July 2020

Global Nuclear Market Assessment Based on IPCC Global Warming of 1.5° C Report

UxC, LLC (UxC), a global leader in nuclear market research and analysis, has prepared this special analysis for the Nuclear Energy Institute with a specific focus on the global market opportunities that will arise as nuclear power is expanded to contribute to global climate change mitigation strategies over the coming three decades. This report's primary objective is to analyze global and regional nuclear power outlooks over the period to 2050 based on the scenarios presented in the October 2018 report published by the United Nations' Intergovernmental Panel on Climate Change (IPCC) entitled *Global Warming of 1.5°C*.[1] UxC used the pathways presented in the IPCC report to analyze the types of reactor technologies that could be deployed in various regions through 2050 to keep global temperatures at no higher than 1.5°C above pre-industrial levels. In addition, UxC extrapolated the resulting potential global nuclear market size and interpreted what this means in terms of export opportunities for U.S. nuclear suppliers based on these projections.

Executive Summary

- A review of the scenarios outlined by the IPCC report to achieve carbon mitigation goals indicate a median target for nuclear power capacity of 840 GWe by 2050. UxC concludes that, based on high confidence shutdown scenarios for existing reactors through 2050, a total of roughly 640 GWe of new nuclear capacity must be built between 2020 and 2050 to achieve the 840 GWe in 2050 target.

- Market expenditures to achieve the 2050 nuclear target are expected to be substantial over the entire forecast period. Cumulative nuclear expenditures are estimated at $8.6 trillion in 2019 US dollars, which includes capital and operating costs. This estimate is very reasonable considering that an independent cost estimate from the International Energy Agency (IEA) projects total costs to achieve a future global clean energy system will surpass $67.7 trillion.[2]

- The U.S. nuclear industry remains a world leader and has multiple opportunities for global exports in the future as nuclear capacity is added to achieve the IPCC 2050 target. UxC estimates the 30-year cumulative total for U.S. nuclear market revenues could range between $1.3 trillion and $1.9 trillion. U.S. suppliers will have numerous opportunities to expand their market presence, including in new reactor construction projects (large, small modular, and advanced designs), maintaining and fueling the global fleet of reactors, as well as decommissioning aging reactors.

[1] See: Global Warming of 1.5°C (https://www.ipcc.ch/sr15/)
[2] See: World Energy Outlook 2018, page 50 (https://www.iea.org/reports/world-energy-outlook-2018)

IPCC Report Implications for Nuclear Energy

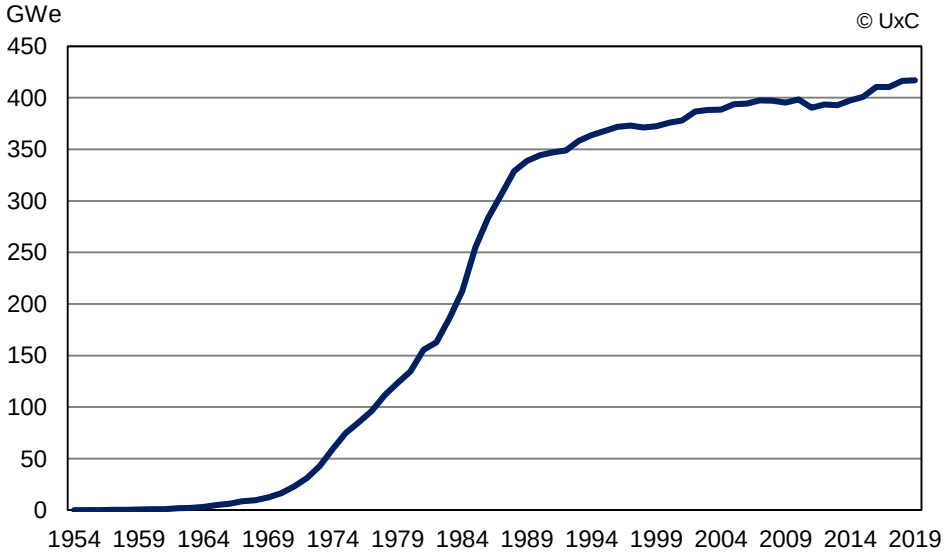
The IPCC report's main objective is to describe pathways outlining scenarios that could limit CO_2 emissions to certain levels through 2050. According to the report, the Integrated Assessment Modeling Consortium (IAMC), in cooperation with the IPCC, issued a call for submissions of scenarios showing ways to limit global warming to 1.5°C by 2050 and related scenarios to facilitate the assessment of various mitigation pathways. Scenarios submitted to IAMC were required to limit warming to between 1.5°C and 2°C over the long term. For the purposes of this study, UxC has focused on the pathways that limit the global temperature rise to 1.5°C by 2050. UxC extracted the relevant data for nuclear power generation from roughly 90 scenarios and converted the data from EJ (exajoules) to GWe (gigawatt-electric) generating capacity. The first step was to convert EJ to TWh (terawatt-hour) power generation, and then TWh to implied GWe capacity using an industry standard (85%) capacity factor.

The IPCC scenarios reflect major differences between minimum and maximum scenarios for implied nuclear capacity with the median falling somewhere in the middle. The minimum and maximum values reflect significant shifts through 2050, especially considering that 2019 nuclear capacity stands at roughly 405 GWe and total generation is a little over 2,500 TWh. For example, using the extreme minimum and maximum results for the year 2050, we find nuclear capacity ranging between 115 GWe and 4,320 GWe and generation between 858 TWh or 32,166 TWh. Given the disparity between these wide ranges, UxC has elected to use the median scenario results as outlined in the 1.5°C pathways. Thus, our analysis focuses on nuclear capacity in the range of 820-855 GWe by 2050 (**with an average ~840 GWe nuclear capacity target by 2050**).

Importance of Maintaining Existing Reactor Fleet

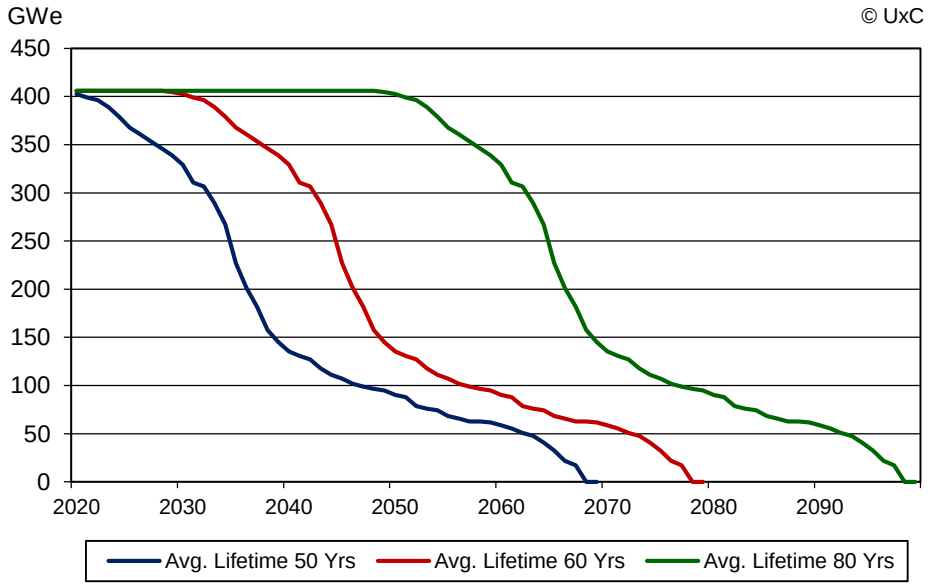
Before discussing the new nuclear build implications, it is critical to understand the state of the existing global reactor fleet. Many markets, especially those in North America, Western Europe, Russia, and Japan, are characterized by large nuclear capacities that were added during the period 1970 to 2000. As seen in the following Figure 1, most of the global nuclear capacity was added during this 30-year period.

Figure 1. Global Nuclear Capacity, 1954-2019



Some of the reactors built in the 1970s and 1980s have already begun to reach the end of their operational lives, and many more units are scheduled for closure in the coming few decades. Efforts to prevent these closures are critical to ensuring that nuclear power capacity remains stable in the near- and medium-term. UxC has analyzed the potential impacts of different average global reactor lifetimes on the world's total nuclear power capacity. As seen in Figure 2, if global lifetimes only average 50 years, the current level of ~405 GWe could be cut in half by around 2035 and reach zero operating reactors by 2070. Keeping the current fleet operating 60-80 years means extending the lifetimes of existing units, and thus reduces the burden on the new build sector to achieve the 2050 targets.

Figure 2. Impacts of Average Reactor Lifetimes on Existing Global Capacity

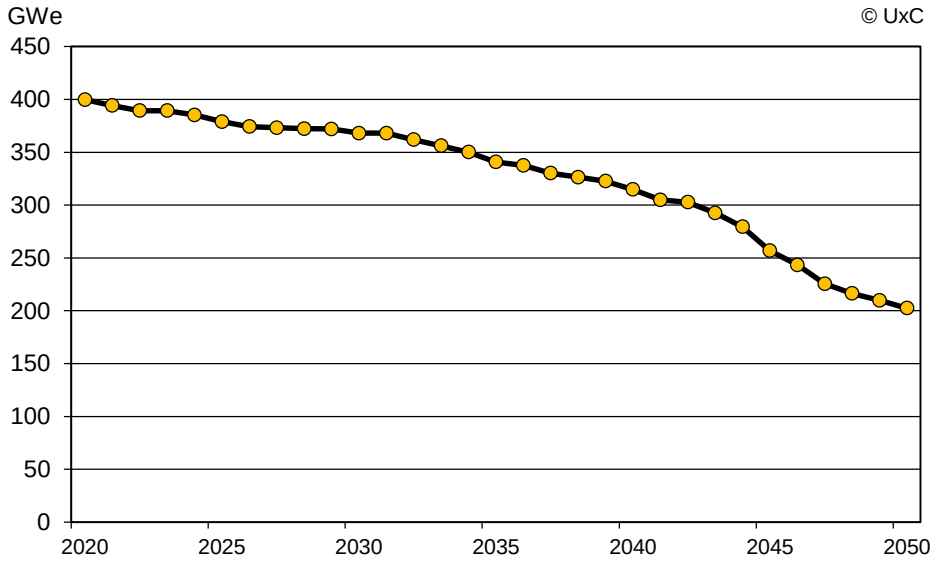


The above chart demonstrates how important it is to maintain as much of the current reactor fleet as possible to allow for adequate new builds to reach the ultimate long-term growth objective of 840 GWe by 2050. Various actions must be taken to promote existing plant lifetime extensions, including:

- Actions by power market system operators that provide consistent revenue streams for non-emitting, baseload generation and that properly places nuclear plants into an emerging flexible power mix that is becoming more heavily reliant on intermittent, renewable power supplies.
- Utility and supplier efforts to improve power plant operational performance through innovative new technologies that effectively fit into existing plant infrastructures.
- Ongoing public awareness efforts to espouse the value of the existing nuclear fleet and ensure public understanding that older facilities can continue operating safely and economically.
- Reasonable regulatory mechanisms that ensure ongoing high safety levels at existing plants, including prioritization of safety-related upgrades that are cost-effective and technically feasible.
- Government policies that value existing non-emitting nuclear power plants to guarantee adequate financial rates of return and stable operating environments.
- Efforts to reinvigorate the nuclear energy workforce as the current human resource base ages and must be replaced.

As long as these and other important measures are taken to maintain the current fleet for as long as possible, there is confidence that a reasonable level of the existing nuclear fleet can be preserved over a longer period of time, which includes many units that were built during the rapid new build era before the year 2000. UxC has high confidence in the following forecast for shutdowns of the current nuclear reactor fleet (see Figure 3). As the chart shows, gradual reductions in current capacity are projected through 2035, but a more rapid decline is foreseen in the post-2035 period as detrimental government policies and technological age-related constraints prompt additional reactor closures. The result is that the current nuclear fleet still operating in 2050 is expected to total just 200 GWe, marking a reduction of about 50% from 2020 levels.

Figure 3. UxC Forecast for Current Nuclear Capacity, 2020-2050



Impact of Reactor Closures on Decommissioning Market

The implications of reactor closures around the world between 2020 and 2050 as it relates to the growing nuclear decommissioning market can also not be overlooked. Although the primary aim of this study is to evaluate the implications of nuclear power expansion to achieve climate goals, UxC's forecast for reactor closures suggests that the ~202.5 GWe of shuttered reactors will require decommissioning spending of $350-$500 billion in 2019 US dollars over the coming 30-year period. Many U.S. companies are already leaders in the nuclear decommissioning market and thus would be well positioned to access additional market shares in this expanding global sector over the coming decades.

Achieving IPCC 2050 Median Nuclear Growth Targets

The 840 GWe of nuclear capacity by 2050 target set out by the IPCC median pathway scenarios is a lofty but achievable goal. Based on UxC's analysis of the existing nuclear capacity outlook, reaching 840 GWe by 2050 will require the world to build new reactor capacity of roughly 640 GWe over the coming 30 years. It should be noted that beginning with the first commercial nuclear power plant's completion in 1954 up through the end of 2019, a total of roughly 500 GWe of nuclear capacity has been built – of course almost 100 GWe of this capacity has since been decommissioned. This equates to an annual growth rate of about 7.0 GWe per year, which indicates a compound annual growth rate (CAGR) over the 65-year period of 19%. This impressive growth suggests that the world is capable of

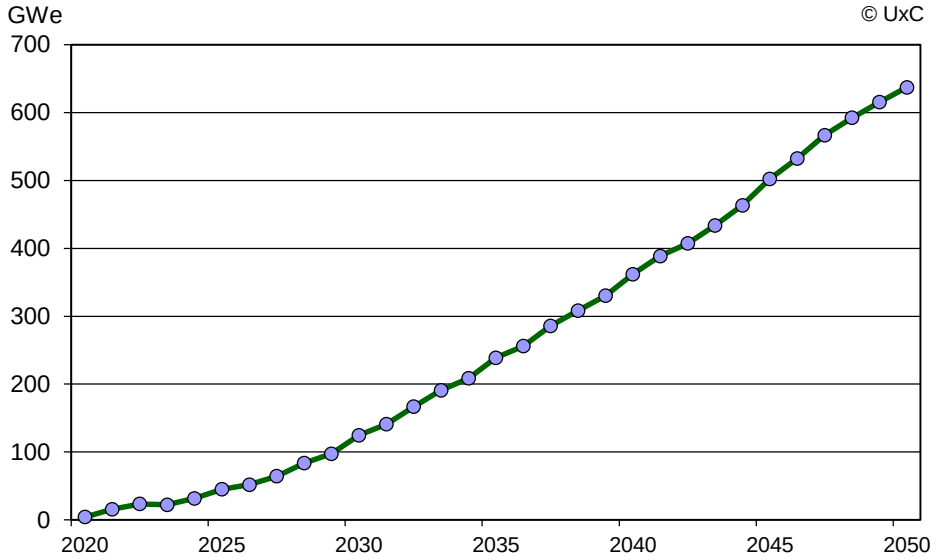
reaching the new target of 840 GWe by 2050. However, as seen in Figure 1 on page 2, the world has not added nuclear capacity over the past two decades at the same rate as it did from 1970 to 2000.

There have been varying rates of global nuclear power over the past 65 years. The peak growth period was 1970-1990, when an average of ~16.5 GWe was added each year over a 20-year period. Thus, there is clear historical evidence that a rapid expansion of nuclear power is achievable. While recent experience has not reflected the same pace of growth, there should be no question that the world can accelerate the pace of new reactor construction to attain the 840 GWe by 2050 target. Moreover, given various recent enhancements in areas of component manufacturing, large project management, as well as innovative construction techniques, a new fast-paced global reactor build program is certainly feasible.

New Build Requirements

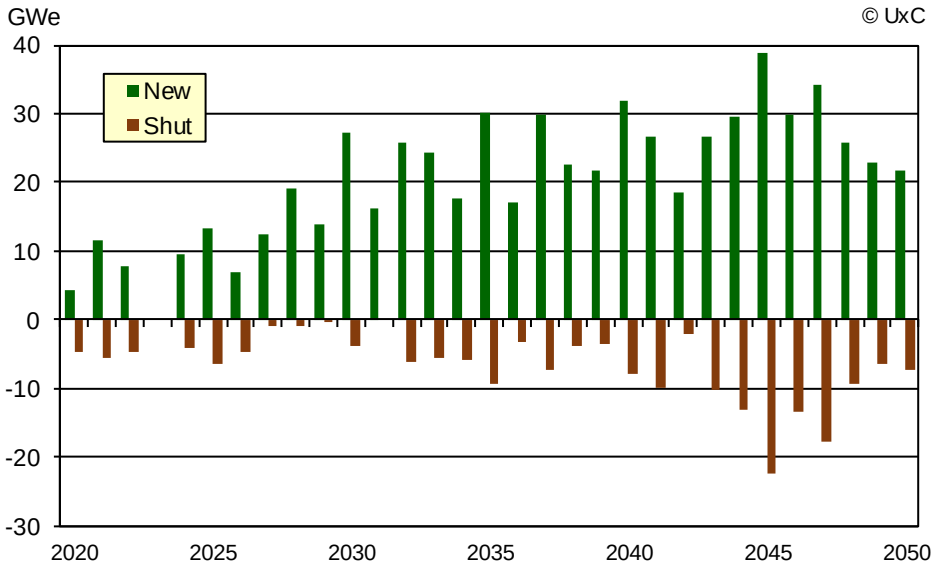
Although the CAGR required to achieve the 840 GWe level by 2050 is roughly 2.5% given our current starting position of ~405 GWe, the reality is that much more nuclear capacity must be added given the looming 50% decrease in the current fleet by 2050. This leads to the forecast of 640 GWe of new build requirements over the coming 30 years, with an average annual new build level of 21 GWe per year. Using the 840 GWe by 2050 target as a baseline objective, UxC has analyzed the level of new builds required per year given the anticipated best case scenario for capacity loss previously outlined. The results of this analysis are depicted in the following Figure 4.

Figure 4. UxC Forecast for Nuclear New Builds, 2020-2050



The near-term will see only a modest amount of new construction, but the pace of new builds should expand much more rapidly by the late 2020s and maintain this higher pace through 2050 to attain the 840 GWe goal. As noted, UxC's new build forecast also incorporates expected shutdowns over the period 2020-2050. As seen in Figure 5 (next page), certain years show high levels of both capacity additions and subtractions, although additions are generally much higher than subtractions throughout the forecast period.

Figure 5. New Builds vs. Shutdowns, 2020-2050



Regional Nuclear Growth Trajectories

Long-term nuclear power prospects in UxC's six regional markets vary significantly. The traditional two largest nuclear markets in North America and Western Europe, which together account for ~55% of today's global share, are expected to decline while the markets in Asia, Eastern Europe, Africa & Middle East, and South America all expand at faster rates. UxC's regional forecast is presented in Figure 6 below and the accompanying Table 1 (next page).

Figure 6. UxC Regional Nuclear Capacity Forecast, 2020-2050

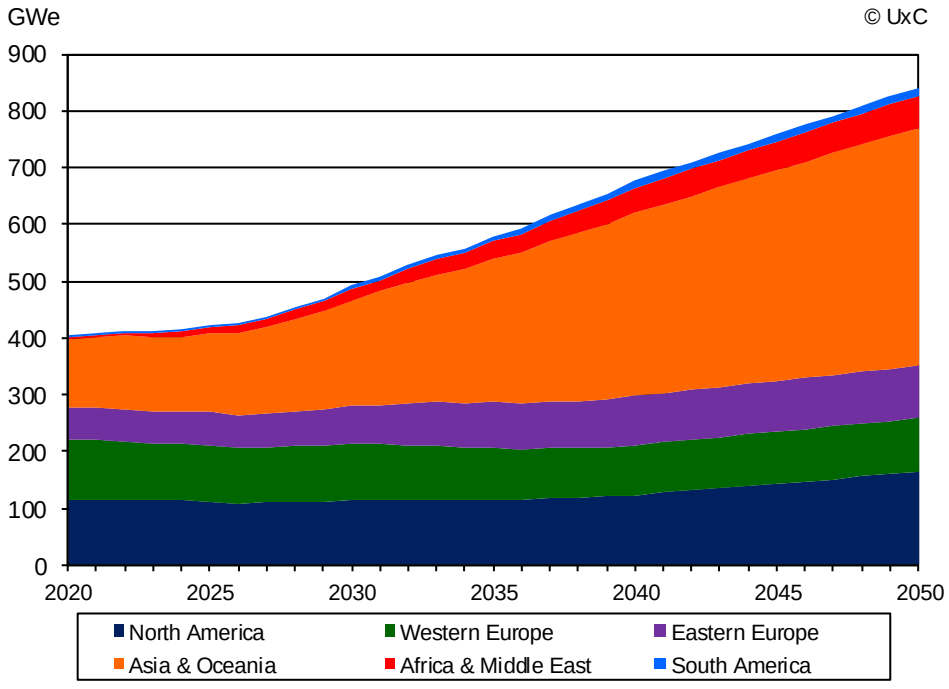


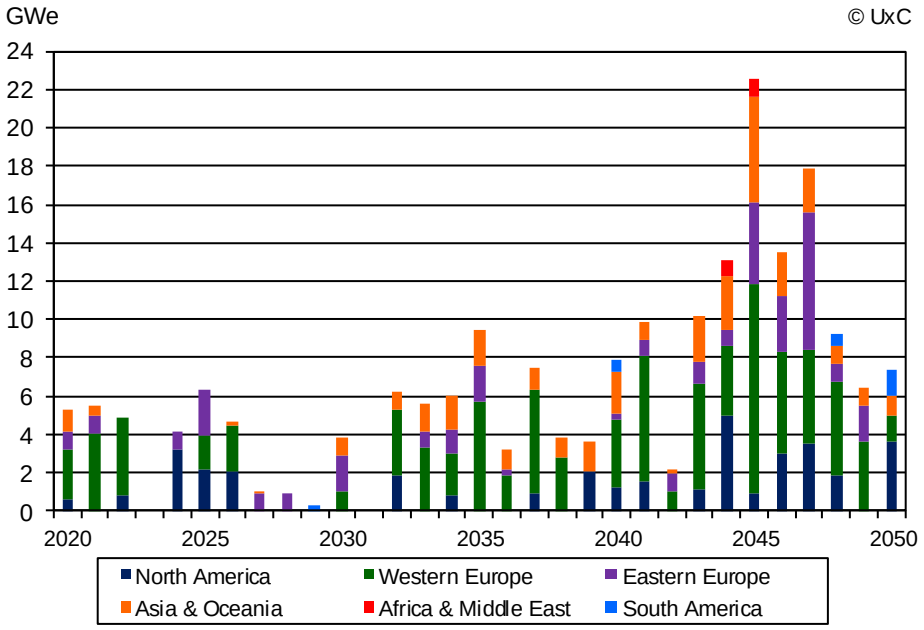
Table 1. UxC Regional Nuclear Capacity Forecast, 2020-2050								
Region *Capacities shown in GWe*	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**CAGR**
North America	113	112	113	115	124	144	164	**1.2%**
Western Europe	108	100	99	93	88	92	96	**-0.4%**
Eastern Europe	57	58	67	80	86	89	91	**1.6%**
Asia & Oceania	119	140	187	249	323	372	419	**4.3%**
Africa & Middle East	3	10	19	33	44	50	56	**10.6%**
South America	4	5	7	9	12	13	14	**4.6%**
World Total	**404**	**424**	**493**	**580**	**677**	**759**	**840**	**2.5%**

The above data provides several important insights. First, North America and Western Europe see their combined market share fall well below the current level (i.e., ~31% in 2050). Meanwhile, Asia increases rapidly to 50% in 2050 from a 29% share today. The largest total growth is obviously in Asia, but on a CAGR basis, Africa & Middle East experiences the fastest expansion followed by South America. Only Western Europe reflects a net reduction in capacity. Meanwhile, North America's CAGR reflects moderate growth, although lower than some of the other regional markets. Naturally, the pace of shutdowns and new builds in each of the regional markets plays an important role in determining their future nuclear outlooks to 2050.

Shutdowns by Region

Figure 7 presents UxC's regional reactor shutdown forecast over the next 30 years. This forecast is based on reasonable estimates for life expectancies of existing reactors taking into account current policies as well as regulatory, economic, and technological factors that affect future operating conditions. Clearly, the majority of closures will be in Western Europe and North America, although higher numbers of retirements are expected in other regions after 2035.

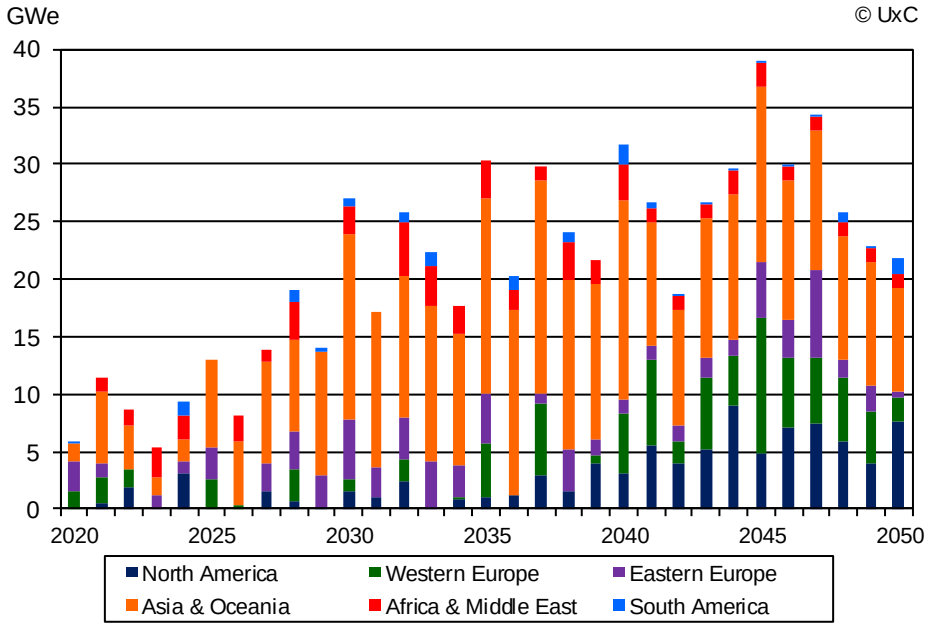
Figure 7. UxC Regional Reactor Shutdown Forecast, 2020-2050



New Builds by Region

As seen in Figure 8, the new build picture on a regional level also tells a different story depending on the particular market analyzed. In the near- and medium-term, most of the new builds are forecast in Asia, Africa & Middle East, and Eastern Europe. However, given higher shutdown rates, North America and Western Europe are expected to see significant levels of new builds through the 2040s.

Figure 8. UxC Regional New Build Forecast, 2020-2050



New Reactor Technologies

The selection of reactor technologies to meet this growing nuclear capacity requirement is another important factor to consider. Although the near-term outlook is primarily centered on extended operation and new construction of large, traditional reactor types (e.g., light water reactors or LWRs and pressurized heavy water reactors or PHWRs), the longer-term future is likely to see a transition to a mix of emerging new technologies, including small modular reactors (SMR), microreactors, and other advanced designs. There are many promising new technologies in various levels of design, licensing, and development. Some initial projects are already underway to prove these advanced designs, but there is strong anticipation that the post-2025 period will see a more rapid buildout of the next generation of advanced nuclear reactors. There are many drivers for SMRs and advanced reactors, including lower upfront capital costs per project, modular addition of capacity (i.e., adding generating capacity as needed to better align with demand), ability to build in new geographies (e.g., islands, remote locations, etc.), potential to supply power and heat to industries, for desalination, or for military applications, safety enhancements, potentially lower licensing barriers, among various other benefits.

UxC has analyzed the future outlook for all the different reactor technologies and remains confident that the largest percentage of new capacity will come from large reactors as the history of the industry and the trends of the past several decades point to a continued buildout of mature and proven technologies. However, over time, SMRs, microreactors, and advanced designs (e.g., fast reactors, high-temperature designs, and liquid metal designs), will begin to see much larger market penetration. The percentage of non-traditional reactor designs could reach upwards of 25% of the total market by 2050.

Implications of 2050 Outlook for U.S. Nuclear Industry

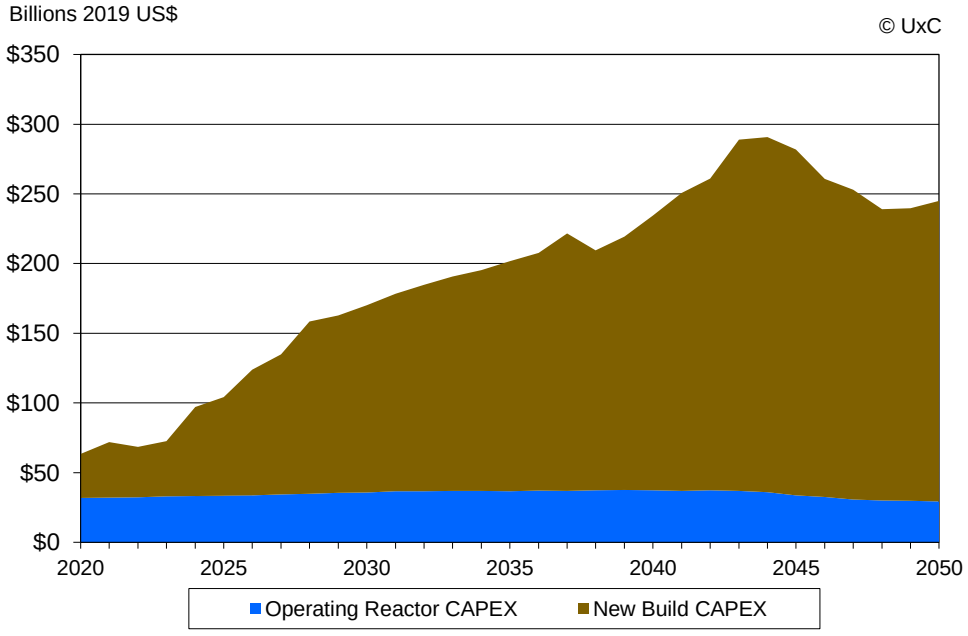
Many U.S. companies already active in this industry stand to gain considerable revenues if the global nuclear market expands to achieve the target of 840 GWe by 2050. Large sums of money will have to be spent around the world to build all the new reactors required to meet the IPCC 2050 goal. However, opportunities will not be limited just to the construction sector as operating units will require a host of ongoing support services over the entire forecast period. Moreover, the increasing decommissioning market accompanying reactor closures presents significant opportunities for U.S. suppliers.

Global Nuclear Market Capital Expenditures

Naturally, a major focus of attention is on the amount of capital expenditures (CAPEX) needed to achieve massive growth in new builds to meet the IPCC target. However, significant CAPEX will also be required to maintain much of the current fleet and extend reactor lives as envisioned under UxC's projections. UxC has analyzed the various CAPEX requirements to achieve the 840 GWe by 2050 target and has found that the main categories for these expenditures fall into three sectors: operating reactor CAPEX, large reactor new build CAPEX, and SMR/advanced reactor new build CAPEX. Figure 9 presents the breakdown of cumulative capital expenditures for operating reactor and new build CAPEX by year over the next 30 years, which aligns with the 840 GWe target. Note that these totals are presented in terms of 2019 billion US dollars adjusted for inflation into the future.

As Figure 9 on the next page shows, CAPEX for operating reactors remains relatively stable throughout the forecast period. However, a higher level of investment will be needed as many new reactors are built after 2025. The resulting global total CAPEX over the 30-year period is $5.9 trillion.

Figure 9. Cumulative Global Nuclear Capital Expenditures by Type, 2020-2050



Global Nuclear Market Operating Reactor Expenditures

Reactors also require ongoing operating expenditures (OPEX) over their lifetimes to maintain operations. UxC has analyzed the operating costs of most reactors around the world to arrive at an average level of operations and maintenance (O&M) expenditures. For the most part, these external expenses are either on materials and supplies (including fuel) as well as on external labor (e.g., refueling outage contractors or for specialized testing and maintenance activities).

Figure 10. Cumulative Global Nuclear Operating Expenditures, 2020-2050

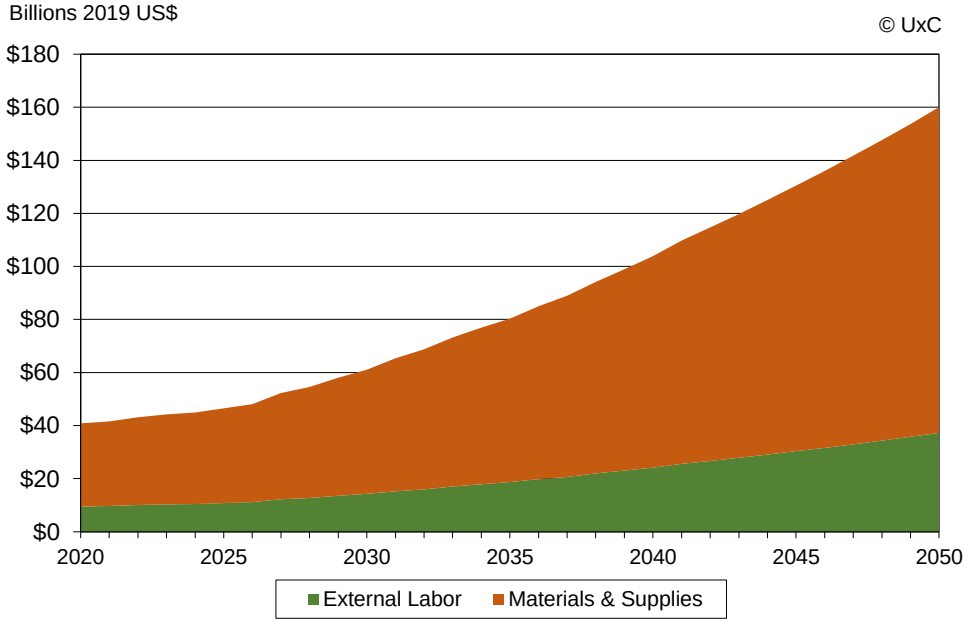
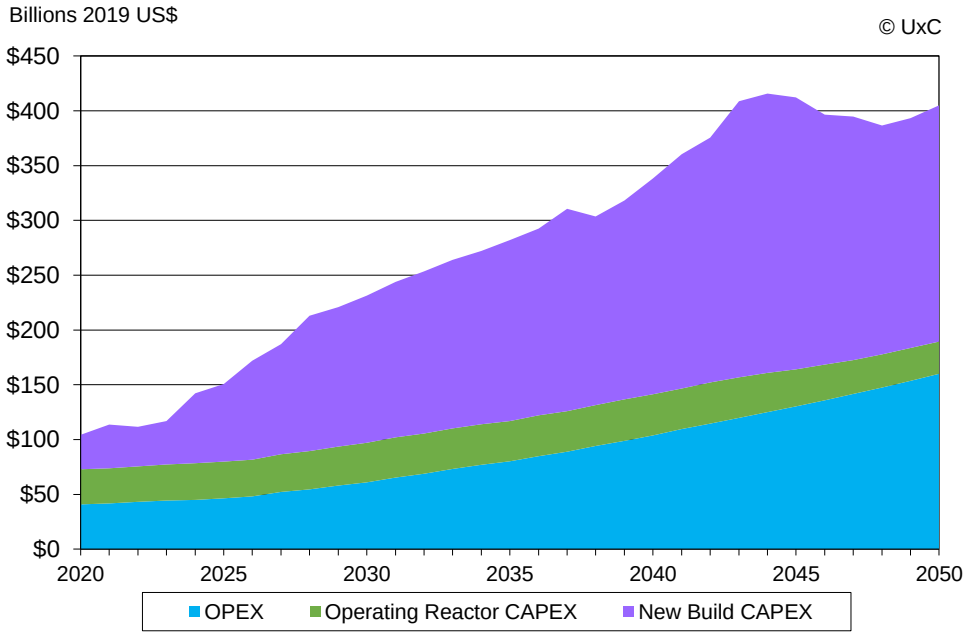


Figure 10 above presents the anticipated amount of OPEX to be spent externally by utilities, which reflects the available market opportunities for nuclear suppliers across the fuel cycle and reactor maintenance industries. Global OPEX will continue to increase over the 30-year period as more reactors are built and operated. The net result is that UxC projects global cumulative OPEX spending to total $2.7 trillion over the 30-year period.

Global Nuclear Market Size Projection

Combining all the above analyses, we arrive at a total market size projection as seen in Figure 11. Annual expenditures to achieve the IPCC 2050 target are substantial over the entire forecast period. Cumulative nuclear market expenditures through 2050 are estimated at $8.6 trillion in 2019 US dollars.

Figure 11. UxC Global Nuclear Market Size Projection, 2020-2050



Notably, the International Energy Agency (IEA) estimated in its *World Energy Outlook 2018* report[3] that to achieve a low carbon energy system just through 2040 would require over $67.7 trillion (in 2017 US dollars). As such, UxC's nuclear cost estimate of $8.6 trillion through 2050 represents only a small portion of anticipated global spending to achieve future climate goals.

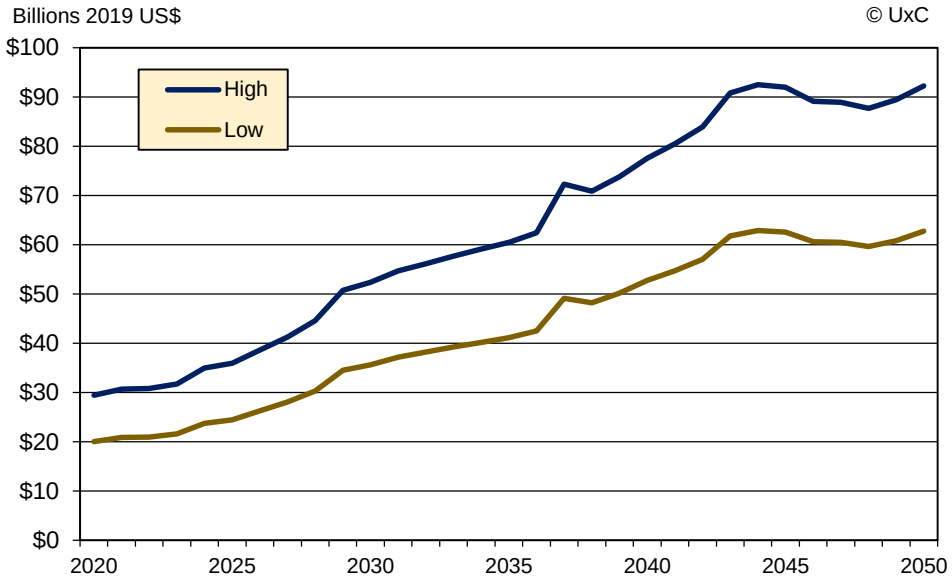
Market Opportunities for U.S. Nuclear Industry

The ability of U.S. suppliers to access these various markets will depend on many different factors. Currently, much of the new build money is being spent in Asia, Eastern Europe, and the Middle East, while U.S. suppliers have yet to make heavy in-roads into many of these markets. Naturally, the traditional markets of North America and Western Europe as well as parts of Asia, such as Japan, Taiwan, and South Korea, remain fertile ground for U.S. suppliers. Over time, it is anticipated that U.S. companies will make further progress in accessing the larger growth markets in Asia, Africa, Middle East, and elsewhere. Based on this view and additional analysis, UxC has arrived at the following estimates for global nuclear sales for U.S. nuclear suppliers in light of the 840 GWe IPCC 2050 target.

As noted, there are many factors that could shape the future course of the U.S. nuclear industry's access to various global markets and the rate of market penetration in key growth sectors. As such, UxC has created a High and Low estimate for future U.S. nuclear market revenues through 2050, assuming the IPCC 2050 target of 840 GWe is achieved (see Figure 12 on the next page).

[3] See: World Energy Outlook 2018, page 50 (https://www.iea.org/reports/world-energy-outlook-2018)

Figure 12. UxC High-Low Projections for U.S. Nuclear Market Revenues, 2020-2050



As the above chart indicates, the 30-year cumulative total for estimated U.S. nuclear market revenues ranges between $1.3 trillion and $1.9 trillion. Clearly, U.S. nuclear vendors and related companies would see significant new sales opportunities throughout the world.

Most Promising Market Opportunities for U.S. Nuclear Industry

The U.S. nuclear industry remains a world leader and has ample opportunities for global exports in the future. UxC considers the following to be the most promising future prospects driven by the IPCC target of 840 GWe in global nuclear capacity 2050:

- Since the U.S. nuclear reactor fleet is the first to take on 80-year lifetime extensions, the industry should see significant CAPEX to support these longer lifetimes of U.S. reactors. Given the country's extensive experience with extended reactor operations, U.S. vendors have significant advantages to support similar lifetime extensions in markets across the globe. Since much of the existing global reactor fleet has its origins in U.S. technology and suppliers, U.S. vendors continue to enjoy an advantage in selling services and components to existing reactors.
- Although most global new builds are expected to be based on large reactor technologies (e.g., 1,000 MWe-sized light water reactors), there will also be a rapid expansion of the SMR/advanced reactor market. U.S. firms have several of the world's leading SMR and advanced reactor technologies under development. As long as U.S. projects can be proven within the next decade, U.S. vendors should be able to access a sizeable portion of the global SMR/advanced reactor market, which is expected to grow substantially in the next 30 years.
- The operating reactor services market will expand rapidly as new units are added around the world. U.S. suppliers active in engineering services, component supply, fuel cycle services, etc. will be able to access this growing market.
- Finally, the rapidly growing nuclear decommissioning market due to continued shutdowns of aging reactors in many countries around the world over the coming three decades will create significant new opportunities for U.S. suppliers active in this area.