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Options for Achieving Cost Reduction in Advanced Reactors through Open Architecture

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ABSTRACT

A key contributor to high capital costs and schedule overruns for new nuclear power plants is lack of standardization, driven by site-specific customization and construction of multiple designs by competing vendors rather than commitment to a single standardized program. While advanced reactor vendors typically individually target repeat construction of standardized units, the many competing designs could exacerbate the problem. "Open Architecture", the open specification of requirements and interfaces for structures, systems and components (SSCs), has been proposed as a means of promoting standardization, by facilitating existing non-nuclear suppliers to enter the industry and/or allowing some SSCs to be configured for more than one reactor within the same technology type. Here we seek to prioritize areas where this is most beneficial. A preliminary scheme is presented for selection of SSCs for which such strategies could be adopted, based on a vendor make/buy decision model and stakeholder interviews. SSCs are categorized according to number of suppliers and their contribution to the reactor's competitive edge. SSCs with many potential suppliers and a high contribution to competitive edge may be attractive for widening the supply chain via open specification of system requirements and interfaces, e.g., SSCs in the power island. SSCs with few suppliers and low contribution to competitive edge may be potential avenues for common system specification between vendors, e.g., some of the auxiliary SSCs. Potential cost reductions from such strategies will depend upon the size of the build program and the reactor type.

Keywords: open architecture, standardization, modularity, SMR, advanced reactor.

1. INTRODUCTION

In North America and Europe, a key contributor to high capital costs and schedule overruns for new nuclear power plants is lack of standardization, driven by site-specific customization and construction of multiple designs by competing vendors rather than commitment to a single standardized program. Vendors of new reactors (both water-cooled and non-water-cooled[†]) are currently typically targeting smaller systems (~500 MWe or less), aiming to make individual projects financeable, and then taking advantage of modularity and standardization over repeat constructions to bring down costs. However, the large number of reactor vendors could ultimately act against standardization unless a much smaller subset of "winners" emerges.

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† In this paper, we use the terminology SMR for a water-cooled small modular reactor and advanced reactor (AR) for a non water-cooled reactor

The current nuclear industry model utilizes closed architecture, with vendors working individually on proprietary designs. Component purchases from factories represent only a minority of power plant costs; the majority is design work and on-site cost. Although most current reactors are Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWR) built by relatively few vendors, each new build project in North America and Europe typically has significant differences from previous projects. Design changes are typical even far into the construction process. There is limited learning or transfer of experience gained during licensing, design and construction between vendors. Causes of high cost and long lead times in the nuclear industry include site-specific customization of proprietary designs; multiple rounds of regulatory review and modifications; design changes after construction has begun; cumbersome systems of proprietary information exchange; complex project management; low labor productivity while designs are revisited; and accumulation of interest [1]. There is much recent work on the potential for modularity, standardization and improved project management practices to improve nuclear cost and schedule outcomes [1], [2]. However, the benefits of standardization can only be realized across construction of multiple units of each vendor-specific design. Additionally, such strategies can only partially address the immense barrier to entry associated with developing and licensing a new reactor design, which takes several years, costs billions of dollars and involves substantial capital at risk for an extended period of time.

Open architecture (OA) involves collaboration among stakeholders including vendors, customers and regulators to agree on a common but customizable modular architecture with standardized interfaces. This could be applied to a subset of the plant. This enables production learning across advanced reactors (AR) types through reuse of some standardized modules within modular designs. From Ref [3] "the key advantage of open collaborative innovation is that each contributor can undertake some of the work but rely on others to do the rest." Multiple organizations can collaborate on shared platforms to specify parameters for interface requirements. Innovations can propagate rapidly throughout the industry, and multiple SSCs can be improved simultaneously by different organizations. New and smaller vendors can specify their designs according to the OA standard and may focus on the design of a nuclear heat source that can be interfaced with a standardized balance of plant, reducing the currently very substantial barriers to entry and enabling scale up. Design risk can be reduced as the standards required to guide the design work become well understood. This concept has been applied to shipbuilding [4], the aerospace sector [5] and in defense systems [6]. It is noted that some SSCs are currently nonetheless already standardized products. Salient examples include the steam turbines (which are off-the-shelf customizable products) and the fuel.

Most non-water-cooled ARs envisage reducing the number of safety-classified SSCs, in many cases confining these to the SSCs within the primary heat exchanger. Some ARs plan to use molten salt thermal energy storage (TES) in an intermediate loop both to enable dispatch at times of peak demand and to facilitate separating the nuclear island from the balance of plant. Ref. [7] proposes using such a scheme to enable standardization of the balance of plant between reactors. i.e., if many different types of reactor supply heat to a nitrate 'solar' salt system operating at around 560°C, then these could in principle utilize a common balance of plant design as this would become independent of the nuclear heat source. This could be somewhat challenged by differences in reactor thermal output, but some variation could be accommodated.

Ref. [8] additionally proposes the use of a standardized reactor building. Vendors could then design a nuclear heat source to fit within this building. This approach is potentially compelling because the building is a significant contributor to reactor costs [9] due to the need to design for seismic events and external hazard, notably aircraft crashes. A challenge of this scheme is that different reactor concepts can be of very different sizes and profiles, and, as discussed further below, vendors' approaches to external hazard differ significantly between concepts.

These two schemes could be generalized into an overall standardized approach to a nuclear heat source. Such a strategy for standardization has been proposed by Terra Praxis (Figure 1).

Such an approach must be applied strategically in order to be compatible with the very different sizes and coolants (water, gas, molten salt, liquid metal) pursued by advanced reactor vendors. Additionally, designs are at very different levels of technical maturity which can exacerbate commercial barriers to information sharing. The goal of this work is therefore to present a set of priorities, opportunities and strategies where common ground could be found, and a methodology for estimating the potential cost reduction that such strategies could achieve, and therefore enable a cost-benefit decision to be made. The work presented here is preliminary and is intended for feedback from the community.

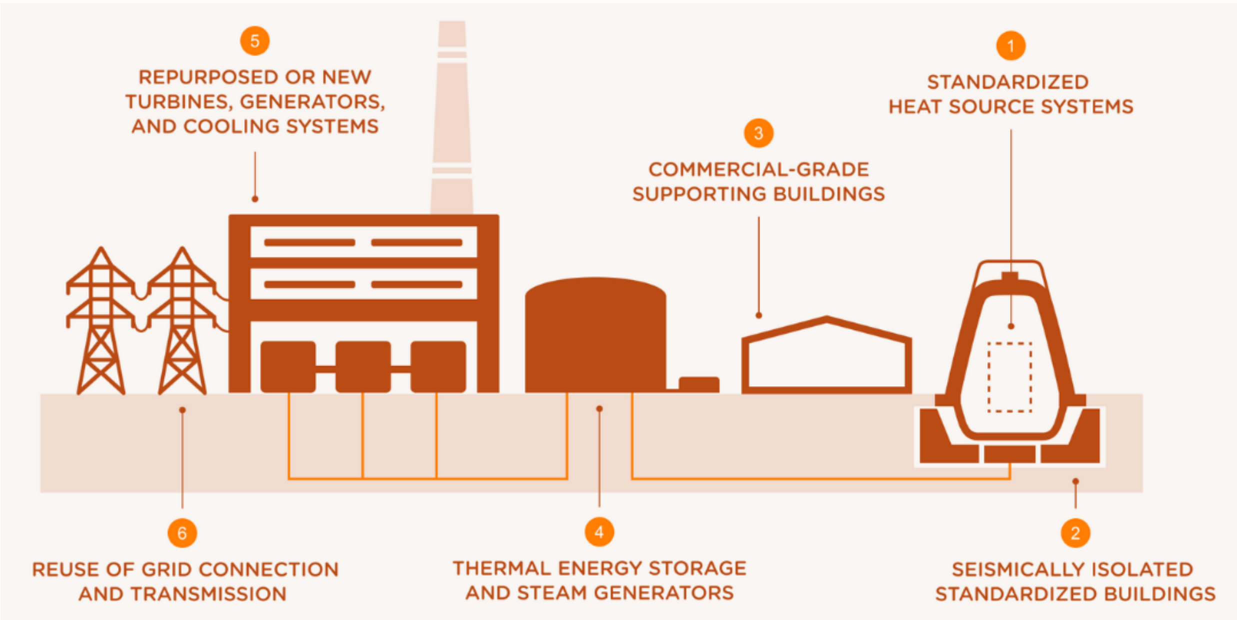

Figure 1. Strategy for Standardization developed by Terra Praxis [8]

In this paper, we consider two overlapping approaches for implementation of OA in SMRs and ARs, where OA is defined here **as defining and publishing requirements of SSCs in functional and/or interface terms, utilizing technical standards in widespread use.**

- This approach firstly presents a route to widening the supply chain for nuclear plant SSCs through facilitating traditionally non-nuclear suppliers to participate in the design and supply chain, thus exploiting optimization and learning in these suppliers (**one-to-many OA**).
- Furthermore, if functional and interfacing requirements can be harmonized for a particular system or component, this can then be used in multiple reactor designs, and thus the design of the system does not need to be repeated, and the frequency with which it is constructed is increased, hence leading to improved learning and reduced costs (**many-to-one OA**).

The objective is therefore to develop a method for OA-enabled standardized design of modules and interfaces across the wide variety of ARs of different temperatures, sizes, pressures and producing different energy products and evaluate the extent to which this is possible. This work forms part of a larger overall U.S. Department of Energy-funded project which additionally considers standardized design across sites; licensing implications; and project delivery systems that harmonize with OA practices.

2. METHODOLOGY

A combination of qualitative and quantitative methods is performed:

- Interviews are conducted with reactor vendors to determine (among other things) the SSCs vendors regard as crucial to self-perform (i.e., make rather than buy) and protect from a commercial standpoint, and those they do not.

- The breakdown of SSCs within an SMR and AR is utilized. SSCs are classified according to various criteria to determine their suitability for the OA strategies identified above, based in part on the vendor interviews.
- A cost analysis is performed using code of accounts cost data (as available) for the various reactor types, along with existing cost models for modularization and production learning, to estimate the savings that could be achieved as a result of these strategies.

The methodologies used for each portion of the analysis are described in more detail below.

2.1. Stakeholder Engagement

So far, 13 SMR and AR vendors have been interviewed to gather information on the potential for OA within such systems. The size ranged from microreactors to systems at the ~500 MWe power level. These include:

- Three water-cooled SMRs.
- Four high temperature gas-cooled reactors
- Two sodium-cooled reactors
- Three molten salt reactors
- One which does not fit into the above classifications.

Data relevant to this paper was gathered on:

- The overall configuration of the reactor (i.e., which SSCs it contained and high-level information on their physical layout).
- The SSCs that the vendors regarded as being crucial to design and supply vs SSCs where performance is less of a differentiator.
- The SSCs that may be procured through the supply chain.

Only summary information is presented at this time to protect anonymity of responses. Future publications may provide a more detailed breakdown of responses.

2.2. System Categorization

Four factors are utilized to categorize SSCs in order to determine OA availability:

1. The outcomes of the stakeholder engagement are used to inform SSCs that the vendor would not consider openly specifying or outsourcing to the supply chain.
2. Safety classification of a system may disincentivize its applicability for OA because the vendor may wish to own the design of the system as they are ultimately responsible for reactor safety.
3. Modularization is a useful criterion because road transportation of modular reactor components allows work to be moved off-site and schedules shortened, reducing interest during construction (IDC) and related indirect labor costs [10]. For LWRs, modularization percentage is measured based on the work done by Stone & Webster Inc. on a reference nuclear power plant (NPP) design [11] and Ref. [10].
4. Make-buy decision that accounts for customer value in SSCs, i.e., the degree to which they differentiate the reactor and drive overall performance. The four-box model, displayed in Figure 2, is adapted from [12], [13] and forms a make-buy decision on the part of reactor vendors in classifying which SSCs must be controlled, and which could be completed through market suppliers.

The quadrants are numbered row-wise from left to right: quadrant 1 (High Competitive Edge, Low Number of Suppliers), quadrant 2 (Highly Competitive Edge, High Number of Suppliers), quadrant 3 (Low Competitive Edge, Low Number of Suppliers), and quadrant 4 (Low Competitive Edge, High Number of Suppliers).

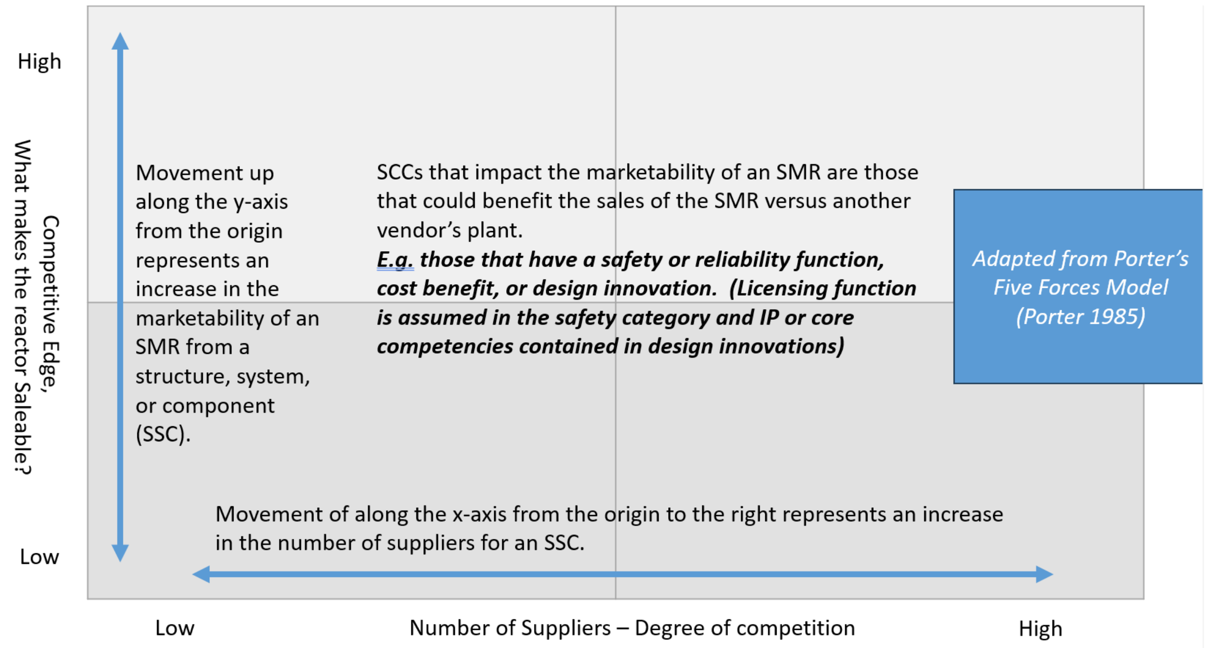

Figure 2. Make/Buy matrix process

Assigning SSCs to quadrants in the model is a multi-step process by assessing the SSC's importance to the marketability of the SMR and assessing the number of suppliers for the SSC with a "High/Low" result in each case. Each quadrant results in different market power for the vendor or supplier and sourcing choices completed through the SSC's design specification and supplier relationship. The market power dynamic is represented below in Figure 3 where supplier power is high in the left column and vendor power is high on the right. Power here is the ability to set prices or retain cost-reduction benefits from learning. The ability to set prices is related to the barriers to entry for competitors.

It is envisaged that different strategies will be applicable to different areas of Figure 2. One-to-many OA, as a means to widen the supply chain for nuclear SSCs through facilitating traditionally non-nuclear suppliers to participate in the design and supply chain, is most applicable to the top right box, as there are a large number of potential suppliers but the market power of such SSCs is high, so there is potential to capture value from production learning.

For SSCs in the bottom left box, a supplier has significant power to capture value from production learning, but there are few suppliers and therefore widening supply chain participation may be difficult. However, OA may reduce barriers to the entry of new suppliers which would reduce supplier power. Also, there may be opportunities for standardization between reactors (many-to-one OA) as:

- The impact of the SSC on marketability is low, so optimizing the system for a particular application is less important and the performance hit associated with using a cross-standardized design is lower.
- As there are few suppliers, there are opportunities for one supplier to supply the system to more than one reactor vendor.

A challenge of this approach is that the potential for the supplier to capture value is high, so strategic partnership between vendor and supplier is important. This is also potentially an area for strategic intervention as part of a state program. Also, cross-standardization is more applicable to lower technical maturity designs, where the whole plant has not yet been designed.

SSCs in the top left box are likely to be either self-performed or performed by a strategic partner/controlled source. SSCs in the bottom right box could be outsourced by competitive tender.

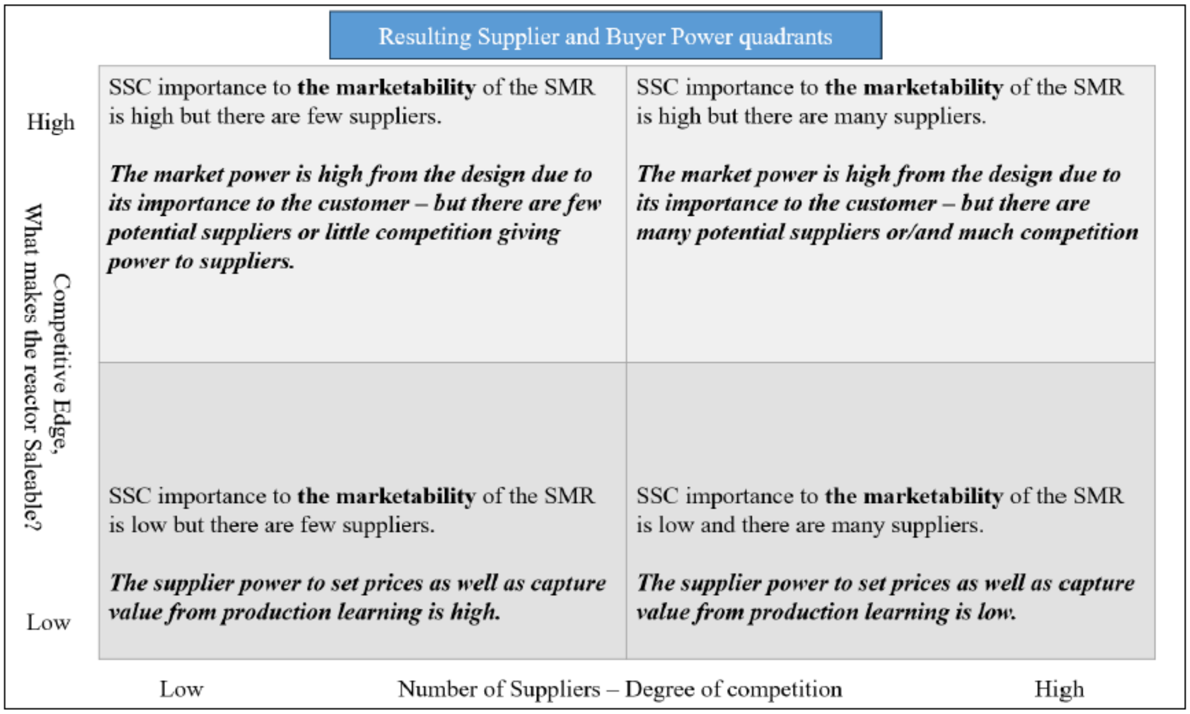

Figure 3. Supplier and Buyer Power Quadrants Based on the Market

2.3. Baseline Cost Model

Light water SMR cost data was sourced from Energy Economic Database (EEDB). Modifications were performed to this data to account for modularization and standardization, sourced from previous work in Refs. [10], [12] (which describe the full model), along with an estimate for inflation. Development of a cost model for ARs is a work in progress. Three reference ARs will be considered with associated costs estimates: sodium-cooled fast reactor [14], high temperature gas-cooled reactor [15] and a molten-salt cooled, solid fueled reactor [16]. The key criterion here is to capture the breakdown of costs between SSCs to the extent possible, so that percentage cost reductions may be estimated. Absolute costs are less important, and no inference is intended on the relative cost between SMR and the various advanced reactor types.

A full description of the cost model is provided in Ref. [17]. For non-OA systems, the production learning rate is proportional to the logarithm of the production rate, with 2% learning at 1 unit/year and 15% at 12 units/year [12]. Site learning is set to 2% [12].

OA is modelled in four steps [17]. First, a higher learning rate of 20% is applied to EEDB accounts found eligible for OA based on learning rates from other modular energy technologies [18]. Second, prior learning of OA suppliers is applied using an adaptation of the Stanford-B learning curve [19] and Ref. [20],Third, additional labor savings are sought based on [21] and modularization labor savings assumptions are applied. Fourth, accounting for prior learning in [20] is done by providing a "Spillover Factor" (B), taken here as 7 doublings [22], starting the "number produced" at 128. The form variation in this equation is an alternative method of writing the Wright learning equation [23]. Utilized in this study's model, spillover results in a lower initial cost for OA-eligible SSCs due to knowledge transfer.

$$\text{Cost}_i = \text{Cost}_0 \times (1 - \text{Learning Rate})^b \text{ where } b = \frac{\ln(\text{Number Produced} + B)}{\ln(2)}$$

3. RESULTS

3.1. Findings from Stakeholder Interviews

From the stakeholder interviews, it was found that:

- Most reactor vendors were focused on the core and primary system as their point of differentiation, which would be self-performed. In most cases, the AR vendors are focusing on designing the core and associated SSCs as their primary competency. There we exceptions here, with one vendor stating that their entire system would be self-performed. This concept was at the smaller end of the surveyed power levels.
- One AR vendor targeted separation of the core and primary system from the balance of plant. This presents opportunities for use of traditionally non-nuclear suppliers for balance of plant SSCs.
- For reactor vendors with relatively mature designs and programs, there were in many cases concerns around harmonizing system design or openly sharing system specifications due primarily to intellectual property concerns, but also maintaining a competitive edge when compared with less mature vendors. Maintaining control over the design was also mentioned by some vendors.
- The large majority of the AR vendors were open to using SSCs designed elsewhere if & when they became available and met their requirements. This includes sourcing SSCs from the supply chain.
- At least four of the surveyed vendors intend to use molten salt TES with separation of the nuclear and power islands. This presents an opportunity for harmonization of the SSCs downstream of the TES. It was noted by multiple vendors that at least the connection of the TES to the primary system would generally be considered proprietary.
- There are a wide range of approaches to design for external hazard, leading to varying interest in a standardized reactor building. Some vendors were interested in a standardized reactor building, subject to it being compatible with their specific technology. Other approaches included fully siloing the reactor so that there is no external hazard claim against the building (at least two vendors) and using a compact concrete structure around the core and primary SSCs to protect against external hazard. For microreactors, there is interest in using commercial grade structures if a safety case can be made here.

Note that there is a significant overlap between the factors identified in Section 2.2 and the position of vendors. For example, the core and primary system tends to be part of the vendor's core competence, is also of highest safety classification and is typically a strong driver of overall performance.

3.2. Potential for Cost Reduction in Water-cooled SMRs

A system of classification for water-cooled SMRs was developed according to the methodology described above. Here, it was also assumed that systems that were not modularizable would not be suitable for OA as production could not be moved offsite, although this assumption will be relaxed in future work as a standardized design is still a means to reduce construction costs. These are summarized in Figure 4. The analysis focused on SSCs that could be sourced from the wider supply chain (Box 2 in Figure 4), with 36% of the code of accounts found eligible by this metric.

Cost savings due to OA were stacked with other projected savings as described in Section 2.3. When many reactors are built (e.g., 250 MWe reactors, 100 units built), production learning is projected to be significant and the benefits from additional learning through OA are relatively small (3% in our analysis).

OA is projected to be more beneficial in cases where the production rate is lower. For a program of 50 units of a 500 MWe reactor, the cost saving from OA increased to 8% (Figure 5). While the exact value is a function of the model parameters, this is indicative that OA may be effective at reducing costs if relatively few units are built, due to the potential to take advantage of existing learning in suppliers. As vendors are yet to build reactors, cost reductions achieved in the first few reactors are likely to be attractive.

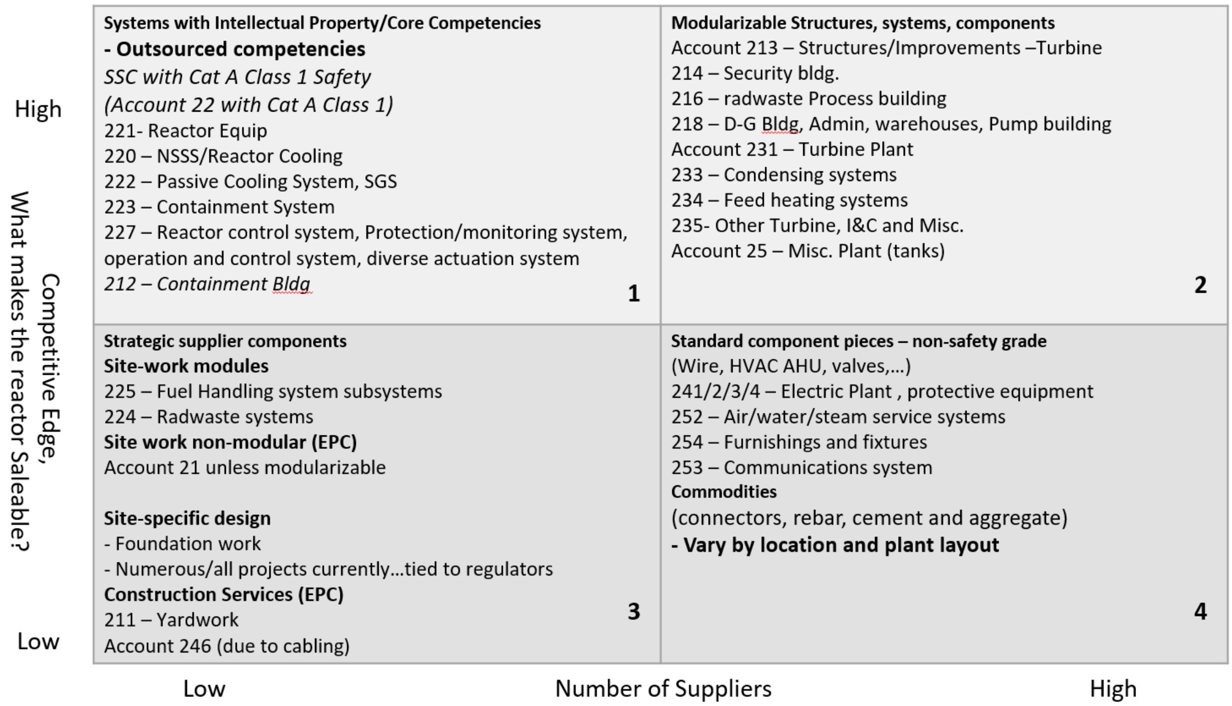

Figure 4. Supplier and Buyer Power Quadrants Based on the Market

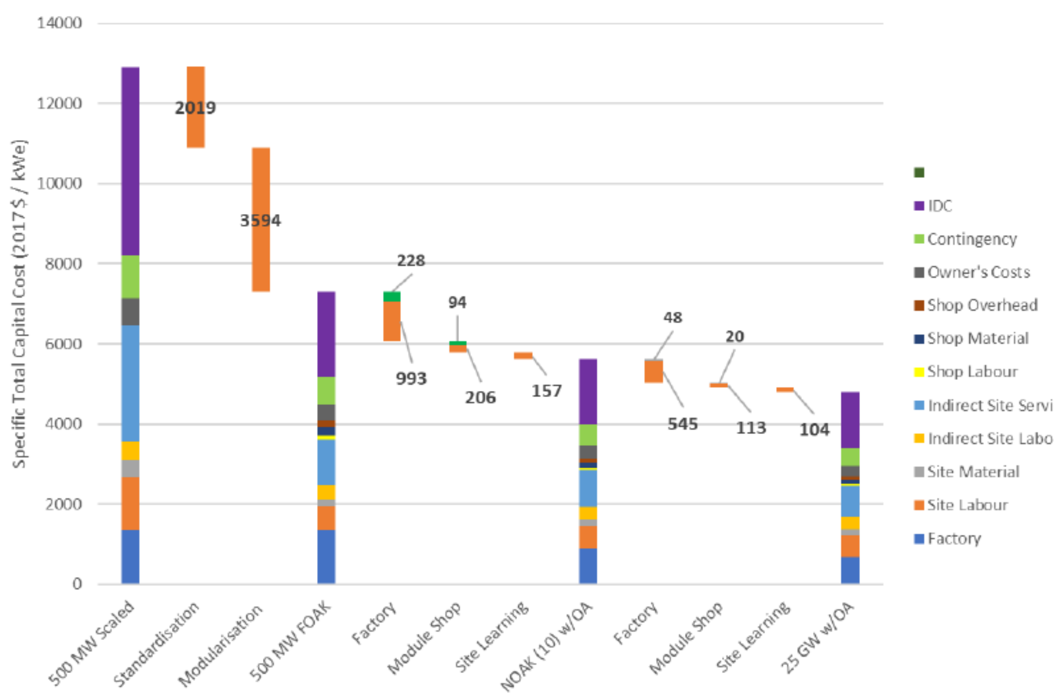

Figure 5. Cost model for a Reference 500 MWe SMR then adjusted account to standardization, modularization and repeat built. OA cost reductions shown in green

4. CONCLUSION AND FUTURE WORK

Vendors are typically seeking to design and construct SSCs in the reactor island, typically the core and primary system. Most vendors are open to sourcing other SSCs from suppliers. There is therefore potential to define and publish requirements of SSCs in functional and/or interface terms, utilizing technical standards in widespread use, for SSCs outside of the core and primary system. SSCs that have a high impact on system performance, and a high number of suppliers are particularly well suited to procuring through such a process. Favorable SSCs include systems in the turbine building and some generic auxiliary systems. OA is a favorable strategy when a smaller number of reactors are built, as the importance of spillover learning is then greater, thus making it easier for AR vendors to enter the market.

SSCs that have a low impact on system performance and low number of suppliers may be suited to harmonization of specifications between reactors of the same type. A preliminary example is the sodium purification and auxiliary liquid metal SSCs in an SFR, which have a non-trivial impact on cost due to the complexity of handling sodium and are a specialized system anticipated to have few suppliers but which will perform essentially the same function in all SFRs and have a low impact on reactor marketability. Standardizing such systems can help reduce system costs, and also, perhaps more importantly, the one-off costs associated with designing and licensing a reactor.

This analysis does not preclude attempts to standardize the buildings (in particular, the reactor building) as this was not generally identified as a core competence by the vendors. However, it is noted that the approach to external hazard varies significantly between vendors. Similarly, the strategy of using a nitrate molten salt TES with ARs potentially allows both widening the supply chain and converging on specifications for the balance of plant, perhaps for a set of prescribed size options for the TES system (which would combine 'many-to-one' and 'one-to-many' OA within a single scheme). This is because a TES allows some variation in the power output of the nuclear system to be accommodated with the same TES and turbine size by changing the dispatch profile of the system.

Future work will include:

- A qualitative and quantitative analysis of impact of the project delivery system. This is important as it impacts the vendor/supplier relationship, and also it is postulated that project delivery systems that facilitate information sharing (e.g., Integrated Project Delivery) may synergize with OA.
- Completion of the AR cost model, followed by utilizing this to investigate the impact of OA strategies, extending the work performed on light water SMRs.
- Quantification of the degree of cross-standardization that may be possible in ARs and identification of OA case studies.

NOMENCLATURE

AR – (non-water-cooled) Advanced Reactor; **OA –** open architecture; **SMR** – (water-cooled) Small Modular Reactor; **SSC** – systems, structures and components; **TES** – thermal energy storage

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