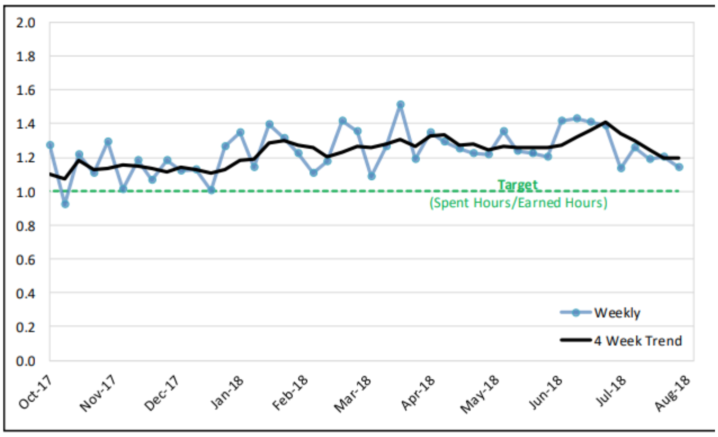
Some microreactor developers are promoting their technologies as modular microreactors that can function alone with minimal on-site work. In the United States, there are approximately ten microreactors, sometimes referred to as fission batteries, under development. All vendors have plans to incorporate some degree of modularity in their designs. Canadian scientists are also studying modular reactors, particularly for remote mining as a replacement for diesel generators (Canadian Nuclear Laboratories, 2022; SaskPower et al., 2021; Ontario Power Generation et al., 2021).

Involvement and compatibility of modular approaches in the nuclear industry

The nuclear industry has stringent regulations and rules that require regulatory inspectors to devote significant time and resources to verifying the licensee's completion of the requisite inspections, tests, analyses and acceptance criteria (USNRC, 2021). This on-site inspection inherently makes nuclear energy deployment relatively slower than a comparable infrastructure project. Additionally, any divergence from the regulatory requirements will result in rework at the site, such as remanufacturing of an out-of-compliance component or reconstruction of shielding wall elements with predefined tolerances. Thus, conventional nuclear energy deployment can be classified as monolithic (non-modular) and time-consuming in general, rather than modular and efficient. Recent examples of non-modular and time-consuming deployment environments include Flamanville (Nuclear Newswire, 2022) or Olkiluoto (YLE News, 2019). Non-modular designs are custom built, which imposes difficulties in achieving the benefits of standardization, for example in terms of learning (World Nuclear News, 2016). They also prevent ease of iterations in future deployments.

As discussed earlier, the methods that were used to construct Tesla's Gigafactory are different from conventional construction practices, with the former's facility composed of minimum viable units of product that are operational and functional as soon as they are deployed. Such an approach allows revenue generation and satisfies the supply needs of businesses even before the facility is 100% complete. Conversely, a commercial nuclear power plant (NPP) project that is 99% finished has zero output or revenue. Non-modular approaches also make it difficult for nuclear energy to scale, either up or down. As an example, additional capacity cannot be easily added when needed with a monolithic build, which caps business expansion and the potential profitability of nuclear energy.

Figure 1. Direct CPI at the Vogtle site between 2017-2018



Source: (Letter from Kyle Leach, 2018; see Figure D).

The earlier chapters of this study discuss how the nuclear industry has tried to use modularity through different approaches. SMRs are reactor-level modularity attempts, and steel-plate composite (SC) construction, such as Vogtle and VC Summer, are balance-of-plant (BOP)-level attempts at modularization. While it would appear from the examples emanating from other industries that moving towards modularity in deployment could be considered a positive means to make nuclear energy cost-competitive, it is nonetheless important to take into account the technology selection and approach for achieving modularity, and whether these are compatible with the nuclear sector. The challenges and hardships of recent modularization attempts involving the BOP was discussed in earlier chapters. Additionally, challenges in the selected modular technology and supply chain issues have resulted in inefficient management of the deployment site. Figure 1 (see page 23) shows the construction cost performance index (CPI) (hours spent/hours earned) during an approximately one-year time frame at the Vogtle site (Letter from Kyle Leach, 2018). If the CPI was above 1.0, the project was spending more hours than planned to complete the tasks. The Vogtle site was experiencing a cumulative direct CPI of approximately 20% more than planned at the time of the report. Hence, the choice of the modularity approach and the compatibility of the technology are highly important for the success of projects. It can therefore be argued that an inefficient modular deployment approach produces similar results to a monolithic and time-consuming approach.

Efficient modular deployment

Global nuclear energy markets have favored large-scale light water reactors (LWRs), usually in the order of 600-1200 MWe output. LWRs have supplied clean energy all over the world since their inception. However, hardship in delivering and deploying such plants has been observed in the last few decades, especially in the West.

As mentioned earlier in the report, the nuclear industry has attempted to reduce the costs of large-scale projects via several avenues, including modularization of the balance of plant (BOP). A limited number of choices exist in relation to the modularity of large LWRs given the inherent safety requirements of this reactor technology. The containment building structure that houses the reactor must be designed against technology-specific accidents – such as high internal pressure events – making them heavy and expensive buildings. Immediate challenges thus arise when deploying large-scale LWR nuclear power plants (NPPs) in terms of supply chain management, and high and sustained on-site quality control and management.

Consistent with the purpose of this ANTSER study, new approaches are being considered to identify efficient modularity strategies for advanced nuclear energy technologies. With the transition to non-LWR reactor technologies, with their own unique safety requirements, new regulations and approaches to design cost-efficient BOP are emerging. The functional containment design and regulations permitting risk-informed, performance-based and technology-inclusive design approaches could potentially allow flexible designs and new technologies to be used for the cost competitive deployment of nuclear power (Shropshire et al., 2021b). The functional-containment concept makes possible a reduction in the cost of the NPP project by decreasing the amount of nuclear-grade construction (imposed by the American Society of Mechanical Engineer N-stamp requirements on the design and implementation in real life). Within the functional-containment approach, candidate technologies or approaches used by industry help to reduce the risk and design requirements of structures or components accompanying advanced reactors. These candidate technologies (such as seismic protective systems) or approaches (e.g. deeply embedded structures) can ensure that the risk-informed, performance-based and technology-inclusive design of structures meets functional requirements at a reduced cost (Shropshire, 2021b).

As described in ANTSER Cost Reduction Strategy No. 1 (2021), functional containment could be applied at different scales:

- Mid- to large-size Gen-IV reactors, such as modular high-temperature gas reactors (HTGRs) or very high-temperature reactors, may not need costly and heavy containment structures. The possible internal hazards associated with these non-LWR reactor designs are also different from traditional LWRs. The necessary pressure-related containment boundary for the LWR design is not required for these types of designs. Because the safety features and the release environment are different from traditional LWRs, they provide the basis for functional containment. New technologies, engineering approaches and combinations of the two may be considered, including modular deployment approaches used by the non-nuclear industries, seismic isolators, deeply embedded and relatively small footprint structures and tristructural isotropic (TRISO) fuel. Such technologies and approaches will allow engineers and designers to optimize their overall plant designs so as to satisfy safety and functional requirements while maintaining cost competitive design.
- Similarly, for advanced small modular reactors (SMRs) and microreactors, functional containment would involve scaling down containment for smaller reactor sizes and for their particular risk profiles. Functional containment could be implemented by

embedding the reactor underground or modifying the design of the containment structure. The enveloping structures could be thinner or lighter, or they could be constructed more easily with advanced concrete and other innovative materials.

- Although functional containment can provide flexibility in the design and use of new engineering approaches in nuclear energy, not all of the technologies can be expected to have the same level of economic impact. Modular technologies, both at the reactor level and BOP level, as shown in previous chapters, are expected to have positive cost impacts; however, not all reactors can benefit from some modularity concepts (e.g. reactors requiring high-pressure resistant containment).
- To illustrate the concepts described in this report, Table 4 outlines the potential compatibility of reactor technologies with modular construction technologies applied to the BOP. LWRs need high robust containment structures as a result of their safety requirements. As shown in the red cells, modular precast construction is not compatible with large- and medium-sized LWRs. On the other hand, modular steel-plate composite (SC)-type construction is compatible with LWRs, although the data demonstrates considerable challenges during deployment. Modular precast construction is potentially compatible with HTGRs and sodium-cooled fast reactors (SFRs) given the operational environment and containment at the fuel (see discussion below). Modular precast construction is a more mature technology compared to modular SC-type technologies. It is widely available among global suppliers and is less dependent upon site services, such as those that require high volumes of concrete or nuclear grade welding.

Table 4. Illustration of the compatibility of different modular reactor technologies to modular BOP

	Modular precast construction			Modular SC-type construction		
	Large-size plants	Medium-size plants	Microreactors	Large-size plants	Medium-size plants	Microreactors
LWR						
HTGR						
SFR/thermal microreactor						

Legend: Red=not compatible; Green=compatible; Yellow=marginally compatible.
Source: (GIF, 2022).

Table 5 on the following page assesses potential modularity concepts for reactors and their BOP, assessed in terms of: i) their applicability to the different plant sizes; ii) the potential cost implications; iii) their technology readiness level for nuclear applications; iv) their transportability; and v) further research, development and demonstration needs.

- LWRs are mostly applicable to mid- and large-size plants; however, their high-pressure environment has and will hinder cost-effective modular approaches at the BOP level.
- HTGR and SFRs operate at lower pressures compared to LWR reactors. Additionally, the new fuel technologies, such as tristructural isotropic (TRISO) fuel, may enable new modular approaches at the BOP level for these types of reactors through newly developed regulation of the functional containment approach. These reactor technologies have been deployed at relatively smaller scales, but fuel development and investigations into their safety performance are still being conducted.
- Modular precast construction has not been applied to costly safety significant structures or systems in the nuclear domain because of the lack of performance of connections under high-pressure environments and high-intensity seismic events. However, with the safety features of Gen-IV reactors and the functional containment approach, precast

modular systems are potential candidates for reducing costs, if it is shown that their designs satisfy the risk-informed and performance-based approaches.

- Modular SC systems have been used in nuclear applications. Their codes and standards have been fully developed and the technology is ready to be deployed for every reactor type. However, given their high on-site activity demand, it is still uncertain whether they will be able to bring down costs and compress schedules for the next-generation plants.

Table 5. Assessment of potential modular approaches

Technology	Scale applicability	Cost implications	Technology readiness in nuclear	Transportability	Further RD&D
LWR	Mid- to large-sized plants	Hinders cost-effective modularization of the BOP.	TRL 8-9	Not transportable as modules due to large size of factory equipment (reactor vessel and internals, steam generators, heat exchangers, etc).	Ready to use.
HTGR	Micro- to medium-size plants	Enables high degrees of modularization (DoM) at the reactor and BOP levels. Allows for the creation of standardized units.	TRL 8-9	Transportable in single units or multiple containers to the deployment site.	Needs further RD&D on fuel certification.
SFR	Micro- to medium-size plants	Enables high DoM at the reactor and BOP levels. Allows for the creation of standardized units.	TRL 8-9	Transportable in single or multiple containers to the deployment site.	Needs further RD&D on safety and performance.
Precast construction	Micro- to large-size non-LWRs	Enables standardization of structures, such as containment buildings. Requires on-site assembly.	TRL 6	Precast components are transportable but limited to the weight of individual modular units, depending on road and site regulations and equipment.	Requires research on whether performance satisfies regulatory requirements against external hazards.
Steel-plate composite construction	Micro- to large-size reactors	Enables standardization of structures, such as containment buildings. Requires welding, high volumes of concrete casting, workmanship and assembly on-site.	TRL 9	Only the steel portions of the modules are transportable.	Has been approved, developed, and demonstrated in real nuclear energy applications.

Source: (GIF, 2022).

Conclusions and further directions

The present study, "Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review: Cost Reduction Strategy No. 2: Design – Modularity at Scale" applies the ANTSER framework to the evaluation of cost reduction opportunities for Generation IV nuclear concepts, based on modularity at different scales and on the types of advanced reactors. This second cost strategy is intended to inform the Generation IV International Forum (GIF) and international stakeholders on the potential uses of modularity to reduce advanced reactor costs. The greatest potential for cost savings on advanced reactors may be achieved through design strategies that employ proven modularity concepts along with functional containment to create flexible designs. Further alignment of modularity concepts that have been successfully deployed by the non-nuclear industry is encouraged. The outcome of this strategic cost reduction activity is to expand information sharing within the GIF and among other stakeholders to accelerate progress towards the global deployment of cost-competitive nuclear plants.

References

Abou-Jaoude, A., A. Foss, Y. Arafat and B. Dixon (2021), "An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept", Idaho National Laboratory, INL/EXT-21-01201.

Barry, K. (2009), "Modularization of Equipment for New Nuclear Applications: Testing and Preservation," Electric Power Research Institute (EPRI), Palo Alto, CA:1021178.

Bent Flyvbjerg (2021), "Make Megaprojects More Modular," *Harvard Business Review*, November-December, pp. 58-63, https://medium.com/geekculture/tesla-gigafactory-1-as-the-future-of-construction-bcca1f0a0062.

Bertram, N., S. Fuchs, J. Mischke, R. Palter, G. Strube and J. Woetzel (2019), *Modular construction: From projects to products*, McKinsey & Company: Capital Projects & Infrastructure, pp. 1-34.

Buongiorno et al, (2018), "The future off nuclear energy in a carbon-constrained world, an MIT interdisciplinary study", MIT Energy Imitative, Massachusetts, USA.

Canadian Nuclear Laboratories (2022), *Canada's Small Modular Reactor Action Plan*, https://smractionplan.ca/, Minister of Natural Resources, Chalk River, Ontario, Canada.

Carelli, M. D., P. Garrone, G. Locatelli, M. Mancini, C. Mycoff, P. Trucco and M. E. Ricotti (2010), "Economic features of integral, modular, small-to-medium size reactors", Vol. 52(4), *Progress in Nuclear Energy*, Elsevier, Amsterdam, pp. 403-414, https://doi.org/10.1016/j.pnucene.2009.09.003.

Collins, G. and M. C. Grubb (2008), *A Comprehensive Survey of China's Dynamic Shipbuilding Industry*, CMSI Red Books, Study No. 1., China Maritime Studies Institute, US Naval War College, Newport, Rhode Island.

De La Torre, M. L. (1994), "A review and analysis of modular construction practices," (Thesis presented to the Graduate and Research Committee of Lehigh University). https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-3100780.

Duffey, R. (2019), "Cost, Size and Markets," IAEA Workshop, Idaho Falls, ID, USA.

Garver S. and J. Abbott (2014), "Embracing change: Reducing cost and maximizing mission effectiveness with the flexible warship," Society of naval architects and marine engineers, Alexandria (VA, USA), Vol. 51(3), *Marine Technology*, pp. 22-28.

GIF (2007), "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems", Revision 4.2., GIF/EMWG/2007/004, GIF Economic Modeling Working Group (EMWG), Paris.

GIF (2005), "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems", GIF EMWG, Paris, www.gen-4.org/gif/jcms/c_40408/cost-estimating-guidelines-for-generation-iv-nuclear-energy-systems

Gollier, C., D. Proult, F. Thais and G. Walgenwitz (2005), "Choice of nuclear power investments under price uncertainty: Valuing modularity," *Energy Economics*, Science Direct, 27(4):667-685, https://doi.org/10.1016/j.eneco.2005.04.003.

Google (2009), "Google container data center tour," YouTube video, www.youtube.com/watch?v=zRwPSFpLX8I (accessed on 14 September 2022).

Hussein, M. and T. Zayed (2021), "Critical factors for successful implementation of just-in-time concept in modular integrated construction: A systematic review and meta-analysis," *Journal of Cleaner Production*, Vol. 284, Elsevier, Amsterdam, 124716, https://doi.org/10.1016/j.jclepro.2020.124716.

IAEA (2020), *Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2020 Edition*, IAEA, Vienna, https://aris.iaea.org/Publications/SMR_Book_2020.pdf.

Lawson, R. M., R. G. Ogden and R. Bergin (2012), "Application of Modular Construction in High-Rise Buildings," Vol. 18(2), *Journal of Architectural Engineering*, American Society of Civil Engineers, Reston, VA, pp. 148-154, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000057.

Letter from Kyle Leach with Georgia Power to Reece McAlister with Georgia Public Service Commission, RE: Georgia Power Company's Nineteenth Semi-Annual Construction Monitoring Report for Plant Vogtle units 3 and 4; Docket No. 29849 (2018), https://assets.sourcemedia.com/a0/5b/de057dbb4d6dab264cfc857a7008/gpc-19th-construction-mon.%20report.pdf (accessed August 13, 2022).

Lloyd, C. A., T. Roulstone and R. E. Lyons (2021), Transport, constructability, and economic advantages of SMR modularization. Vol. 134, *Progress in Nuclear Energy*, Elsevier, Amsterdam, 103672. https://doi.org/10.1016/j.pnucene.2021.103672.

Lloyd, C. A. (2020), "Modular Manufacture and Construction of Small Nuclear Power Generation Systems," (Doctoral thesis, University of Cambridge), https://doi.org/10.17863/CAM.46941.

Maronati, G. (2018), "Explaining large observed variation in construction cost of nuclear power plants through correlated random variables" (Doctoral dissertation, Georgia Institute of Technology), https://smartech.gatech.edu/handle/1853/59904.

Mignacca, B., G. Locatelli, M. Alaassar and D.C. Invernizzi (2018), "We Never Built Small Modular Reactors (SMRs), but What Do We Know About Modularization in Construction?" Proceedings of the 2018 26th International Conference on Nuclear Engineering (Vol. 51432, p. V001T13A012). London, England, https://doi.org/10.1115/ICONE26-81604.

MMR® (n.d.), "MMR® Energy System: Micro Modular Reactor Energy System," Ultra Safe Nuclear, https://usnc.com/mmr-energy-system (accessed 13 August 2022).

National Precast Concrete Association (2010) "Why Precast Cost Less," NCPA, https://precast.org/2010/05/why-precast-costs-less/ (accessed 13 August 2022).

Nuclear Newswire (2022), "Another delay, cost bump, for Flamanville-3," www.ans.org/news/article-3573/another-delay-cost-bump-for-flamanville3/ (accessed 13 August 2022).

Office of Nuclear Energy (2021), "New MARVEL Project Aims to Supercharge Microreactor Deployment," www.energy.gov/ne/articles/new-marvel-project-aims-supercharge-microreactor-deployment (accessed 13 August 2022).

Ondrey, G. (2009), "Modular design would shorten construction times for nuclear plants," Vol. 116(10), *Chemical Engineering*, Elsevier, Amsterdam, pp. 16-18. Gale Academic OneFile, link.gale.com/apps/doc/A210441029/AONE?u=anon~c6c762d0&sid=googleScholar&xid=f7118978.

Ontario Power Generation, Canadian Nuclear Laboratories and Mirarco Mining Innovation (2021), *Small Modular Reactor (SMR) Economic Feasibility and Cost-Benefit Study for Remote Mining in the Canadian North: A Case Study*, Toronto, Canada.

Planet (n.d.), "Our Approach," www.planet.com/company/approach/ (accessed 13 August 2022).

Planview (n.d.), "What is Lean Manufacturing," www.planview.com/resources/guide/what-is-lean-manufacturing/ (accessed 13 August 2022).

Ramana, M. V. (2015), "The Forgotten History of Small Nuclear Reactors", Vol. 52(5), *IEEE Spectrum*, Institute of Electrical and Electronics Engineers, pp. 44-58.

SaskPower et al. (2021), *Feasibility of Small Modular Reactor: Development and Deployment in Canada*, Ontario Power Generation Inc, Toronto, Canada.

Shira Teitel, A. (n.d.), "How does SpaceX build its Falcon 9 reusable rocket?" *Science Focus*, www.sciencefocus.com/space/how-does-spacex-build-its-falcon-9-reusable-rocket/ (accessed 14 September 2022).

Shirvan, K. (2022), Overnight Capital Cost of the Next AP1000. Center for Advanced Nuclear Energy Systems, Massachusetts Institute of Technology, Cambridge, MA, USA.

Shropshire, D.E., G. Black and K. Araújo (2021a), "Global Market Analysis of Microreactors," INL/EXT-21-63214-Rev 0, Idaho National Laboratory, Idaho Falls, ID.

Shropshire, D.E, A. Foss and E. Kurt (2021b). *Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review*, GIF/EMWG/2021/001, GIF EMWG, Paris.

Stewart, W.R. and K. Shirvan (2021), "Capital cost estimation for advanced nuclear power plants", Vol. 155, *Renewable and Sustainable Energy Reviews*, Elsevier, Oxford, England, UK, p.111880.

Stone & Webster Engineering Corporation (1977), "Plant systems/components modularization study: Final report. [PWR]," University of North Texas Libraries, UNT Digital Library, Stone & Webster, Boston, Massachusetts, UNT Libraries Government Documents Department, https://digital.library.unt.edu/ark:/67531/metadc1067426/.

Toyota (n.d.), "Toyota Production System," Toyota Production System | Vision & Philosophy | Company | Toyota Motor Corporation Official Global Website (accessed 19 September 2022).

Upadhyay, A.K. and K. Jain (2016), "Modularity in nuclear power plants: a review", Vol. 14(3), *Journal of Engineering, Design and Technology*, Emerald Group Publishing Limited, Bingley, pp. 526-542, https://doi.org/10.1108/JEDT-11-2013-0080.

USNRC (2021), "Construction Inspection Program for New Reactors," Accessed August 13, 2022 www.nrc.gov/reactors/new-reactors/oversight/cip.html.

USNRC (2020), "Aurora – Oklo Application," Application for a custom combined license for a compact fast micro-reactor, www.nrc.gov/reactors/new-reactors/col/aurora-oklo.html (accessed 13 August 2022).

USNRC (n.d.), 52.1 Definitions. www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0001.html (accessed 13 August 2022).

US Department of Defense (2021), "Strategic Capabilities Office Selects Two Mobile Microreactor Concepts to Proceed to Final Design," www.defense.gov/News/Releases/Release/Article/2545869/strategic-capabilities-office-selects-two- mobile-microreactor-concepts-to-proce/ (accessed 13 August 2022).

Wikipedia (n.d), s.v. "Sun Modular Datacenter," last modified 27 January 2022, 11:56, https://en.wikipedia.org/wiki/Sun_Modular_Datacenter.

Winters, J. W., M. M. Corletti and M. Thompson (2001), "AP1000 construction and operating costs," International Conference on Nuclear Engineering, Nice, France.

World Nuclear News (2016), "The benefits of standardization for nuclear projects," www.world-nuclear-news.org/RS-The-benefits-of-standardisation-for-nuclear-projects-22091601.html (accessed 13 August 2022).

YLE News (2019), "Olkiluoto 3 delayed yet again, now 12 years behind schedule," https://yle.fi/news/3-11128489 (accessed 13 August 2022).

THE GENERATION IV INTERNATIONAL FORUM

Established in 2001, the Generation IV International Forum (GIF) was created as a co-operative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by 2030. The GIF brings together 13 countries (Argentina, Australia, Brazil, Canada, China, France, Japan, Korea, Russia, South Africa, Switzerland, the United Kingdom and the United States), as well as Euratom – representing the 27 European Union members and the United Kingdom – to co-ordinate research and develop these systems. The GIF has selected six reactor technologies for further research and development: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very-high-temperature reactor (VHTR).

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