TRANSITION FROM TRADITIONAL NUCLEAR ENERGY

TO FUNCTIONAL NUCLEAR ENERGY IN THE GLOBAL ENERGY MARKET

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EXECUTIVE SUMMARY

Nuclear energy is an important aspect of U.S. national security due to control of non-proliferation in the world and by providing long-lasting political and economic relationships between the U.S. and other nations. However, the current global nuclear energy market growth is dominated by the Asia-centric state-sponsored enterprises. This situation raises concerns on the future U.S. export potential of nuclear energy and the stability of U.S. national security. Although the domestic energy demand growth is expected to have a slow growth, the global energy market has a growth potential with estimates of a total value of around $20 trillion by 2050. It is estimated that nuclear energy can capture ~5% of this dollar estimation with the markets focused in non-OECD countries.

There is an on-going transition from the traditional nuclear energy to functional advanced nuclear energy, where advanced nuclear energy options provide the flexibility in new functions aside from producing electricity. The developed next generation nuclear reactor portfolio composes of small-scale reactors to remote communities or businesses to large-scale nuclear energy options for baseload production along with feeding other industries, heat or hydrogen production as examples. Given the sufficient investment and support on the development of advanced reactors, they have the potential not to suffer from the cost and schedule delays that the traditional nuclear energy has been experiencing for a considerable time.

The U.S. government and private industry have the longest history of expertise in nuclear energy among other nations in the world. The historical expertise can enable U.S. to gain large shares in the international nuclear energy market with the successful and timely development and deployment of advanced nuclear energy options. The strengths and weakness of the U.S. nuclear energy companies/government and the opportunities and threats in achieving this goal is summarized below.

The biggest hurdles for a successful export of advanced nuclear energy in near future may be summarized under the following topics: 1) cost-competitive and sustainable nuclear energy, 2) first-of-a-kind challenge, and 3) stable and supportive policy environment. These hurdles with potential approaches to resolve them are provided below.
Meanwhile the developments are continuing in

Figure E1. SWOT analysis of U.S. nuclear energy export potential: strength, weaknesses, opportunities and threats

Strengths

US companies
- Strong technical innovation culture in nuclear
- Renowned high-quality manufacturing capabilities
- Rooted knowledge and expertise in nuclear energy
- Esteemed quality assurance for delivered products
- Highest safety standards in nuclear energy deployment and operation

US government
- "Gold standard" regulatory knowledge around the world
- Strong international diplomatic, investment, R&D and fuel cycle relationships
- Support from International Development Finance Corporation
- Funding nuclear energy R&D, programs and demonstrations (National Laboratories, NRIC, ARDP, ARPA-E)

Weakness

US companies
- Cost and schedule overruns for recent US nuclear projects
- Challenges in establishing global supply-chain for nuclear energy deployment
- Public perception on nuclear energy
- Focusing solely on nuclear related aspects and finalizing balance of plant at later stages
- Not established business models to get the most out of advanced nuclear opportunities

US government
- Non-proliferation requirements may become burdensome for advanced nuclear energy
- Strict export control requirements may dispel potential customers
- Long timelines for nuclear energy R&D and demonstrations may result in US advanced nuclear energy to be deployed during an established global market

Opportunities
- Global energy growth ahead, especially non-OECD
- Potential cost reduction with advanced nuclear energy
- Gain unmatched experience in next generation nuclear energy by domestic nuclear projects
- Transition from traditional to functional nuclear energy through hydrogen production, industrial process heat, and residential and commercial district heating
- New business opportunities leveraged at remote communities, mining operations and marine shipping
- Long-term strategic relationships at nuclear energy exported countries

Threats
- Domination of Asia-centric state-owned enterprises in the global nuclear energy market
- Skewed global manufacturing supply chain distribution around the world
- Dependency on fuel supply chain on other nations
- Potential faster learning curve for state-owned enterprises in advanced reactor deployment
- Increased influence of China in global markets through world-wide infrastructure deployment activities
- Increased cost-competitiveness of other energy sources against nuclear energy in short and mid term
- Instability in US policies for nuclear energy development

advanced nuclear energy, the U.S.: 1) needs to preserve the baseline domestic nuclear energy market and industry, 2) continue challenging the state-sponsored enterprises in the nuclear energy market arena, and 3) adapt the government and business strategies based on the capabilities and unique opportunities arising from advanced nuclear energy.

GLOBAL EXPORT OPPORTUNITY FOR NUCLEAR ENERGY

U.S. Energy Information Administration (EIA) projects a 50% increase in global energy demand by 2050. The reported data[3] show relatively steady energy consumption projections for countries in the Organization for Economic Cooperation and Development (OECD). However, the projected demand is different for non-OECD countries, where the expected increase is around 50% with the hot spot being Asia. The same study estimates a ~50% increase in the nuclear energy source capacity, but a decrease in terms of percentage in the energy portfolio comprising renewables, natural gas, coal, petroleum and other liquids. World Energy Council (WEC) estimates that a significant investment is required to meet the electricity demand until 2050. The dollar value of these estimates has a lower bound of $19 trillion and upper bound of $26 trillion. WEC also reports that the majority of this value will be captured by renewables. However, it is argued that the percentage share of each energy source depends on the availability of the investment funds.

The future of the export of US-involved nuclear energy will also depend on the energy source distribution pattern across the world. Some of the current major factors affecting the distribution pattern and stability of global energy pool and demand include: i) Russia's political influence on several energy options and ii) the centralization of global supply chains in China and the economic growth of China. A potential shift in the distribution of the global supply chain across other countries will definitely change the energy demand pattern across the globe. However, the unforeseeable events, such as the outbreak of the novel coronavirus pandemic in 2019, may force countries to focus on economic recovery or sustainability rather than growth in economy and energy demand in near future.

GENERAL OUTLOOK OF NUCLEAR ENERGY

International Atomic Energy Agency (IAEA) provides projections on energy[4], electricity and nuclear power up to 2050. IAEA expects that world energy consumption will increase by 40% by 2050 with an annual growth rate of about 1%. The share of electricity in total final energy consumption is projected to be around 25%. Meanwhile, IAEA estimates that world nuclear energy electrical generating capacity will increase by 80% at the upper bound until 2050. This kind of increase puts nuclear electric capacity at 5% in the world total electric capacity portfolio.

IAEA also provides projections for the nuclear energy generation capacities at different regions of the world from 2018 to 2050. The Northern America, and Northern, Western and Southern Europe regions' nuclear electrical generating capacity will be reduced by 30-50%. However, Central and Eastern Asia region is expected to double their capacity by 2050, where the markets are already dominated by state-sponsored enterprises. Southern Asia, Western Asia, Eastern Europe and Latin America are expected to have nuclear energy as an emerging electricity generation source by 2050.

EMERGING NUCLEAR ENERGY OPTIONS AND TECHNOLOGIES

The traditional nuclear energy option is unique in the sense that iterations or recursive approaches in product development is not efficiently possible due to i) infrequent deployment of the plants, ii) high cost of the end product, and iii) physical size of the complete product. The infrequent deployment of the nuclear energy and no established active market for future plants in the U.S. also hinder the entry of possible private entities to the nuclear space that focus and have expertise on technologies outside the reactor technologies. The traditional light water reactors (LWRs) have been successfully operational for decades. However, they have been challenged in recent builds with cost and schedule overruns. These challenges have been experienced at the deployment of balance of plant level, but not the reactor technology. There are several reasons for this including loss of experience in the deployment to unique safety and regulatory requirements of LWRs.

The recent challenges occurring in the industry with the new builds may also seem preventative for any future investments by the industry. Therefore, an effort is required to increase the confidence of the industry for future investments and alleviate the variable demands of the nuclear energy deployment for different reactor concepts and designs. Such an effort requires a high degree of collaboration among research institutions, utilities, designers, contractors and many other branches of the nuclear industry and business and government. Often mentioned but usually not discussed in detail, commercial viability proven modern construction techniques and approaches such as modularization and pre-fabrication requires crafts, engineers, and personnel with different skill sets to efficiently work together to minimize on-site disputes.

The available and near-future nuclear reactor concepts may be housed in structures with different materials, construction approaches, dimensions and sites. The opportunities that arise from such flexibilities have the potential of increasing the customer base, kick start the nuclear energy sector and may ease the entry point of different scale companies and create a competitive environment that will be beneficial for every party involved in terms of efficiency, cost and safety.

The U.S. nuclear enterprises have been investing in developing and licensing alternative nuclear energy technologies to the current LWR technologies and practices for decades. These reactor technologies are sometimes referred as advanced reactors or next generation nuclear power plants although they have a history going back to the '60s. Some advanced reactors will be different from LWR technologies and use gas, molten salt, or liquid metal as a coolant. Some of them will be LWR-based technologies with smaller footprints than the current ones. Microreactors are also gaining attention for military or space applications.

The Advanced reactors, from microreactors to small modular reactors (SMRs) to high temperature gas-cooled reactors, pose unique opportunities and safety features different from the large-scale LWRs. The safety features of advanced reactors enable using off-the shelf components and significant cost reduction potential in construction through the functional containment approach.

The vision from DOE's perspective for the advances in nuclear energy for the technologies discussed above is as follows[1]:

> *The large light-water reactors common in today's market will, in the future, be joined by new advanced reactors, including light-water advanced small modular reactors (SMRs), advanced non-light water reactors, and a subset of SMRs known as micro-reactors. Some of these advanced reactors will provide electricity to remote locations while others will provide high-temperature process heat for nonelectrical services such as desalination. Other technologies under development could also provide options for the management of waste from nuclear power.*

ROADBLOCKS AND REMOVING THEM

COST-COMPETITIVE NUCLEAR ENERGY

It is usually emphasized that nuclear energy has a vital role in a carbon constrained world. Although this argument holds one of the key points in slowing down the air pollution attributed environmental risks, nuclear energy's sole role as a clean energy source may not make it a commercially desired product. If the goal of the world's strongest economy is to export nuclear energy to the other parts of the world, the product itself needs to be also economically attractive to the counterparts.

Advanced reactors, micro reactors and small modular reactors provide hope for possible cost reductions and increased competitiveness in the nuclear energy projects. However, the actions taken today by the nuclear industry and DOE play a crucial role for the faith of the domestic and global nuclear energy capabilities of the U.S. in the next decades. The future energy demand growth in the country may hinder the need or desire for a strong domestic nuclear energy sector. Such a potential domestic energy market environment increases the importance of understanding the need for export of nuclear energy.

If the high cost of nuclear energy is dominated by the issues related to what-is-outside the reactor, then the question is: how will the advanced reactors become cost-competitive? Economies of scale is one of the arguments that is often discussed. Some of the advanced reactors and their balance of plant are relatively smaller in size compared to current plants. This allows less financial and schedule overburdens and associated risks. Additionally, using off-the-shelf components for the advanced light water and non-LWR reactors and plants will ease the supply chain challenges. There is an emerging approach, functional containment[16], in the regulatory environment that has the potential to change the course of nuclear energy deployment in near future, specifically for advanced reactors. This approach has not found the time to have a widespread recognition, yet. When the regulator and the supporting entities make it a reality, cost-competitive deployment of nuclear energy will be highly possible. Many of the current regulations have been written based on safety requirements of the LWR technologies. They are mostly prescriptive and deterministic. Functional containment approach provides the flexibility in design as long as each safety barrier's performance for preventing radioactive material release is met. This concept is referred as the "functional containment". These barriers may include from the fuel to structures surrounding the reactor.

Functional containment does not specifically mean a structure like the containment structure, but a set of barriers designed to prevent any release of radioactive material to the environment. These set of barriers include from the cladding of fuels to passive safety systems to possible structures that prevent the release if the fuel barriers are breached.

Functional containment approach will shift the prescribed engineering environment in the nuclear domain towards more risk-informed and technology inclusive engineering design approaches. This brings a variety of availability of engineering decisions, approaches and technologies as long as the required safety is satisfied.

FIRST-OF-A-KIND (FOAK) CHALLENGE

It is a commonly accepted argument that the first of a kind (FOAK) deployment of a nuclear power plant is more costly than Nth-of-a-kind plants. The reduction in the cost as time passes can be attributed to the learning in the deployment phase and mature supply-chain management. FOAK cost of advanced reactors may discourage some of the investors as the uncertainty in the cost and schedule will be at a maximum level compared to the subsequent deployments. The first deployment also requires high confidence and stability in the regulatory environment that prevent costly changes during deployment. At this stage, support from the government plays a crucial role for the future export potential of advanced reactors in the global market.

National Reactor Innovation Center (NRIC) is a DOE program led by Idaho National Laboratory, allowing collaborators to harness the world-class capabilities of the U.S. National Laboratory System[17]. NRIC is charged with and committed to demonstrating advanced reactors by the end of 2025. Demonstration of advanced nuclear systems will have lots of positive impacts on the deployment of FOAK advanced nuclear power plants in near future. Construction schedule and costs have the highest impact during the deployment of the recent builds. Such delays in the schedule and increased cost also have cascading effects on the overall cost due to accumulated interest. Not only nuclear engineering related demonstration of advanced nuclear power plants is necessary, but also demonstration projects and increased experience in construction technologies are necessary. NRIC has also initiated their efforts in this area along with the reactor technology demonstrations. NRIC aims to partner related to the development and demonstration of advanced construction technologies and processes that would be transformative in improving nuclear power new-build economics and scheduling.

Financial support for the FOAK plants is also an important pillar for the success of the U.S. nuclear energy. DOE has approved a cost sharing award over $1 billion for the FOAK domestic deployment of NuScale SMR[18]. Although this deployment will reduce reliance on coal-based energy, the uncertainty on the construction cost is causing concerns and delays in the deployment. While the discussions on the FOAK deployment of SMRs are going on, the US International Development Finance Corporation has signed a Letter of Intent in supporting the export of SMR technology to South Africa[19].

POLICY AND PUBLIC OPINION SUPPORT

Although fossil-based fuels will last more than half a century, they are still time-limited resources. Innovation and support for innovation in nuclear energy are necessary for clean, sustainable and scalable energy that the world needs in the short and long term. It is also hard to predict how long the honeymoon on low natural gas prices will last in the international markets. For small modular reactors (SMRs), there has been an on-going discussion whether economies of scale will make them cost-competitive. In the case of energy demand in the U.S. does not increase significantly in the following decades, SMR technology needs to be exported to get the best out of potential economy of scale.

Most of the advanced reactors including microreactors will require a fuel that is not available at commercial scales: high-assay low-enriched uranium (HALEU). This type of fuel is different than the ones used and readily available in the traditional nuclear energy markets. DOE has near-term and long-term approaches for the production of HALEU [21]. The short term includes working with the national laboratories to provide small amounts of HALUE to nuclear vendors. The long-term approach is partnering with private industry for establish the manufacturing capabilities that support the demonstration of advanced reactor projects and nuclear vendors. Therefore, a stable policy environment support of DOE's approaches with national laboratories and private industry in fuel production is critical for the success of advanced reactors.

Section 123 of the U.S. Atomic Energy Act generally requires the conclusion of a peaceful nuclear cooperation agreement for significant transfers of nuclear material, equipment, or components from the United States to another nation[22]. Improvements in the efficiency of 123 agreements at every branch of the government is necessary in order to expand the export of advanced nuclear energy options to other countries, especially non-OECD countries. The slow processes may result in loss of competitive advantage in the global markets, where bureaucracy may take longer than the deployment of relatively smaller size advanced reactors.

TRANSITION FROM TRADITIONAL TO FUNCTIONAL ADVANCED NUCLEAR ENERGY

The U.S. may pursue a threefold approach in order to compete with the state-sponsored enterprises in the global nuclear energy market:

PRESERVING

~20% of the energy in the U.S. is generated by the existing nuclear power plants. There is already an industry formed around these clean energy sources supporting the maintenance and operations of the existing fleet. Although the existing fleet may struggle with cheap natural gas at the moment, having a baseline nuclear energy market and industry is the first step in the right direction for the U.S. nuclear energy industry. A sharp decrease in the amount of operational nuclear energy in the U.S. will adversely affect the nuclear accredited N-stamp vendors and manufacturers in the country. Although the expectation with the advanced nuclear reactors and the balance of plant to reduce the number of N-stamp components in the overall design, it is crucial to have experts, engineers and practitioners for the nuclear energy in the U.S. for the long-term success around the world. It can be argued that when orders for new builds are in place, the relevant suppliers in the U.S. will grow over time.

CHALLENGING

The U.S. still has lots of capabilities that can be leveraged in the global market. Leaving the nuclear energy market arena to state-sponsored enterprises should not be an option, while waiting for the development, demonstration and deployment of next generation nuclear energy options. In order to sustain the baseline existence in the global nuclear energy business, both the government and the private business have duties that need to be continuously pursued.

The challenge in the world markets cannot be easily isolated to U.S. nuclear industry. The competition has been ramping up in other industries such as the automotive or heavy manufacturing industries that directly impact the U.S. enterprises. The challenge needs to be handled as a common national security problem. The actions taken by the U.S. government should focus on challenging state-sponsored industries from penetrating the current technology and product export. Otherwise, competition between U.S. privately owned enterprises and state-sponsored enterprises will always cause systematic problems.

ADAPTING

The safety and technical uniqueness of nuclear energy among other high-technology products makes it longer to get it off the ground. Given the political, regulatory and mixed public opinion for traditional nuclear energy around the world, it is challenging to make the advanced reactor business adopted globally without any frictions. This is particularly important for the next generation nuclear energy innovators and businesses. The time required to develop advanced nuclear reactors requires sustained capital inflow, adoption to new business models that will successfully work in the next decades, protection of intellectual property, and communication with the public and governments for increased awareness in safety and value proposition of advanced reactor technologies.

Whether the nuclear reactors are commercially introduced by the U.S. enterprises or not, it needs to be planned in advance to extend the life, profitability and cost-competitiveness of the nuclear energy products that are being developed. It is important to introduce new business strategies such as variety in the usage of nuclear energy, expanding the market by thinking of nuclear energy as the building block for other business cases.

Globalization in world markets has also influenced the nuclear energy business, manufacturing and deployment. Distribution of the heavy manufacturing industries across the globe has resulted in challenges in supply-chain and communication. These challenges were present in the recent builds in the U.S. The anti-thesis of the globalization has been seen by some through isolation/de-globalization and bringing back some of these capabilities to the U.S. A synthesis of the globalization thesis and de-globalization anti-thesis may be required for a successful U.S. nuclear energy business around the world. Cooperation with allies in the global nuclear supply-chain in the near term for advanced reactor deployment will have positive impact in the success of the near-term deployment of advanced reactors.

The discussions above related to the hurdles and possible approaches in resolving them for a successful US nuclear in the global market can be summarized as follows:

Table E.1 Summary of hurdles and possible approaches for export of US nuclear energy

Hurdles	Possible Solutions/Approaches
Cost-competitive nuclear energy	• Regulatory support for enabling reduction of the cost of nuclear energy through functional containment approach for advanced reactors • Government support for increasing the human and corporate experience in field • Public-private partnerships and investments for expedited R&D in nuclear energy
First-of-a-kind-challenge (FOAK)	• Policy and capital support for continuation of demonstration projects at National Reactor Innovation Center • Demonstration of advanced construction approaches along with advanced nuclear energy technologies • Increased public and government awareness for FOAK advanced reactor deployment in the U.S.
Stable and supportive policy environment for export of nuclear energy	• Preserving the baseline U.S. nuclear energy capabilities and industry for future export activities • Aligning the pace of government to government nuclear energy agreements with the potential deployment pace of small-scale to large-scale advanced nuclear options • Sustained support for the manufacturing of nuclear fuels for advanced reactors

I. INTRODUCTION

The U.S. created a domestic and global nuclear energy market and industry since nuclear energy illuminated the first light bulbs at EBR-I in Idaho. The domestic and international markets were dominated by the U.S. technologies, industries and policies resulting in positive economic and political impacts for the country. The U.S. and its allies had been the decisive authority for who can use the nuclear energy and to what extent. However, the global nuclear energy market arena has considerably changed. These acquired economic benefits and political leverages in the global energy market are being threatened by the state-sponsored nuclear energy enterprises from Russia and China for the last couple of decades. Additionally, the recent unsuccessful attempts of the U.S. nuclear energy industry to construct new domestic plants have not been encouraging for potential future investors. The domestic issues further exacerbate the concerns that the acquired values in nuclear energy will be damaged in the global nuclear energy market. It can also be argued that such an environment in nuclear energy markets will threaten the economic and political interest of the U.S. causing stagnation in important aspects of the national security of the country.

The Department of Energy (DOE)[1]: 1) recognizes the issues related to the current state of the nuclear energy, 2) acknowledges that the U.S. has lost its competitive global position as the world leader in nuclear energy to state-owned enterprises, and 3) provides an approach to overcome the related issues including national fuel development, supporting U.S. research, development and demonstration activities and advancements in regulatory environment. Advanced reactors, micro reactors and small modular reactors provide hope for possible cost reductions and increased competitiveness in the nuclear energy projects. However, the actions taken today by the nuclear industry and DOE play a crucial role for the faith of the domestic and global nuclear energy capabilities of the U.S. in the next decades. The unappealing future energy demand growth in the country[2] may hinder the need or desire for a strong domestic nuclear energy sector. Such a potential domestic energy market environment increases the importance of understanding the need for export of nuclear energy.

This study asks the simple question: "Is the U.S. preparing effectively for the global future of nuclear energy?", where it is assumed that the best bet lies in international markets and opportunities. The first step in answering this question requires briefly exploring the potential global energy needs, the general outlook of nuclear energy around the world and baseline potential opportunity for nuclear energy. Then an introduction to the emerging nuclear energy options and technologies is needed. It is believed that competing in the traditional nuclear energy practices and technologies, where the U.S. has already lost the competitive edge to established state-sponsored enterprises, does not seem to be the best option for the U.S. This requires understanding a new mindset of transition from traditional to functional nuclear energy, which means the new use cases and variety of safety and functions of nuclear energy coming alongside with the next generation nuclear energy options. The roadblocks hindering such a transition in the global nuclear energy market need to be explored including the regulatory environment, nonproliferation concerns, and finance, export and international policies.

II. GLOBAL EXPORT OPPORTUNITY FOR NUCLEAR ENERGY

GLOBAL ENERGY DEMAND AND NUCLEAR ENERGY

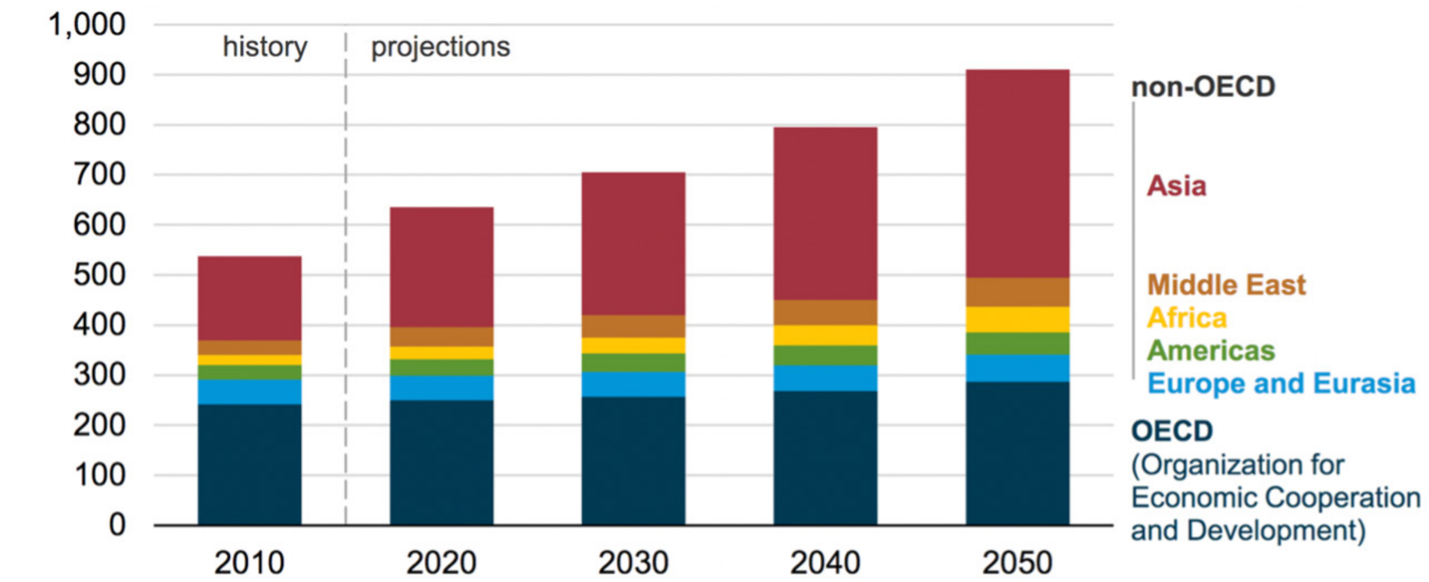
It is usually emphasized that nuclear energy has a vital role in clean energy production in a carbon constrained world. Although this argument holds one of the key points in slowing down the air pollution attributed environmental risks, nuclear energy's sole role as a clean energy source may not make it a commercially desired product. If the goal of the world's strongest economy is to export nuclear energy to the other parts of the world, the product itself needs to be also economically attractive to the counterparts. This is especially important where the state-sponsored enterprises set the gameplay in today's global energy markets and offer "full package" deals including financing, construction, training, life-cycle support and disposition of used fuel.

Can the U.S. compete with her opponents in the world nuclear energy arena with the rules and strategies defined day by day by the opponents or should the U.S. define the game rules as she did in the first place? Before digging into details of possible ways of structuring a new way of thinking and approach, let's take a look at what is the balance sheet in terms of global energy market and baseline potential for nuclear energy. After all, nuclear energy may become an economically viable product, but if there is no market for it, then the future of nuclear energy may not be so bright.

U.S. Energy Information Administration (EIA) projects a 50% increase in global energy demand by 2050. Figure 1 shows the reported global energy demand projections by EIA until 2050[3]. The reported data show relatively steady energy consumption projections for countries in the Organization for Economic Cooperation and Development (OECD). However, the projected demand is different for non-OECD countries, where the expected increase is around 50% with the hot spot being Asia. The same study estimates a ~50% increase in the nuclear energy source capacity, but a decrease in terms of percentage in the energy portfolio comprising renewables, natural gas, coal, petroleum and other liquids. World Energy Council (WEC) estimates that a significant investment is required to meet the electricity demand until 2050. The dollar value of these estimates has a lower bound of $19 trillion and upper bound of $26 trillion. WEC also reports that the majority of this value will be captured by renewables. However, it is argued that the percentage share of each energy source depends on the availability of the investment funds.

Similar findings and trends are available from the existing literature that tend to predict a steady increase in global energy demand in the next couple of decades. There are also counter arguments to these projections due to decrease in energy usage in manufacturing sectors with higher efficiency enabling advanced technologies. The accuracy of such predictions may vary due to global economic and political conditions, but it can be concluded that the trend is towards an increase in the global energy demand.

Figure 1. Global primary energy consumption by region between 2010 and 2050 (in quadrillion British thermal units), source: EIA



The future of the export of US-involved nuclear energy will also depend on the energy source distribution pattern across the world. Some of the current major factors affecting the distribution pattern and stability of global energy pool and demand include: i) Russia's political influence on several energy options and ii) the centralization of global supply chains in China and the economic growth of China. A potential shift in the distribution of the global supply chain across other countries will definitely change the energy demand pattern across the globe. However, the unforeseeable events, such as the outbreak of the novel coronavirus pandemic in 2019, may force countries to focus on economic recovery or sustainability rather than growth in economy and energy demand in near future.

International Atomic Energy Agency (IAEA) provides projections on energy[4], electricity and nuclear power up to 2050. IAEA expects that world energy consumption will increase by 40% by 2050 with an annual growth rate of about 1%. The share of electricity in total final energy consumption is projected to be around 25%. Meanwhile, IAEA estimates that world nuclear energy electrical generating capacity will increase by 80% at the upper bound until 2050. This kind of increase puts nuclear electric capacity at 5% in the world total electric capacity portfolio.

IAEA also provides projections for the nuclear energy generation capacities at different regions of the world from 2018 to 2050. Table 1 shows the 2018 generation capacities and projections at 2030, 2040 and 2050. It is reported that the study team has considered all the operating reactors, possible licenses renewals, planned shutdowns and possible new constructions. The average projected change by 2050 are derived from IAEA's lower and upper bound estimates for each region. It can be concluded that the Northern America, and Northern, Western and Southern Europe regions' nuclear electrical generating capacity will be reduced by 30-50%. However, Central and Eastern Asia region is expected to double their capacity by 2050, where the markets are already dominated by state-sponsored enterprises. Southern Asia, Western Asia, Eastern Europe and Latin America are expected to have nuclear energy as an emerging electricity generation source by 2050. Figure 2 shows the nuclear energy market readiness by 2050, where it is expected that most of the growth will be experienced at Central and Eastern Asia, Eastern Europe and South America.

In summary, the U.S. does not recently have the best reputation in deploying traditional nuclear

Table 1. World nuclear electrical generating capacity, Gw(e)[4]

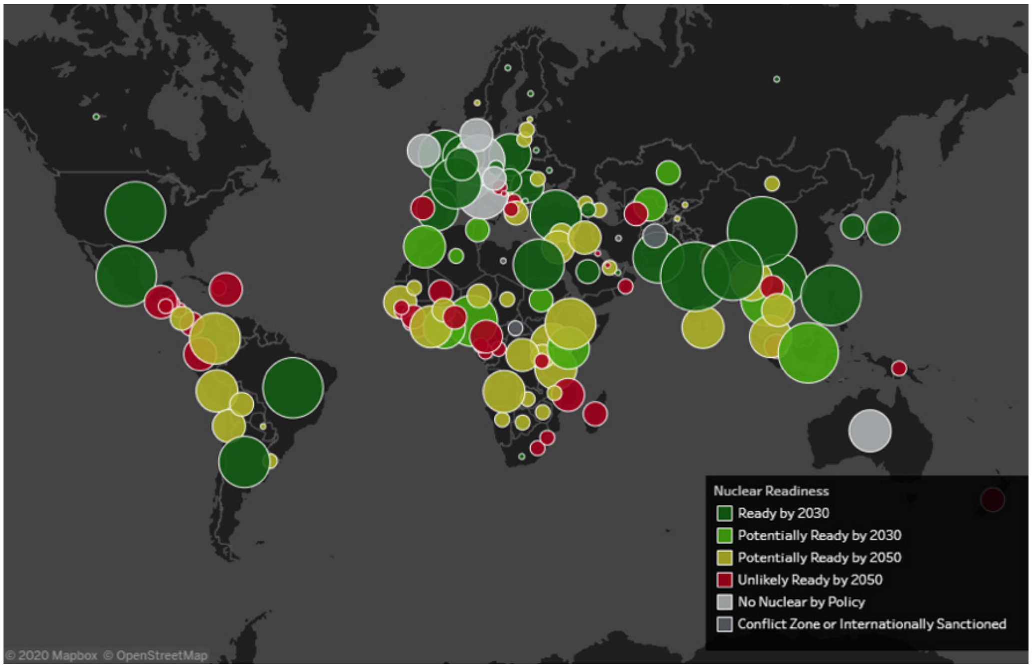
Region	2018	2030	2040	2050	Average projected change by 2050
Central and Eastern Asia	106.2	145	195	227	121
Southern Asia	8.5	23	40	67.5	59
Western Asia	0.4	9	16	19.5	19
Eastern Europe	51.3	60	66	67	16
Africa	1.9	3.5	7	11	9
Latin America and the Carribbean	5.1	7	11	14	9
South-eastern Asia	-	-	2	6	6
Ocenia	-	-	-	1	1
Northern America	112.6	100	87	77	-36
Northern, Western and Southern Europe	110.5	85	69	54.5	-56

power plants due the issues discussed above, although the U.S. has been the inventor of this energy source in the first place. On the other hand, the global nuclear energy market is dominated by the state sponsored enterprises as also noted by the Department of Energy. The concentration of the global supply chains in China causes a skewed economic development pattern throughout the world. Such a concentration causes high energy demands in China, where the state sponsored companies are handling the deployment of the different energy options including nuclear energy. The future of the global energy markets is promising, where nuclear energy is expected to have a baseline share of 3-5% in the global energy pool.

III. TRADITIONAL NUCLEAR ENERGY AND ITS CHALLENGES

Pressurized water reactors (PWR) and boiling water reactors (BWR) are the two common types of reactor technologies used in the commercial nuclear energy around the world. The fuel, the control rods and water are housed in a high-pressure resistant reactor vessel. Water serves as moderator and coolant in the U.S. reactor designs. The temperature in these reactors rises far above the boiling temperature of water. The main difference between these two reactor technologies is how the steam is gen-

Figure 2. Nuclear Markets Based on Readiness (Color) and Future Growth in Electricity Demand[5]



erated and circulated to drive the turbines for electricity generation. The common designs use enriched uranium as fuel and light water as moderator. These types of reactors are referred as light-water reactors (LWRs).

As discussed above and recognized by the DOE, the new nuclear energy builds in the U.S. are not cost-competitive and struggling with deployments. The challenges with the LWR power plant deployments relate primarily to balance of plant rather than the LWR reactor or fuel development. There are LWR reactors operating in the U.S. and around the world without any history of safety-related operational issues and making profits to their operators. However, regulatory ratcheting over the course of years has made deployment of nuclear power plants challenging. Even if the private entities have extremely valued experience in delivering large-scale infrastructure projects on time and budget, lack of recent experience in the current nuclear regulatory dynamics and unique expectations of nuclear space are causing stagnations in deployment of nuclear energy. Traditional LWR type reactors also have unique features affecting the balance of plant and structures, that make these kinds of projects immediately challenging mega projects. These mega nuclear energy projects require experience in the domain and lots of financial commitments even before the plants start to be operational.

If the discussion is that the high cost of nuclear energy projects occurs during the deployment phase of the new builds, then the question that needs to be asked is whether there are any future possibilities and nuclear energy options for nuclear energy to be deployed with characteristics and safety features that will not make deployment of nuclear energy extremely challenging. The answer to this question lies in the opportunities resulting from next generation nuclear energy options including advanced non-LWR and small modular LWR reactors. The unique safety features of these technologies may even make a considerable portion of the nuclear power plant deployment outside the highest safety categories attracting highly trained and experienced contractors, engineers, and workforce outside of nuclear domain to work relatively easily on the projects. The future and reliability of nuclear energy will be a combination of different nuclear energy options from the smallest footprint to the mega projects. In order to assess the future of nuclear energy, it is important to understand the challenges that are experienced by the U.S. enterprises. Some of the important challenges and considerations for the deployment of nuclear energy are summarized below:

1. LWR nuclear power plants are complex engineered machines that require substantial effort for successful deployment. These complex systems require a holistic approach and effort in order to be successfully deployed. LWRs are designed against extreme internal and external hazards. The design of the plant requires relatively heavy and large pressure resistant reactor containment buildings with highest quality standards possible for ensuring the safety of the public. Nuclear-grade material selection and construction practices cause large financial burdens on the nuclear energy enterprises. The state-of-the-art studies show that the majority of the cost of nuclear energy is related to components and systems outside the reactor (i.e., “balance of plant”). When the technologies or overall deployment of balance of plant is not successful in real life, these major cost contributions are far above initial cost expectations due to maintaining the continuation of deployment activities, costly iterations at the site and interest rates accumulated throughout the extended period of the projects.

2. The traditional nuclear energy option is unique in the sense that iterations or recursive approaches in product development is not efficiently possible due to i) infrequent deployment of the plants, ii) high cost of the end product, and iii) physical size of the complete product. The infrequent deployment of the nuclear energy and no established active market for future plants in

the U.S. also hinder the entry of possible private entities to the nuclear space that focus and have expertise on technologies outside the reactor technologies.

3. U.S. nuclear reactor vendors are mostly interested in developing their technology and finding appropriate avenues to proceed with their product. The efforts of the government entities are distributed across several low technology readiness level technologies with the few exceptions of topics related to nuclear fuel development and production.

4. The successful deployment of nuclear power plants, irrespective of their size, is dependent on effective implementation of different components and technologies together. The efforts in the domain usually focus on sub-optimization of nuclear-related technologies. These technologies include development of perfect reactor concepts to technologies affecting the siting of nuclear power plants. The approach of sub-optimization does not guarantee success during the commercial deployment of nuclear energy, if the pieces don't fit together. Efforts need to focus towards assessing the collective meaning of the technologies and approaches developed for future plants.

5. As an example, reduction of cost has been attempted for two new nuclear power plant projects in the U.S. by using a modular composite wall design at Georgia and South Carolina. It was assumed that this process would speed up and ease the construction process and ultimately decrease the overall cost of the projects. Yet the desired outcomes by using this new technology were not achieved due to design and implementation problems and lagging of R&D readiness. In addition to having not finished the complete development of the technology, the simplification in the nuclear domain provided by this modular approach did not replace the need for experience in deploying such a new technology. This suggests that a high level of technology readiness and human experience are vital components of the path for success in the nuclear domain.

6. Nuclear energy also lacks the environment for incremental product development, specifically for balance of plant related technologies. There is a gap between low-to-mid readiness level technologies developed at universities and national laboratories to real life implementation by the private industry. Such an environment will also challenge the US advanced reactor industry globally because the competition will be against nations with records of finishing the costly and challenging LWR projects almost on time and budget.

7. The efficiency in the nuclear construction practices and overall business in nuclear are within national interests of the country without any doubt. The path to increased efficiency passes through steady and well-defined plan rather than a 30-years of waiting period followed by a rush. The unsuccessful attempts occurring in the industry after long periods of inaction followed by rush is also preventative for any future investments by the industry. Therefore, an effort is required to increase the confidence of the industry for future investments and alleviate the variable demands of the nuclear energy deployment for different reactor concepts and designs. Such an effort requires a high degree of collaboration among research institutions, utilities, designers, contractors and many other branches of the nuclear industry and business and government. Often mentioned but usually not discussed in detail, proposals of modern construction techniques and approaches such as modularization and pre-fabrication requires crafts, engineers, and personnel with different skill sets to efficiently work together to minimize on-site disputes.

8. The necessary technological capabilities, such as automation, advanced manufac-

turing methods, modularization and digital twins, need to be assessed and increased in order to get the best possible value without compromising nuclear safety.

9. When nuclear reactors are deployed, nobody expects to finalize the design and solve any disagreements in the last minute. Likewise, any balance of plant design requires investing in up-front research and detailed design and planning. Last minute changes not only put the designers in strict schedules, but make the industry suffer from time-consuming and costly procurement changes. How well, fast, secure, safe and competitive the U.S. can build depends on the successful collaboration of the entities mentioned earlier. It needs to be kept in mind that the associated effort to recover and make the industry stand on its own feet after a weakened work and employment environment in nuclear energy deployment for decades followed by the recent attempts of the business is not an easy task.

10. The available and near-future nuclear reactor concepts may be housed in structures with different materials, construction approaches, dimensions and sites. The opportunities that arise from such flexibilities have the potential of increasing the customer base, kick start the nuclear energy sector and may ease the entry point of different scale companies and create a competitive environment that will be beneficial for every party involved in terms of efficiency, cost and safety.

IV. THE PROMISE IN NEXT GENERATION NUCLEAR POWER PLANTS

The U.S. nuclear enterprises have been investing in developing and licensing alternative nuclear energy technologies to the current LWR technologies and practices for decades. These reactor technologies are sometimes referred as advanced reactors or next generation nuclear power plants although they have a history going back to the ‘60s. Some advanced reactors will be different from LWR technologies and use gas, molten salt, or liquid metal as a coolant. Some of them will be LWR-based technologies with smaller footprints than the current ones. Microreactors are also gaining attention for military or space applications.

Among the advanced non-LWR reactors, high temperature gas-cooled reactors provide high levels of safety through their design of materials and inherent safety features[6]. The materials used in the reactor design are chemically stable and retain their integrity at high temperatures. The ceramic coated fuels have high temperature capability and high radionuclide retention. The helium coolant is chemically inert and has low heat capacity. The design of the fuel provides the capability of retaining the radionuclides within the fuel. The shape and size of the reactor allows for passive heat removal from the reactor core. The overall design does not rely on operator actions or AC-power to perform the necessary safety functions. The average coolant exit temperature is higher than the LWR designs, which provides additional commercial and economic opportunities.

Next Generation Nuclear Plant (NGNP) project[7] was established by the Energy Policy Act of 2005 with the goal of developing, licensing, building and operating a prototype modular high temperature gas-cooled reactor plant that would generate electric power along with high-temperature process heat for use in hydrogen production and other energy-intensive industries. Although the high temperature gas-cooled reactor design has a rich history, improvements in the HTGR technology and increase in the economic viability are aimed through the NGNP project. The NGNP concept is based on coated particle fuels that have been extensively studied over the past five decades. These fuels are composed of layers of carbon and silicon carbide surrounding a uranium kernel; tri-isotropic (TRISO)-coated fuel particle. The TRISO layers provide robust protection for the uranium kernels and superb retention of the radioactive material produced during fission. The compacted shapes of these fuels are called pebbles in the shapes of tennis-ball sized spheres or chalk-sized cylinders. The passive plant safety features and the safety performance of this type of fuel provide the opportunity for an NGNP reactor to be sited in an industrial complex to provide heat and electricity to that complex.

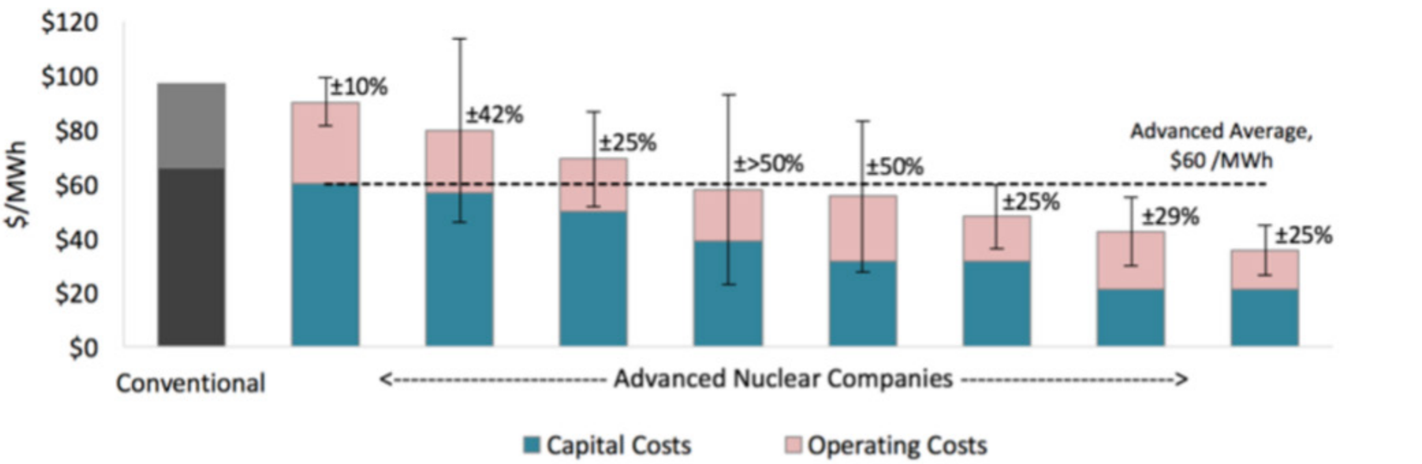
Alternatively, there is interest in reactor technologies using molten salt[8]. The roles of molten salt in molten salt reactors (MSR) include using it as a coolant or mixture with the fuel. The MSRs operate in relatively higher temperature and low-pressure environment compared to LWRs. There are several different forms of MSR design providing enhanced safety features over the existing plant designs. These include using the combination of the safety from TRISO fuels and molten fluoride salt as coolant. In general, the design of MSR type reactors needs to continue in order for them to be commercially viable and mature. U.S. based and international entities are working on several designs to make this a realty. Liquid metal cooled reactor technologies such as sodium-cooled fast reactors are also considered for commercial applications. Sodium allows the reactors to operate at higher temperatures and lower pressures than the current conventional reactor technologies. Efforts in U.S. enterprises exist in developing commercial sodium cooled reactors in order to export nuclear energy around the world. The Japanese and French government had been showing great interest in the sodium cooled reactor technologies[9].

Advanced small modular reactors (SMRs) are relatively smaller output capacity and size compared to the current designs and other advanced reactor concepts. The coolant may be water, gas, molten salt or liquid metal. The most promising development has been the design by NuScale Power's Advanced PWR[10] with high technology readiness level for commercial deployment and progress in licensing efforts. NuScale design may house multiple reactor units based on the initial demands with the capability of increasing the number of modules for future demands. Due to their size and innovative safety features, it is expected that the manufacturing and deployment of the plant and its components will be relatively easier and cost competitive. The initial financial risk and burden for the potential customers are expected to decrease, creating a more attractive investment environment.

Energy Options Network surveyed advanced reactor companies that are based in the U.S., U.K. and Canada. These private companies provided their cost estimates on the advanced technologies that they are developing including molten salt reactor, sodium-cooled fast reactors, advanced PWR and HTGR. Figure 3 shows the levelized cost of electricity estimated by the advanced reactor companies with self-reported confidence bounds compared to the conventional nuclear energy option[11]. It is expected by the advanced nuclear energy developers that the upcoming nuclear energy options will be more cost-efficient than what the traditional nuclear energy market has been offering. This creates an opportunity for nuclear energy to spread across the world with more cost-efficient options.

Microreactors are gaining attraction due to interest from military applications in recent years. DOE defines[12] the features of microreactors as: 1) factory fabricated, 2) transportable, and 3) self-adjusting. These features mean that the microreactors are small in size so that they are factory fabricated without complex construction at site, plug-and-play ready, easily transportable on a truck and designed with passive safety features. Microreactors pose a unique business opportunity, as they are also considered for supplying energy to remote communities besides their potential applications in military. Nuclear Energy Institute published a case study on the nominal timeline for deployment of microreactors for defense installations[13]. The study estimates of construction and operation of microreactors of no greater than 50 MWe at Department of Defense (DoD) and DOE facilities by December 31, 2027. It is also stated that the 10MWe or less are also aligned with the energy demands at DoD installations. The pilot program location by the

Figure 3. Estimated levelized cost of electricity comparison of advanced reactors



DoD for the first deployment is located at an Air Force base in Alaska. It is assumed that NRC will license and regulate the construction, operation and decommissioning of microreactors for defense installations.

The vision from DOE's perspective for the advances in nuclear energy for the technologies discussed above is as follows[1]:

> *The large light-water reactors common in today's market will, in the future, be joined by new advanced reactors, including light-water advanced small modular reactors (SMRs), advanced non-light water reactors, and a subset of SMRs known as micro-reactors. Some of these advanced reactors will provide electricity to remote locations while others will provide high-temperature process heat for nonelectrical services such as desalination. Other technologies under development could also provide options for the management of waste from nuclear power.*

V. ROADBLOCKS

COST-COMPETITIVE NUCLEAR ENERGY

Buongiorno, J. et al.[14] (referred as MIT study in the following text) analyzes several key topics related to nuclear energy including the cost of new projects and possible ways to reduce the costs of nuclear energy. The study includes comparison of the overnight costs of nuclear power plants from 1960s to 2010s, where the range of the overnight costs is quite large. The high cost of the nuclear projects during the '70s-'80s time frame in the US is attributed to the significant fluctuations in electricity demand, construction delays, and regulation turbulence followed by the Three Mile Island accident.

The MIT study associates the aforementioned relative high cost of the specific nuclear power plant projects with: i) the cost of learning being high if the country has not built plants in a generation (experience in the field), ii) rework and supply-chain issues extending the construction schedule thus impacting the cost even before considering interest costs, iii) non-standardized designs adversely impacting the schedule hence the cost of the projects, iv) failure of construction management practices, and v) lack of strong government support.

Figure 4 shows the overnight cost breakdown of AP1000 and EPR plants. Similar distribution exists for other nuclear power plant projects. It is reported that the reactor and power conversion system equipment represent only 25% of the total cost on average. The majority of the cost is related to site preparation, installation of components and associated field and home engineering, and owner's cost. The ratios shown in Figure 4 do not include the interest during construction.

Based on the data, the authors of the MIT study recommended that cost reduction efforts need to be focused not only on the nuclear steam supply system (NSSS), but i) improvements in how the overall plant is constructed, and ii) ways to accelerate the construction process to reduce interest costs during this period.

Electric Power Research Institute (EPRI) also compiled a report[15] for economic-based research and development roadmap for nuclear power plant construction. Consistent with other studies, the EPRI study also found that civil and structural design and work are significant cost drivers. It is found in the study that over half of the potential cost savings in these cost drivers can be achieved through schedule reduction. It was also claimed that many cost overruns during plant construction occur because the first-of-a-kind (FOAK) plant designs are not 100% completed prior to beginning the construction. One of the main conclusions of the study is that the most significant cost reduction strategies are those that reduce construction duration in addition to savings in labor and to a lesser extent materials. The reduction in cost is amplified even more when accounting for reduced interest costs during the course of the projects.

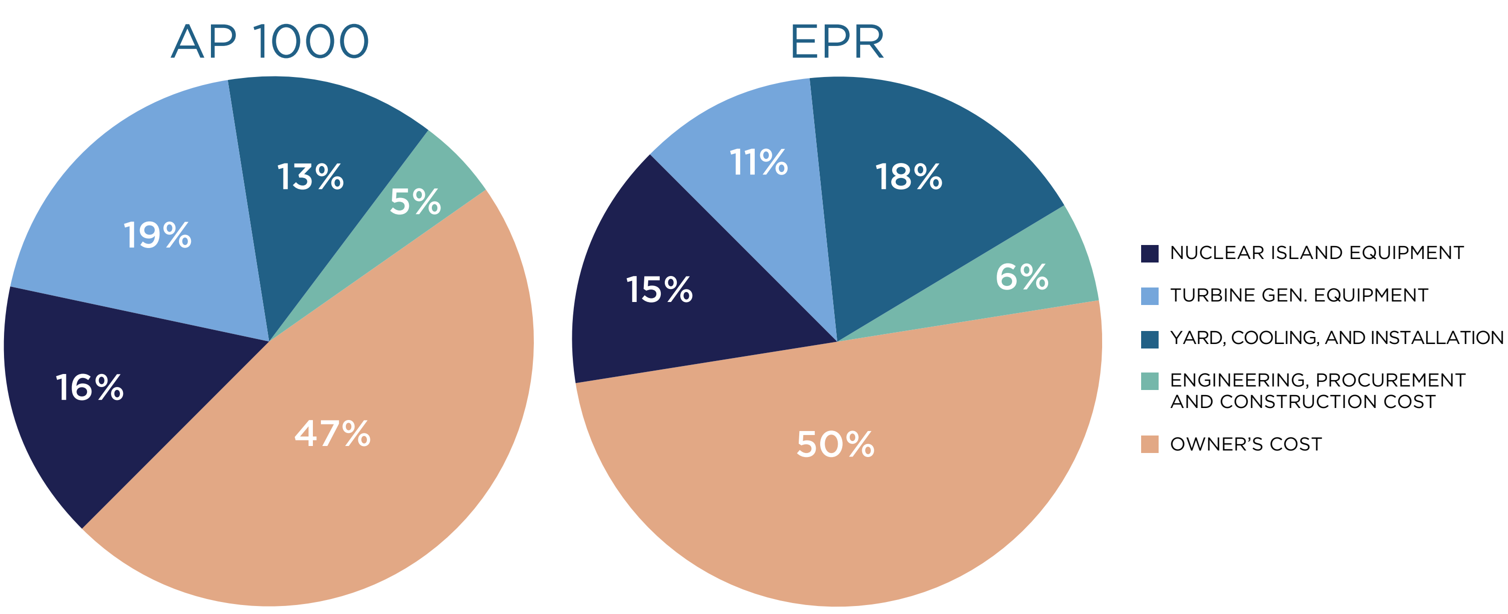
The two state-of-the art studies, MIT and EPRI reports, provide the knowledge that i) most of the cost of the nuclear power plant projects is outside the core, ii) design completion (maturity) of the overall project is a key parameter for the success of the project, iii) the cost of the projects is amplified with schedule delays meaning requiring more money for increased work duration and interest compounding during this time, and vi) cost reduction strategies need to mostly focus on balance of plant and what can reduce the uncertainties in construction of the plants.

No matter what information is extracted from the literature or different sources of information, which can be for or against the nuclear option, the cost of traditional nuclear energy is an issue that hinders the investment and interest in this energy source. A movement of change is necessary if there will be an economically viable and sustained nuclear energy in the US and around the world.

REDUCING THE COST OF NUCLEAR ENERGY THROUGH FUNCTIONAL CONTAINMENT

If the high cost of nuclear energy is dominated by the issues related to what-is-outside the reactor, then the question is: how will the advanced reactors become cost-competitive? Economies of scale is one of the arguments that is often discussed. Some of the advanced re-

Figure 4. Cost breakdown for AP1000 and EPR (generated from Buongiorno, J. et al., 2018)



actors and their balance of plant are relatively smaller in size compared to current plants. This allows less financial and schedule overburdens and associated risks. Additionally, using off-the-shelf components for the advanced light water and non-LWR reactors and plants will ease the supply chain challenges.

There is an emerging approach, functional containment[16], in the regulatory environment that has the potential to change the course of nuclear energy deployment in near future, specifically for advanced reactors. This approach has not found the time to have a widespread recognition, yet. When the regulator and the supporting entities make it a reality, cost-competitive deployment of nuclear energy will be highly possible. Many of the current regulations have been written based on safety requirements of the LWR technologies. They are mostly prescriptive and deterministic. Functional containment approach provides the flexibility in design as long as each safety barrier's performance for preventing radioactive material release is met. This concept is referred as the "functional containment". These barriers may include from the fuel to structures surrounding the reactor.

The historical trend in nuclear power plants is that they have been built with a containment structure to prevent the radiological releases in case a severe accident condition occurs. Advanced reactors, such as modular high temperature gas cooled reactors, provide safety features that do not exist in the traditional light water reactors. The possible internal hazards associated with these non-LWR reactor designs are also different from traditional LWRs. The necessary large and labor-intensive pressure-related containment boundary for LWR design is not really required for these types of designs. The safety features and the release environment being different from traditional LWRs provide the basis of functional containment.

Functional containment does not specifically mean a structure like the containment structure, but a set of barriers designed to prevent any release of radioactive material to the environment. These set of barriers include from the cladding of fuels to passive safety systems to possible structures that prevent the release if the fuel barriers are breached.

It is discussed above that the cost overruns in the nuclear power projects have been occurring during the construction (for balance of plant technologies). With the functional containment concept, it is possible to reduce the cost of the next generation nuclear power plant projects by decreasing the amount of costly nuclear grade construction (imposing ASME special requirements on the design and implementation in real life). Within the functional containment approach, there can also be candidate technologies or approaches used by the industry to help with reducing the risk/design requirements of accompanying structures or components to the advanced reactors. These candidate technologies (such as seismic protective systems) or approaches (such as deeply embedding the structures) will make the risk-informed, performance-based and technology-inclusive design of structures meet their functional requirements with reduced cost.

Functional containment approach will shift the prescribed engineering environment in the nuclear domain towards more risk-informed and technology inclusive engineering design approaches. This brings a variety of availability of engineering decisions, approaches and technologies as long as the required safety is satisfied.

FIRST-OF-A-KIND (FOAK) CHALLENGE

It is a commonly accepted argument that the first of a kind (FOAK) deployment of a nuclear power plant is more costly than Nth-of-a-kind plants. The reduction in the cost as time passes can be attributed to the learning in the deployment phase and mature supply-chain management. FOAK cost of advanced reactors may discourage some of the investors as the uncertainty in the cost and schedule will be at a maximum level compared to the subsequent deployments. The first deployment also requires high confidence and stability in the regulatory environment that prevent costly changes during deployment. At this stage, support from the government plays a crucial role for the future export potential of advanced reactors in the global market.

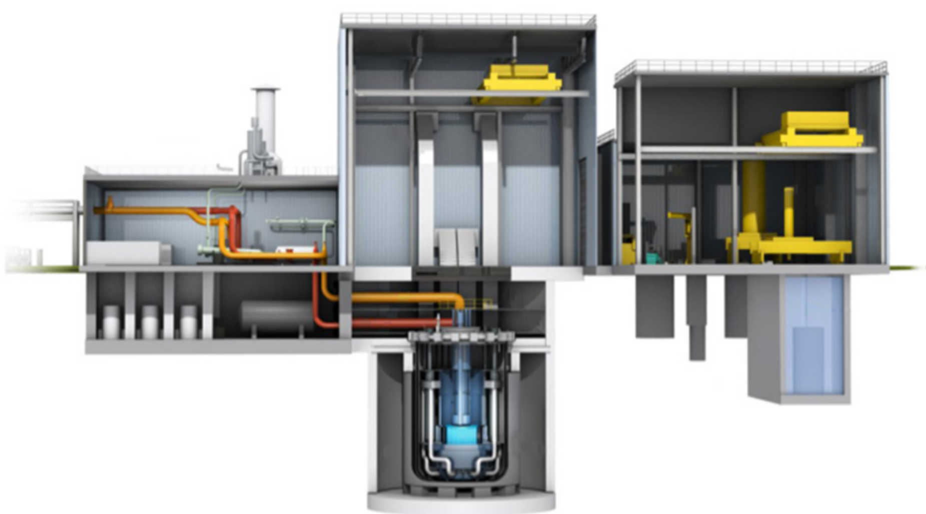
National Reactor Innovation Center (NRIC) is a DOE program led by Idaho National Laboratory, allowing collaborators to harness the world-class capabilities of the U.S. National Laboratory System[17]. NRIC is charged with and committed to demonstrating advanced reactors by the end of 2025. Demonstration of advanced nuclear systems will have lots of positive impacts on the deployment of FOAK advanced nuclear power plants in near future. Construction schedule and costs have the highest impact during the deployment of the recent builds. Such delays in the schedule and increased cost also have cascading effects on the overall cost due to accumulated interest. Not only nuclear engineering related demonstration of advanced nuclear power plants is necessary, but also demonstration projects and increased experience in construction technologies are necessary. NRIC has also initiated their efforts in this area along with the reactor technology demonstrations. NRIC aims to partner related to the development and demonstration of advanced construction technologies and processes that would be transformative in improving nuclear power new-build economics and scheduling.

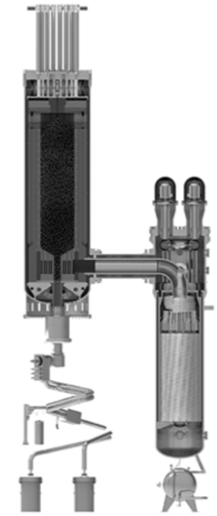
Financial support for the FOAK plants is also an important pillar for the success of the U.S. nuclear energy. DOE has approved a cost sharing award over $1 billion for the FOAK domestic deployment of NuScale SMR[18]. Although this deployment will reduce reliance on coal-based energy, the uncertainty on the construction cost is causing concerns and delays in the deployment. While the discussions on the FOAK deployment of SMRs are going on, the US International Development Finance Corporation has signed a Letter of Intent in supporting the export of SMR technology to South Africa[19]. Figure 6 shows an illustration of NuScale Power's SMR.

Figure 6. NuScale Power design illustration

The next generation nuclear energy options from microreactors to advanced LWRs and non-LWRs will create a portfolio satisfying different energy needs and business cases. While these technologies provide unique business opportunities for nuclear energy, they also generate unique technical challenges that need to be overcome. Some of the most important challenges for these reactors are the initial and relatively costly research and development and the fuel cycle. DOE recently announced that two advanced reactor developers will each receive $80 million initial funding towards the demonstration of their reactor designs[20]. X-energy is developing a high temperature gas-cooled reactor with potential additional business opportunities including process heat for a variety of industrial applications. TerraPower is developing the Natrium reactor (Figure 7), a sodium-cooled fast reactor that leverages technologies already used in solar thermal generation systems. The initial funding will also support fuel fabrication facilities for demonstration of these reactors and as well as TRISO fuel fabrication in commercial scale.

Figure 7. Natrium™ reactor and energy system architecture (left) (Source DOE/TerraPower), and Xe-100 reactor by X-energy (right) (source: DOE/X-energy)





POLICY AND PUBLIC OPINION SUPPORT

Although fossil-based fuels will last more than half a century, they are still time-limited resources. Innovation and support for innovation in nuclear energy are necessary for clean, sustainable and scalable energy that the world needs in the short and long term. It is also hard to predict how long the honeymoon on low natural gas prices will last in the international markets. For small modular reactors (SMRs), there has been an on-going discussion whether economies of scale will make them cost-competitive. As the energy demand in the U.S. is not expected to increase significantly in the following decades, SMR technology needs to be exported to get the best out of potential economy of scale.

Most of the advanced reactors including microreactors will require a fuel that is not available at commercial scales: high-assay low-enriched uranium (HALEU). This type of fuel is different than the ones used and readily available in the traditional nuclear energy markets. DOE has near-term and long-term approaches for the production of HALEU[21]. The short term includes working with the national laboratories to provide small amounts of HALUE to nuclear vendors. The long-term approach is partnering with private industry for establish the manufacturing capabilities that support the demonstration of advanced reactor projects and nuclear vendors. Therefore, a stable policy environment support of DOE's approaches with national laboratories and private industry in fuel production is critical for the success of advanced reactors.

Section 123 of the U.S. Atomic Energy Act generally requires the conclusion of a peaceful nuclear cooperation agreement for significant transfers of nuclear material, equipment, or components from the United States to another nation[22]. Figure 8 shows the government-to-government agreements in place for peaceful cooperation of nuclear energy in the world. Finalizing the approvals for these agreements between U.S. and another nation may take up to 400 days, which slows down the export of nuclear energy business[23]. Improvements in the efficiency of 123 agreements at every branch of the government is necessary in order to expand the export of advanced nuclear energy options to other countries, especially non-OECD countries. The slow processes may result in loss of competitive advantage in the global markets, where bureaucracy may take longer than the deployment of relatively smaller size advanced reactors.

Figure 8. The United States has agreements in force that govern peaceful nuclear cooperation with 48 countries, the IAEA, and the governing authorities on Taiwan, as of March 28, 2019.[23]

TRANSITION FROM TRADITIONAL TO FUNCTIONAL NUCLEAR ENERGY

The U.S. may pursue a threefold approach in order to compete with the state-sponsored enterprises in the global nuclear energy market:

1. PRESERVING

~20% of the energy in the U.S. is generated by the existing nuclear power plants. There is already an industry formed around these clean energy sources supporting the maintenance and operations of the existing fleet. Although the existing fleet may struggle with cheap natural gas at the moment, having a baseline nuclear energy market and industry is the first step in the right direction for the U.S. nuclear energy industry. A sharp decrease in the amount of operational nuclear energy in the U.S. will adversely affect the nuclear accredited N-stamp vendors and manufacturers in the country. Although the expectation with the advanced nuclear reactors and the balance of plant to reduce the number of N-stamp components in the overall design, it is crucial to have experts, engineers and practitioners for the nuclear energy in the U.S. for the long-term success around the world. It can be argued that when orders for new builds are in place, the relevant suppliers in the U.S. will grow over time.

The existing used fuel topic is also a task that needs to find a resolution to support the existing fleet. Science-based approaches need to be carefully articulated and communicated with the public in order to start long-term disposition of the existing used fuel. More effort needs to be spent on public communication not only from scientists, but also professional public engagement in order to shift information asymmetry on this topic.

Supporting the existing fleet, nuclear vendors and long-term disposition of the used fuel are all baseline solutions for the nuclear industry. These will preserve the advantages coming from this carbon free energy source. However, preserving the status quo does not help much with innovation or increase the readiness of the U.S. nuclear industry required to compete in the global nuclear energy arena in the near future. Preserving the nuclear industry in its current shape is also a defensive maneuver, which does not increase the confidence of the nuclear industry or provide the reputation for future market competitions.

2. CHALLENGING

Although the number of nuclear sector businesses has declined, the U.S. still has lots of capabilities that can be leveraged in the global market. Leaving the nuclear energy market arena to state-sponsored enterprises should not be an option, while waiting for the development, demonstration and deployment of next generation nuclear energy options. In order to sustain the baseline existence in the global nuclear energy business, both the government and the private business have duties that need to be continuously pursued.

The challenge in the world markets cannot be easily isolated to U.S. nuclear industry. The competition has been ramping up in other industries such as the automotive or heavy manufacturing industries that directly impact the U.S. enterprises. The challenge needs to be handled as a common national security problem. The actions taken by the U.S. government should focus on challenging state-sponsored industries from penetrating the current technology and product export. Otherwise, competition between U.S. privately owned enterprises and state-sponsored enterprises will always cause systematic problems. Figure 9 shows the nuclear reactors under construction in the global market, where the U.S. can not show any presence in the export market.

Country of origin is an important aspect in the global market. It is believed that U.S. holds a good reputation in terms of delivering high quality products and services compared to competitors in the global nuclear energy market. While sustaining the reputation of high-quality products, U.S. maintain focus on positive relationships with countries showing interest and demand for nuclear energy. It is known that China has been investing lots of infrastructure to tie long-term relationships with countries around the world. The planned new silk road will also increase the ease and cost of transportation. China will have the potential to elevate the ease of engagement and reduced costs for deploying large nuclear energy projects along the new silk road. Civilian nuclear energy cooperation with the allies of the U.S. and establishing long-term strategic ties with potential nuclear energy countries are essential in achieving the success of U.S. nuclear energy presence in the global market.

3. ADAPTING

Nuclear power plants are complex engineering machines. Bringing nuclear power energy to commercially viable product levels requires substantial investments in research and devel-

Figure 9. Nuclear reactors under construction with country of origin[24]

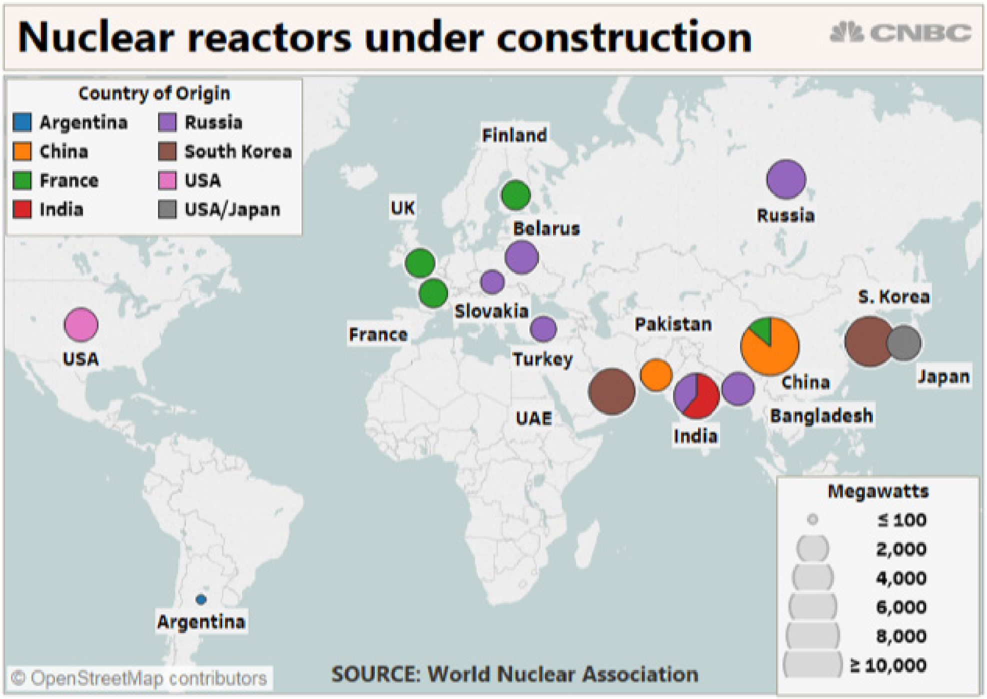
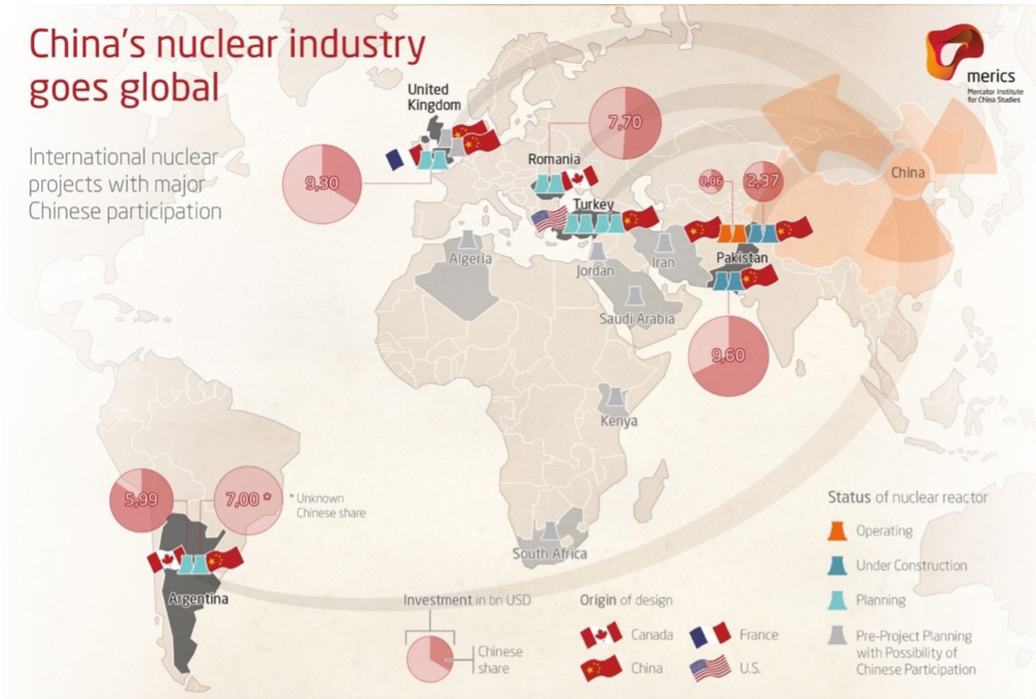


Figure 10. Chinese participation in the global nuclear energy market (note: the planned plant in Turkey, shown as US flag, has been canceled.)[25]



opment, establishing fuel cycle and gaining experience in deployment. The safety and technical uniqueness of nuclear energy among other high-technology products makes it longer to get it off the ground. Given the political, regulatory and mixed public opinion for traditional nuclear energy around the world, it is challenging to make the advanced reactor business adopted globally without any frictions. This is particularly important for the next generation nuclear energy innovators and businesses. The time required to develop advanced nuclear reactors requires sustained capital inflow, adoption to new business models that will successfully work in the next decades, protection of intellectual property, and communication with the public and governments for increased awareness in safety and value proposition of advanced reactor technologies.

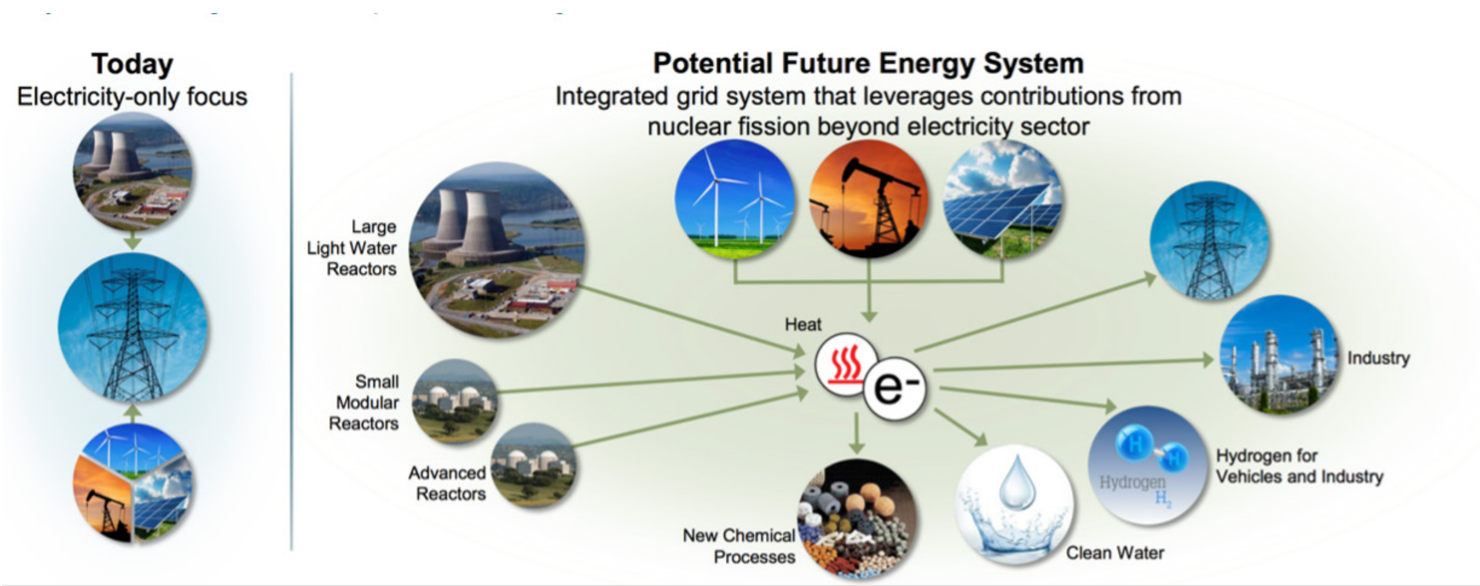
As stated earlier, that the diminishing share of the U.S. nuclear energy business in the global market is captured by the state-sponsored enterprises. A simple reason for this shift in the global share can simply be attributed to the developed know-how in traditional nuclear energy by the competitors. It is hard to convince oneself that the state-sponsored enterprises will take no action in attempting to develop the advanced reactors and compete with the U.S. nuclear energy business in near future as they are doing in the traditional nuclear energy market right now. Competitors have the required capital to develop these technologies. Although the technology development and catch-up may take longer times than the U.S., their regulatory environments are different that the U.S. that may give the advantage to deploy first-of-a-kind plants in comparable time frames.

Whether the nuclear reactors are commercially introduced by the U.S. enterprises or not, it needs to be planned in advance to extend the life, profitability and cost-competitiveness of the nuclear energy products that are being developed. It is important to introduce new business strategies such as variety in the usage of nuclear energy, expanding the market by thinking of nuclear energy as the building block for other business cases.

Globalization in world markets has also influenced the nuclear energy business, manufacturing and deployment. Distribution of the heavy manufacturing industries across the globe has resulted in challenges in supply-chain and communication. These challenges were present in the recent builds in the U.S. The anti-thesis of the globalization has been seen by some through isolation/de-globalization and bringing back some of these capabilities to the U.S. A synthesis of the globalization thesis and de-globalization anti-thesis may be required for a successful U.S. nuclear energy business around the world. Cooperation with allies in the global nuclear supply-chain in the near term for advanced reactor deployment will have positive impact in the success of the near-term deployment of advanced reactors.

NRC has implemented a policy of siting nuclear reactors away from very densely populated centers. The unique safety features of advanced reactors enable geographic flexibility in siting of nuclear power plants. The designs, smaller and slower release of radioactive materials in the case of extreme rare accidents, allow the plants to locate closer to communities and industries. One of the potential usages and business benefits of the advanced reactor designs includes being capable of supplying thermal energy along with the clean energy they will be providing. Up until now, with the traditional nuclear energy approaches, the focus has been on electricity generation. However, integrated energy systems with other energy sources including renewable energy will support several use cases including hydrogen production, heat for industries, support for clean water and new chemical processes (Figure 11). Research and development are still going on in order to diversify the potential of next generation energy sources in these areas. Such an adaptation for nuclear energy has the potential to open new business lines and make the nuclear energy more integrated to other industries.

Figure 11. Nuclear-Renewable integrated energy systems will support several industries increasing the utility of nuclear energy[26]



CONCLUDING REMARKS

- Independence and global market share in nuclear energy are national security issues that need constant support from the government, public and private industries. The current global nuclear energy market is dominated by the Asia-centric state-sponsored enterprises.

- Although the domestic energy market does not have high growth potential in near- to mid-term future, the global energy demand growth by 2050 is estimated to be financially attractive with the focus in non-OECD countries. If nuclear energy is successful in capturing 5% of the expected growth, it will have a $1 trillion market share. It is important that the U.S. can capture the majority of this market with its allies.

- The traditional light water reactors (LWRs) have been successfully operational for decades. However, they have been challenged in recent builds with cost and schedule overruns. These challenges have been experienced at the deployment of balance of plant level, but not the reactor technology. There are several reasons for this including loss of experience in the deployment to unique safety and regulatory requirements of LWRs.

- The Advanced reactors, from microreactors to small modular reactors (SMRs) to high temperature gas-cooled reactors, pose unique opportunities and safety features different from the large-scale LWRs. The safety features of advanced reactors enable using off-the shelf components and significant cost reduction potential in construction through the functional containment approach.
- Some of the advanced nuclear options, SMRs and microreactors, are moving fast in development and licensing. The financial and policy support for their first-of-a-kind (FOAK) deployment of advanced reactors need to be sustained in order to increase the financial attractiveness during export activities.

- For cost-competitive advanced nuclear energy option, the following are important: 1) regulatory support for enabling reduction of the cost of nuclear energy through functional containment approach for advanced reactors, 2) government support for increasing the human and corporate experience in the field, and 3) public-private partnerships and investments for expedited R&D.

- For FOAK challenge to be overcome, the U.S. needs to: 1) have policy and capital support for continuation of demonstration projects at National Reactor Innovation Center, 2) demonstrate advanced construction approaches along with advanced nuclear energy technologies, and 3) increase public and government awareness on the FOAK advanced reactor deployment in the U.S.

- For a successful export of advanced nuclear energy, the U.S. needs to: 1) preserve the baseline U.S. nuclear energy capabilities and industry for future export activities, 2) align the pace of government to government nuclear energy agreements with the potential deployment pace of small-scale advanced nuclear options, and 3) sustain the support for the manufacturing of nuclear fuel needs of advanced nuclear reactors.

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