«NON-TRADITIONAL NUCLEAR REACTOR DESIGN CONCEPTS»

A SYNTHESIZED ANALYSIS OF THE STATE OF THE "ADVANCED" US NUCLEAR INDUSTRY

Fokus USA – An Analysis
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Abstract

Despite a nearly 20-year lull, nuclear energy has seemingly reentered the low-carbon energy conversation in the US with the rise of non-traditional or “advanced” nuclear reactor technologies. Though non-traditional nuclear reactor designs have been in the research and development stage for decades, an “advanced” nuclear hype has burgeoned following a number of awarded subsidies from the US Department of Energy (DOE), a final safety approval of the first small modular reactor design from NuScale Power, as well as announced commitments to bolster the US nuclear industry by the Biden Administration. Given the hype, it is difficult to discern myth from truth: do non-traditional nuclear reactors have a future in America’s low-carbon energy system or are the purported advantages of “advanced” reactors too good to be true and nevertheless to slow to decarbonize the energy system fast enough. Taking insight foremost from a 2021 study by the Union of Concerned Scientists (UCS) on “advanced” nuclear reactors, this short analysis examines three non-traditional nuclear reactor designs based on three UCS defined evaluation criterion—safety and security risk, sustainability, and nuclear proliferation potential—as well as an additional fourth criterion added here new—economics. Then, to provide a consolidated overview of the proclaimed advantages of non-traditional nuclear reactors over traditional ones, an “Expectation vs. Reality” rapid-fire comparison is presented. This analysis investigates whether or not current non-traditional nuclear reactor designs exhibit enough of a significant advantage over both traditional designs as well as other renewable energy technologies to justify the time as well as the financial and material resources needed to commercialize in the face of a climate crisis.

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Abbreviations

Table 1: Description of abbreviations.

ARDP	Advanced Reactor Demonstration Program
DOE	US Department of Energy
GIF	Generation IV International Forum
HALEU	High-assay low enriched uranium
HTGR	High-temperature gas reactor
kW	Kilowatt
kWh	Kilowatt hour
LEU	Low-enriched uranium
LWR	Light-water reactor
MSR	Molten salt reactor
MW	Megawatt
MWh	Megawatt hour
NLWR	Non-light-water reactor
NRC	Nuclear Regulatory Commission
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
TRISO	Tristructural isotropic
UCS	Union of Concerned Scientists

1. Introduction

The deployment of nuclear power in the United States (US) has been stagnant over the last twenty plus years, yet recent indications of an industry wide revival are burgeoning. As the US looks ahead to an ambitious climate target—50% reduction in carbon emissions compared to 2005 levels by 2030, as recently pledged by the Biden administration in April 2021 [1]—they will need the help of all the low-carbon, cheap and readily deployable electricity they can find. One key component to achieving this ambitious target considered by the Biden Administration is nuclear power. The US Department of Energy (DOE), members of the Nuclear Regulatory Commission (NRC) as well as climate and energy envoys within the Biden team have all signaled commitments to reviving the American nuclear industry [2 – 5]. Particularly central to this revival and heavily recited in politics and media are "advanced" nuclear reactors along with a subset of this field, Small Modular Reactors (SMR). "Advanced" reactor designs are conceptually not new. In fact, some of the current designs pushing for commercial development in the US have been continuously explored since the 1950's. The primary approach to expanding the modern nuclear field in the US has been the research and development of "advanced" non-light-water reactors (NLWR), which differ from traditional light-water reactors (LWR) that are deployed at scale in the US today (see Section 1.1 for clarification of terms). With 64 companies[1] and start-ups working on advanced reactor technologies [6], the US has positioned itself as a global leader in advanced nuclear science and is particularly stressing development of small modular and micro reactors. As for SMR technologies, 72 designs are in development both US-wide and worldwide [7]. In theory, some advanced reactor concepts offer higher ensured safety and environmental sustainability, are more economical, and pose less of a proliferation threat than traditional light-water reactors (LWR). When promoting the SMR concept, it is particularly the (theoretical) economic benefits that are often purported by nuclear advocates.[2]

These proclaimed advantages, however, have yet to be widely and consistently observed in the lab let alone at commercial scale. In light of recent financial investments and growing bipartisan political support for low-carbon technologies necessary to meet pledged climate targets, policy-makers and nuclear regulators in the US (as elsewhere) would be wise to fully assess the comparative advantages and disadvantages of advanced nuclear technologies before kick starting an expensive revival of the American nuclear renaissance.

A number of recent studies [8 – 11] have closely examined comparative tradeoffs between traditional (LWR) and non-traditional "advanced" (NLWR) reactors, including SMR designs (which can be LWR or NLWR). Notably, this analysis recognizes a thorough and since publication highly referenced analysis: the March 2021 study from the Union of Concerned Scientists (UCS) titled "*Advanced Isn't Always Better: Assessing the safety, security and environmental impacts of non-light-water nuclear reactors*" [8]. Guided by the question "Is different always better?" the study compares and vets the viability of modern advanced nuclear reactor designs. In short, their answer is no. Most current NLWR designs do not exhibit enough of a significant advantage

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[1] These 64 companies include *all* "advanced" reactor companies such as fusion reactors, nuclear batteries, super-critical CO2 reactors, etc.

[2] As with all "advanced" reactor designs, the idea of SMRs is not particularly new. There have been various earlier efforts to develop and market SMRs, however, they have so far remained unsuccessful [15].

over LWR designs to justify the time as well as the financial and material resources needed to commercialize.

Taking insight and inspiration foremost from the UCS study, and secondarily from other complimentary studies, the following analysis adds to the trending discussion and assessment of non-traditional nuclear reactor feasibility in future low-carbon power systems, with a particular focus on "advanced" NLWRs and SMRs. Notably, in section 2, three non-traditional designs are examined directly from the UCS study. UCS identifies these non-traditional reactor types as the three most prominent technologies researched today in the US. The designs are differentiated and evaluated based on three defined criteria from the UCS study: risk and safety, sustainability, and nuclear proliferation potential. This evaluation is then supplemented with a fourth additional criterion missing from the UCS study: economics. Secondly, in section 3, proclaimed advantages of non-traditional reactors over traditional reactors are consolidated in an "Expectation vs. Reality" rapid-fire comparison.

1.1 Definition of Non-traditional Nuclear Reactor Terminology

In order to be consistent with nomenclature, a short clarification of terms is provided. The category of "advanced" nuclear reactors is quite vague and is in fact more of an umbrella term that encompasses any reactor design claiming to be "advanced" or rather non-traditional. Nearly all nuclear plants operating today in the US are traditional light-water reactors (LWR). They use ordinary water as the coolant and moderator and do not exhibit any distinctly advanced features. Furthermore, most new plants under construction today worldwide are traditional LWRs. "Advanced" nuclear reactors can indeed include advanced LWR concepts, but are often more referring to reactor designs cooled not by water, but by other mediums such as liquid sodium, high temperature gaseous helium, or molten salts. This class of advanced reactors is coined non-light water reactors (NLWR). Unequivocally, LWRs are considered a mature technology. While some NLWRs are also considered by the US DOE to have "*high enough technology readiness levels to support a commercial demonstration in the near future*", others require further demonstration of their performance characteristics and safety reliability [12]. The NLWRs examined in this analysis are Generation IV[3] technologies as identified by the Generation IV International Forum (GIF)[4].

A second distinction of concept categories is the small modular reactor (SMR), a perhaps more commonly referenced term in the media. SMR designs are inherently that—small and modular. They are typically sized at a less than 300 MW capacity and are modular in the sense that the reactor itself can be constructed on site with various components assembled from external factories. This differs quite dramatically from existing reactors in the US nuclear fleet, which have much higher power capacities (around 1GW) and are constructed from scratch on site thereby retaining something of a bespoke or one-off quality [9]. It is important to note that SMRs can

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[3] Reactor designs are broadly categorized in four so-called generations: Generation I reactors refer to the first commercial prototype reactors; Generation II reactors refer to commercial power reactors in operation; more evolutionary power reactors are termed Generation III reactors (among those, the newest concepts are coined as Generation III+); Generation IV relates to future reactor types.

[4] GIF is an international task force initiated by the US DOE that is developing six selected Generation IV nuclear reactor technologies which they believe to be the future of nuclear energy.

involve LWR or NLWR technologies. The term SMR is therefore primarily a reference to the relative size of the reactor as a design characteristic. Still, SMRs do indeed fall under the “advanced” reactor umbrella term (as well as the category of Generation IV reactors).

For consistency and simplicity, as much as possible throughout this analysis the term **traditional** is used to mean non-advanced LWRs (i.e. the existing US nuclear fleet) and the term **non-traditional** is used to mean NLWRs, SMRs or other Generation IV reactors that are presently in development and not yet deployed at scale.

As a third terminology clarification, it is noted that “advanced” does not imply “of-the-future”. Many of the NLWR designs at various stages of technological evolution are products of decades of research and development. Since the 1950’s there has been considerable research on sodium-cooled fast reactors and today there are five such reactors operating in India, Russia and China [8]. High-temperature gas reactors were first initiated in the late 1940’s and in the 1970’s were poised to outcompete light-water reactor technologies, though this did not come to pass. Though molten salt reactors have only recently gained pronounced attention in the industry.

Through both funding and program demonstrations, the first engineering-scale test demonstration was performed in the 1940’s. Similarly, SMRs date back to the 1950’s when the US Atomic Energy Commission funded the construction of several small power reactors [13]. There have since been efforts to develop and market SMRs, but these efforts have been so far largely unsuccessful [14—16]. Non-traditional nuclear reactor technologies have existed for decades—advanced does not mean new.

1.2 Non-traditional Nuclear Reactor Technologies

Non-traditional nuclear reactor technologies differ quite distinctly from traditional technologies and differ as well from each other. In order to compare non-traditional to traditional reactors as well as to assess a variety of non-traditional (more specifically NLWR) classes, a mix of prominent non-traditional technologies in development at notable US companies or startups are selected. In particular, three key non-traditional technologies are examined: sodium-cooled fast reactors, high-temperature gas reactors, and molten salt reactors. These three technologies are briefly described below.

Three key characteristics are helpful to differentiate and describe non-traditional reactor technologies: the fuel, the reactor power resource, which can exhibit different configurations and thermodynamic characteristics as well as different levels of enrichment; the moderator, the primary method of controlling the speed of the chain reaction; and the coolant, the medium that controls the temperature of the reactor core as well transfers heat from the core to the electrical generators. These three characteristics are addressed for each of the three described non-traditional reactor technologies below.

Sodium-cooled Fast Reactor (SFR)

SFRs can be characterized namely by the moderator and coolant type, both of which are liquid sodium metal. Importantly, fast reactors do not attempt to slow down the neutron chain reaction in the radioactive core, but rather utilize the energetic inertia of fast neutrons. To this end, fast reactors are to an extent considered "unmoderated". Second, because water cannot be used as a coolant, as it would slow down the neutrons, fast reactors instead use liquid metal coolants—in this case sodium, a heavier substance with a high thermal capacity that allows for high operating temperatures[5]. Fast reactor fuels can be metal, ceramic oxide, or even nitride based, though US designs currently prefer metal based fuels [8].

NOTE: Fuel enrichment levels for non-traditional reactors differ from that of traditional reactors. Today's LWRs use uranium-based fuels enriched with less than 5% of the isotope uranium-235. Some proposed non-traditional designs (including Company Profile 1 and 2) require high assay low enriched uranium (HALEU) fuel, which has typical enrichment levels of 10-20% uranium-235. Other types of non-traditional designs would use plutonium separated from spent fuel or uranium-233, both of which are highly attractive materials for nuclear weapons.

High-Temperature Gas Reactor (HTGR)

HGTRs are cooled by a high-temperature pressurized gas (typically helium) and moderated by graphite in the reactor core. Temperatures in HGTRs operate between 700-950°C as compared to traditional reactor temperatures which are closer to 300°C. There are two typical reactor configurations for HTGRs: the pebble bed type and the prismatic block type. Pebble bed HTGRs utilize moving fuel elements that continuously circulate within the reactor core. Prismatic block HTGRs use conventional stationary fuel elements. Both configurations, however, employ a special TRISO (tristructural isotropic) fuel that can withstand high operating temperatures[6]. Additionally, waste heat from HTGRs can be used for other energy-intensive processes that require high thermal energy inputs such as hydrogen production or petroleum refining.

SFR and HTGR technologies are by far the furthest along in the research and development process in the US. Both technologies were identified by the DOE in 2017 as two non-traditional reactor designs that are mature enough to proceed with commercial demonstrations [17].

Molten Salt Reactor (MSR)

The MSR technology is distinguished primarily by the fuel type. As opposed to solid form fuel used in traditional reactors, MSRs employ liquid fuel dissolved in a molten salt at operating temperatures of at least 650°C. The dissolved fuel molten salt mixture also operates as the coolant. MSRs can be moderated, with thermal reactor designs that use graphite, or unmoderated with fast reactor designs. A key component of the MSR process is the mid-cycle fuel treatment required to extract radioactive isotopes that detrimentally affect performance from the fuel-coolant mix[7]. Of the three non-traditional technologies, MSRs are the furthest from commercial development.

All three designs are prominently researched in the US today and two of the three are nearing commercialization. For context, GIF has identified internationally six non-traditional reactor types[8] out of 130 evaluated concepts to be appropriate for further research and development. SFRs, HTGRs, and MSRs are included in the

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[5] See GIF, Sodium-Cooled Fast Reactor
[6] See GIF, Very-High-Temperature Reactor
[7] See GIF, Molten Salt Reactor
[8] See GIF, Generation IV Systems

GIF list of six (though take note—the naming convention is not universally consistent).

2. Evaluation Criterion

To provide a critical but comprehensive comparison of non-traditional to traditional reactors, as well as a comparison of different non-traditional NLWR types, four evaluation criterion are employed: safety and security risk, sustainability, nuclear proliferation and terrorism threat, and economics. The first three criterion are discussed in a summary format based on recently published findings from the UCS study, and the fourth criterion, economics, is added here new.

Invariably, non-traditional nuclear reactor technologies assert a number of advantages over traditional technologies. Among the more centrally asserted advantages are lowered costs, improved safety and efficient fuel use [18]. The March 2021 UCS study on advanced nuclear reactor technologies identified three broad evaluation criterion for assessing relative merits of NLWRs and LWRs: safety and security, sustainability, and risks associated with nuclear proliferation and nuclear terrorism[9]. Importantly, this analysis finds the UCS report's assessment criterion to be highly useful and their key findings credibly informative. Below, highlights for each of the three criterion are summarized and cross-referenced with additional studies and sources that support or supplement the UCS conclusions.

2.1 Safety and Security Risk

Definition: Safety and security risk is defined by UCS as the "vulnerability of reactors and fuel cycle facilities to severe accidents or terrorist attacks that result in significant releases of radioactivity to the environment." In particular, this analysis stresses the environmental impact of potential accidents or malfunctions that would lead to radioactive releases.

Overall, UCS rates the three NLWR technologies quite poorly on the grade scale[10] for safety and security risk. The only NLWR design that is designated inconclusive due to insufficient information is HTGRs. SFRs and MSRs, however, have serious safety concerns that have either not yet been adequately addressed or have not yet been overcome in test demonstrations. For the safety and security risk evaluation criterion, each NLWR type is individually summarized as different design concepts have different nuanced safety considerations.

- SFRs: This NLWR type has a number of safety concerns that do not exist for traditional LWRs. One major concern with SFRs is the sodium coolant itself, which can burn if exposed to air or water. Also concerning is the possibility of runaway power excursions: if an SFR experiences rapid power increases that become uncontrollable, the fuel could overheat leading to a sodium coolant boil off, leaving the core compromised as the SFRs power would increase in a positive feedback loop. In the worst-case scenario, the SFR core could explode like a small nuclear bomb. Because of this runaway risk, among other risks, SFRs require additional safety systems that LWRs do not, thus increasing the relative capital cost.
- HTGRs: The safety of HTGRs depends primarily on the TRISO fuel unique to this NLWR. As a refresher, TRISO is a special type of nuclear fuel coating

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[9] Overall, the study performs a sober and thoroughly researched analysis.

[10] The UCS grade scale defines seven qualitative rankings to compare NLWRs with LWRs. These qualitative rankings are: significantly worse, moderately worse, slightly worse, slightly better, moderately better, significantly better, and not enough information.

that allows the fuel to withstand very high operating temperatures. Importantly, TRISO fuel is designed to retain radioactive fission products at these high temperatures, but if the fuel is heated beyond a certain limit (as is highly likely in the Xe-100 HTGR SMR from X-Energy — see Company Feature 1), fission product release speeds up much faster than in radioactive releases from LWRs. Fundamentally, the TRISO fuel design offers increased safety from a radioactive release, but a lot has to go right for these safety advantages to hold. Uncertainty is high and more testing, analysis and demonstration projects are necessary to be confident of the overall safety of HTGRs. In particular, consistent manufacturing of TRISO fuel is key, but this has not yet been demonstrated to exacting precision.

- MSRs: For MSRs, the fundamental safety advantage of the reactor technology is the molten core. As MSR advocates point out, the fuel cannot melt down if it is already molten. UCS finds this argument to be highly simplistic. MSRs pose a host of other unique safety issues, the most serious of which is the release of large quantities of gaseous fission products from the liquid fuel structure as compared to traditional solid fuel cores. These untrapped fission products, if not properly dealt with, decay into highly radioactive isotopes that are environmentally harmful. Overall, MSRs are rated highly unsafe by UCS.

Company Profile 2: A short profile of the X-Energy company and its Xe-100 reactor design

X-Energy and the Xe-100
High-Temperature Gas Reactor – Pebble Bed Reactor – Small Modular Reactor

Dimensions and Specs: The Xe-100 reactor is an advanced modular reactor. Each unit is designed to produce around 76 MWe. Furthermore, the Xe-100 is a specific type of high-temperature gas reactor, namely a pebble bed reactor. This means that the fuel employed in the Xe-100 is pebble shaped and utilizes the tristructural-isotropic (TRISO) particle fuel design.

Who is X-Energy?

X-Energy is a US private nuclear reactor and fuel design engineering company founded in 2009. It employs around 100 employees.

Who is funding X-Energy?

The financial status of X-Energy appears angel-backed. Furthermore, X-Energy is receiving substantial government funding: It received $80 million in 2020 by the DOE through the DOE Advanced Reactor Demonstration Program (ARDP), which is planning further investments in the upcoming years.[11]

Where does the Xe-100 design concept stand?

Pebble bed HTGRs were first proposed in the 1940s. Several small HTGRs (pebble bed and non-pebble bed) have been operating as test reactors since the 1960s, but have not advanced beyond this status. X-Energy's goal is to have a basic design completed by 2021.[12] However, it remains unclear how realistic this goal is.

2.2 Sustainability

Definition: In the context of NLWRs, sustainability has to do primarily with nuclear waste and secondarily with efficiency of mined material. As defined by UCS,

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[11] See: Office of Nuclear Energy, U.S. Departement of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program, October 13, 2020.

[12] See: Office of Nuclear Energy, X-energy is Developing a Pebble Bed Reactor That They Say Can't Melt Down, January 5, 2021.

sustainability refers to the "*amount of nuclear waste generated by both reactors and fuel processing facilities that requires secure, long-term disposal, as well as the efficiency of using natural (mined) uranium and thorium*." For each of the three NLWR types examined, two primary questions are posed: 1) is the NLWR fuel used more efficiently and 2) do NLWRs generate less waste as compared to LWRs.

On the UCS grading scale, the sustainability criterion presents highly mixed results between NLWR types. Some design concepts offer very promising solutions to waste generation and resource efficiency, while others fair moderately worse than LWRs. SFRs have the potential to utilize uranium more efficiently than LWRs by way of the conventional breed and burn reactor design, which uses plutonium transuranic (TRU) waste as recycled fuel[13]. Fuel recycling in a so-called closed fuel cycle is essential for SFRs to realize their full sustainability potential. To date, the most promising SFR company in the US is TerraPower—they are designing together with Hitachi the Natrium reactor which has undergone decades of research and development. TerraPower, along with X-Energy, have each received $80 million in recent DOE funding[14] (see Company Profile 2). However, UCS has found that TerraPower's Natrium would in fact be less uranium efficient than a LWR, as the 18.75%-enriched HALEU fuel core requires ~2.5 times more natural mined uranium per GWe than LWRs [19]. HTGRs are overall comparably less sustainable than traditional reactors. They are no more efficient and in fact produce larger quantities of radioactive waste. Last but not least, MSRs offer the best theoretical option for sustainable non-traditional reactors as they would likely use fuel more efficiently and generate less waste. MSRs are as relatively strong on the sustainability scale as they are challenged on the safety scale. In practice, UCS concludes that the actual sustainability improvements MSRs would offer are simply too small to justify, especially given the highly concerning safety issues.

Efficient use of fuel is often the more prominent argument made for why next generation nuclear reactors are poised for commercialization. With higher percentages of enriched uranium, non-traditional reactors attain lower material utilization for the same power output. Combined with a streamlined fuel collection and reprocessing cycle, non-traditional reactors may have the potential to be transformative. However, such a transformation would necessitate enormous infrastructure deployments required to obtain the theoretical sustainability advantages that non-traditional reactors offer. Moreover, for most non-traditional designs, sustainability benefits from enriched fuel could only be achieved if spent fuel collection and reprocessing cycles are introduced, which in UCS's opinion present unacceptable proliferation risks.

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[13] Breed and burn reactors are not discussed in this analysis as they are presently far from maturity and thus not prioritized within the scope of the study. In short, breed and burn reactors establish a closed fuel cycle in which spent fuel is reprocessed and recovered materials are recycled for use as new nuclear fuel. Closed fuel cycles, though highly sustainable in theory, are not as foolproof as they appear. For a detailed discussion of breed and burn reactors see Chapter 8 of the UCS study [8].

[14] To put this in perspective, the DOE's Office of Nuclear Energy 2022 fiscal year budget request totaled $1.85 billion, which includes over $370 million for the Advanced Reactor Demonstration Program (ARDP) [38].

Company Profile 2: A short profile of the TerraPower company and the Hitachi-Natrium reactor design, a collaboration with GE Hitachi Nuclear Energy.

TerraPower & the Natrium^{TM} Reactor

Sodium-cooled Fast Reactor – Small Modular Reactor

Dimensions and Specs: The Natrium^{TM} reactor is an advanced modular reactor that combines a sodium fast reactor with a molten salt energy storage system. The system features a 345 MWe design. The thermal storage allows for a nuclear reactor design capable of load following.[15]

Who is TerraPower?

TerraPower is a US nuclear reactor design company founded in 2006 by Bill Gates, who is also today's chairman. Its initial research focus was the travelling-wave reactor (TWR), a theoretical concept of a nuclear reactor type that converts breeder material into fissile material. Today TerraPower's focus has shifted to the development of two SMR concepts: the mentioned Natrium^{TM} reactor and the Molten Chloride Fast Reactor (MCFR) concept.

Who is funding TerraPower?

Bill Gates himself is one of TerraPower's primary investors (via Cascade Investments), though other venture capital firms contribute, which is in line with the company's objective of pursuing an independent, privately funded path. However, the company also receives substantial governmental funding, namely $80 million in 2020 from the DOE.[16]

Where does the Natrium^{TM} Reactor stand? How close is TerraPower to commercialization?

TerraPower announced its collaboration with GE Hitachi on the Natrium^{TM} reactor in August 2020. It remains relatively unclear how current development is progressing, however, they are far from commercialization.

for the other two reactor concepts—TWR and MCFR—the story is similar. The TWR is nonetheless still considered the company's flagship advanced nuclear reactor concept.

2.3 Nuclear Proliferation and Terrorism

Definition: The risk of nuclear proliferation and terrorism is defined by UCS as "the danger that nations or terrorist groups could illicitly obtain nuclear-weapon-usable materials from reactors or fuel cycling facilities."

All NLWR types are rated quite poor by UCS for risk of nuclear proliferation and terrorism. The main advantage of SFRs is sustainable fuel use by way of reprocessing and recycling, two processes that inherently elevate the risk of proliferation. Though some SFR reactors could operate in a once-through cycle, thereby avoiding further proliferation risk, this would discard the intrinsic benefit of fast reactor technologies. HTGRs have two primary proliferation concerns: 1) the HTGR design uses high-assay low enriched uranium (HALEU) fuel, which poses a much greater security risk than low-enriched uranium (LEU) fuel used in LWRs, and 2) TRISO fuel fabrication is more challenging to monitor than LWR fuel fabrication. Finally, for MSRs, fuel accounting in the molten mixture poses the greatest security risk, which is a relatively unique security concern for a nuclear reactor. Along with flowing fuel complications is the requirement of some MSR designs to include on-site reprocessing plants that operate continuously as part of the power cycle. This offers additional pathways to divert or steal nuclear-weapons-usable material.

In their review, UCS emphasizes that the above three evaluation criterion are not weighted equally. Risk and safety and risk of nuclear proliferation and terrorism should, in UCS's opinion, take priority over sustainability.

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[15] See TerraPower, Natrium Power, https://www.terrapower.com/our-work/natriumpower/

[16] See: Office of Nuclear Energy, U.S. Departement of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program, October 13, 2020.

2.4 Economics

Notably missing from the UCS study is an assessment of the relative economics of NLWRs. A cost comparison of LWRs and NLWRs was not performed by UCS mainly because "*such an evaluation would depend upon many open and highly uncertain issues such as design details, future regulatory requirements, and supply chain availability*". The study does however comment on estimated NLWR project costs, as well as on fuel processing facility cost projections. Similarly, this analysis does not aim to assess NLWR technology costs on a detailed $/kW or $/kWh basis, but rather intends to expand the UCS framework and focus the economics discussion around a few select issues—economies of scale, infrastructure requirements and associated costs, and manufacturing know-how. This analysis then compares non-traditional nuclear reactors to other clean energy resources, in particular to renewable energy technologies supported by grid-scale battery storage which compete directly with non-traditional nuclear for grid service provision.

The discussion of cost in regards to non-traditional reactors in research and development is difficult to contextualize. Most NLWR designs are far from commercialization. In the US, the advanced SMR (a LWR) from NuScale is furthest along in the regulatory approval process, but still faces a host of concerns needed to be addressed before construction can start (see Company Profile 3). It is therefore inappropriate to compare on a detailed cost basis a technology class that is largely still in the development phase to a class that is not only mature, but has had decades of global operational experience. Instead, the following economics discussion remains conceptual but practically evaluative.

Perhaps unsurprisingly, non-traditional nuclear reactors are not yet cost competitive with traditional reactors let alone with renewable energy technologies or natural gas. In the US today, traditional LWRs have become uneconomical, largely due to increased operational costs and safety requirements for ageing fleets, and in many instances require ample financial assistance from contracted utilities or from the state. Non-traditional reactors similarly require both public and private support, but more importantly suffer from being dually complex technologies—that is, they have a high degree of design complexity and a high need for customization [20]. The resulting rate of progress of non-traditional reactor designs is quite slow and the exhibited learning rates low if not negative.[17] It is therefore unlikely that costs will be driven down fast enough to keep pace with alternative technologies that exhibit high learning rates as well as with pledged climate targets.

Economies of Scale

To begin, the economies of scale concern, specifically for SMRs, is addressed in line with arguments from Ramana (2021) [9]. Per unit power output, SMRs are inherently more expensive technologies. This is exemplified by the classical power law relation of capital costs of production facilities with different capacities—a widely used metric in industrial engineering applications:

$$\frac{K_1}{K_2} = \left(\frac{S_1}{S_2}\right)^{0.6}$$

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[17] The learning rate is described as the percent cost reduction per doubling of cumulative capacity.

Where $\frac{K_1}{K_2}$ gives the ratio of capital costs and $\frac{S_1}{S_2}$ gives the ratio of capacities. An exponent value of 0.6 is typically taken in the literature[18]. Assuming a large LWR generates 1GW of power output compared to the high end 300MW power output from a SMR, the result would give a ~48% capital cost ratio of SMRs to large LWRs. On a $/MW basis, however, the SMR would cost 1.6x more than the large reactor.

Furthermore, while some SMR companies in the US are aiming to provide base-load power supply in a similar manner to the existing large reactor fleets, other companies are designing their technologies as load following power resources. Operating SMRs in a load following mode would inherently give lower capacity factors and thus even higher per-MW operating costs [9,13]. Additionally, load following by steam-based power stations (i.e. nuclear reactors), of whatever size, may also not ramp quickly enough for some requirements.

Company Profile 3: A short profile of the NuScale company and the NuScale Power Module^{TM}.

NuScale & the NuScale Power Module^{TM}
Light Water Reactor – Small Modular Reactor

Dimensions and Specs: The NuScale Power 77 MWe SMR modules use conventional light-water cooling methods that are based on existing light water reactor designs.

Who is NuScale?
NuScale was founded as a research startup and originally funded by the US DOE in 2000.

Who is funding NuScale?
After the initial governmental funding was cut, scientists continued the research by patenting the technology and moving NuScale on the long path to commercialization. Today, the LLC is borne by private investors. Additionally, the project in Idaho Falls (see below) will receive substantial funding by the US DOE.[19]

Where does NuScale stand? How close to commercialization?
The light-water SMR by NuScale is furthest along in the regulatory approval process, which is mainly due to the fact that NuScale modules incorporate traditional LWR concepts, as opposed to yet unproven non-traditional LWR concepts. In August 2020, the NuScale design was the first, and so far only, SMR to receive design approval from the NRC [21]. However, the NRC writes that some safety issues remain to be addressed.[20] In 2027, NuScale will start building a reactor in Idaho Falls, Idaho [22]. Those are two important steps towards commercialization. NuScale intends to build the first SMR *complex* in the U.S. by the end of this decade [21,23]. However, considering the delays of current LWR projects as well as other "advanced" reactor projects in the making, this goal remains highly questionable. In October 2020, NuScale announced to delay its projected completion date from 2026 to 2030, while costs have doubled within two years from $3 billion to more than $6 billion [24].

New Infrastructure Means Money and Time

Deployment of non-traditional reactors requires construction of new reactor facilities as well as other infrastructure for fuel processing and reprocessing to manage and streamline an advanced reactor revolution. A fundamental difference between traditional and non-traditional reactor technologies is fuel enrichment levels and fuel processing procedure. As discussed in section 1.2, the fuel for some non-

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[18] Some studies take other values for the exponent, but none expect the exponent to be one. An exponent value of less than unity implies increasing returns to scale [39].

[19] See: Office of Nuclear Energy, DOE Approves Award for Carbon Free Power Project, October 16, 2020.

[20] The NuScale design approval by the NRC and its final safety evaluation report (FSER) do not mean that the firm can proceed with reactor construction, but rather that utility companies can now apply to the NRC to build and operate NuScale’s design. Since the reactor design faces significant safety questions, which were not resolved by the NRC review, NuScale must complete additional key safety reviews until later this decade [24].

traditional reactors operate with higher levels of enrichment. Moreover, some non-traditional designs plan for fuel recycling and reprocessing as part of the so-called "closed fuel cycle" in order to increase the sustainability of the system. Large-scale deployment of HALEU fuel manufacturing sites as well as spent fuel recycling and reprocessing centers would require tremendous infrastructure build-outs on top of the initial construction of new non-traditional reactors themselves. To contextualize these concerns with an example, the Vogtle advanced LWR AP-1000 nuclear plant from Westinghouse that is currently under construction in Georgia has run exceedingly over budget and behind schedule. Construction costs have surpassed $25 billion from initial estimates of $14 billion [25] and construction completion is now nearly 5 years behind schedule (twice as long as was originally estimated).[21] These complications persist for a reactor design that is relatively mature and a capacity scale that is highly demonstrated. Traditional nuclear reactors have a history of overrun costs and extended construction times. 97% of projects have exceeded their budget with an average overrun cost of 117% and construction times that are 64% longer than expected [13]. Given this bleak and consistently poor record, similar difficulties are anticipated for non-traditional reactor construction times and costs. Thus, nuclear energy, non-traditional or otherwise, cannot be the "silver bullet" for climate change—we have simply run out of time [22].

Manufacturing Know-How (Tacit Knowledge)

The massive infrastructure build-out required to lower the per-unit-electricity cost of non-traditional reactors is contingent upon manufacturing know-how. In the US, non-traditional reactor units have been built sparsely at a demonstrative level and not at all at a mass or even semi-mass level. Advanced nuclear proponents point out that years of experience in traditional reactor construction will likely smooth the manufacturing process of non-traditional reactors, but this is easier said than done. First, non-traditional reactors are fundamentally different from traditional reactors and incorporate novel design features that have yet to sustain refinements and adjustments in the manufacturing stages of mass deployment. Inevitably, there will be failures in early construction stages—failures that are important for improving robustness of design, but nonetheless costly in terms of both money and time. Second, spillover experience from manufacturing of traditional reactors is not guaranteed. Historically, traditional reactor construction costs have increased dramatically in part because of elevated safety regulations and tightened operational requirements, but also because of fading tacit knowledge and construction experience. The US is in fact an extreme case of increasing traditional nuclear plant construction costs over time which has resulted in intensely negative learning rates [26]. Non-traditional reactors are thus plagued by manufacturing immaturity as well as diminishing tacit expertise of traditional reactor design and construction.

Up Against Mighty Renewables

On the one hand, the non-traditional reactor industry faces high cost and construction time barriers and on the other hand, is racing the clock with other technologies that offer similar if not more appropriate solutions for low-carbon power deployment. Assuming non-traditional reactors will soon pass regulatory oversight

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[21] There was only one further new construction project in the US; The project, building two Westinghouse AP1000 reactors at the V.C. Summer plant in South Carolina, was abandoned in 2017 after four years of construction and multi-billion-dollar investments [source: WNISR].

requirements, enter the construction phase of commercialization within the next few years, and deploy reactors by the late 2020's—an extremely optimistic timeline proposed by some non-traditional reactor developers—they will likely still be years behind renewables in terms of both cost and deployment. Renewable energy technologies are today already cheaper than nuclear power on a per-kWh basis, and with high learning rates, they are only getting cheaper.

A recent study on sources of cost overrun in nuclear power plant construction gives a comprehensive summary of various nuclear reactor learning rates for both historical and prospective designs. The most optimistic learning rate estimated for advanced reactor concepts is 7-10% from a future growth study performed by the International Atomic Energy Agency [26]. A second study that performed expert assessments on the cost of light-water SMRs (i.e. NuScale) similarly estimates a high-end 10% learning rate [27]. On the low end, the advanced nuclear industry claims learning rates between 2 and 5% [26]. Currently, solar photovoltaics (PV) exhibit a mean global learning rate of 23% and wind power a mean global learning rate of 14% [28]. To reach the high-end estimation 10% learning rate, a buildout of many thousands of non-traditional reactors would be required to match the per unit electricity cost of traditional reactors let alone the per unit cost of renewables.

Some advanced nuclear advocates argue that the competition for non-traditional reactors is not against renewables but rather in conjunction with renewables. As photovoltaics and wind are highly but predictably variable resources, for a purely carbon-free grid to function, energy storage is required to meet electricity demand in times of low sun and wind as well as during evening power peaks. Presently in the US, natural gas plants fill this need—serving as flexible peaker plants that can ramp up and down whenever necessary. Non-traditional nuclear reactor technologies could potentially fill this role as a low-carbon alternative and complement intermittent renewables on the grid. However, competition for this specific grid service is also high—grid-scale battery storage technologies, which are increasing in prevalence and decreasing in cost, provide ancillary demand response services as well. Estimates today suggest that lithium-ion batteries for grid-scale storage exhibit learning rates between 15-25% [29]. Stationary lithium-ion batteries span a diverse application spectrum: they are able to store energy in both the short and long term[22] and are furthermore able to load follow with minimal round-trip efficiency losses. While grid-scale battery storage is not yet economical in most cases, it is moving rapidly in that direction, largely due to the fact that lithium-ion batteries are a highly mature technology. The infrastructure for lithium-ion battery manufacturing and global supply chains is established and the technology itself has had years of research and development in the commercialization stage. In addition, stationary battery storage technologies gain from external application spillovers, such as from the transportation sector, the consumer electronics market or as well from the medical devices market. Knowledge spillovers are an important component of technological innovation and in turn of technology cost reductions [30]. Furthermore, support policies in the US as well as internationally have not only propelled battery technologies to maturity in recent years, but continue to support and advance the technology today. Lithium-ion batteries are a commercially proven technology, have operational experience in a myriad of commercial applications, have support from both public and private investment and are highly socially trusted.

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[22] Though not as well in the long term – see a recent ETH Energy Blog article for further explanation and context.

Non-traditional reactors are very far from this level of technological prowess and require many years of catch up to reach a healthy innovation environment.

As noted by Ramana in his study on cost estimates for SMRs and advanced non-traditional nuclear reactors, “*the key difference is that the costs of nuclear energy, especially from SMRs, are prohibitively high and rising, whereas the costs of renewables are low and declining*”. As a baseload energy resource, solar PV and wind will be nuclear power’s true competition. As a load-following, flexible, low-carbon technology intended to complement high percentage mixes of distributed renewable energy resources, non-traditional reactors will likely be outcompeted rather by grid-scale battery storage, for which years of R&D and manufacturing experience, combined with global cross-sector knowledge spillovers have demonstrated dramatic cost reductions and technology reliability.

3. Expectation vs. Reality

Given the recent increase in number of non-traditional nuclear reactor start-ups and companies in the US, media attention for non-traditional reactor designs and more specifically for SMRs is high. With varying reactor technology types in development in different companies at different stages of commercialization, it is difficult to make sense of the burgeoning field and to decipher myth from truth.

To provide a flash overview comparison of non-traditional versus traditional reactor technologies, an expectation versus reality table of the main purported non-traditional nuclear reactor *advantages* is consolidated. The expectation column points and counter reality column points presented do not give a complete picture, but rather a snapshot overview of prominent arguments for and against non-traditional nuclear reactor designs.

Table 2: Expectation vs. Reality comparison

	Expectation	**Reality**
Economic promises		
Lower cost	• Non-traditional reactors will be cheaper, in the end, than traditional reactors as a result of efficient uranium use and/or smaller modular designs that offer streamlined construction processes—one large nuclear power plant is replaced instead by many reactors with smaller power outputs.	• Economies of scale for production make non-traditional reactors in fact more expensive—power output from SMRs in particular is not profitably sufficient. ○ In recent years, several attempted smaller nuclear projects have been shut down for this reason [31–34]. • Technologically immature non-traditional reactors have to compete with renewable energy technologies which are already today drastically cheaper on a $/kWh basis and provide of a much higher learning curve.
Built quickly	• Some optimistic non-traditional reactor developers claim commercial deployment will be achievable by late 2020. • SMRs in particular purport faster construction times due to smaller design scales.	• Companies that claim fast construction and deployment of non-traditional reactors is achievable typically assume their designs will not require full-scale performance demonstrations and safety testing. • Construction timelines for traditional reactors have historically been overrun by more than 64% of the estimated time [13]. ○ Similar time overruns are highly likely for an immature non-traditional reactor technology class with no demonstrable large-scale manufacturing or construction experience. • Even with optimistic assumptions for deployment timelines, non-traditional reactors will likely be outcompeted in deployment by renewables and grid-scale battery storage (in some cases, they already are)—a relatively mature technology that is readily being deployed. • It is highly unlikely that non-traditional reactors will be able to ramp-up construction fast enough to stay in-line with climate targets.
Technical promises:		
Small and modular designs	• Small modular reactor designs provide higher flexibility of construction and manufacturing, higher diversity of locational placement, and lower operation complications.	• Nuclear reactors built in a modular fashion are not spared the curse of high capital cost and long construction times in practice. As quoted by the Georgia Public Service Commission overseeing the Vogtle power plant construction, “modular construction has not worked out to be the solution that utilities promised.” [9]

		• Scattered deployment of small modular reactor plants increases proliferation risk as well as increased security risk (i.e. of attack). • Operation and maintenance costs would be higher for non-traditional reactors in particular for the various non-light water coolant mediums that require additional systems.
Passive shutdown and cooling	• Non-traditional reactor designs (in particular the design from NuScale Power) provide passive shutdown and cooling in the event of malfunction or catastrophe, meaning the reactor will cool itself on its own without the need for additional water, power, or even operator action.	• Passive shutdown and cooling is indeed an important advanced feature of nuclear reactors… • This technology, however, is not unique to non-traditional reactors and can be similarly implemented in traditional reactors. ○ Two traditional LWRs, the AP1000 design from Westinghouse, which is still under construction at the Vogtle power plant in Georgia, and the CAP1400[23] design from the State Nuclear Power Technology Corporation (SNPTC) and Shanghai Nuclear Engineering Research & Design Institute (SNERDI) in China (which is based on the Westinghouse design), both use passive cooling [35,36].
Load following	• Some non-traditional reactor designs, in particular SMRs, allow for load following as a grid service. • Load following capabilities would be essential to the deployment of SMR designs ‘’off the grid’’ in remote areas. • Load following would allow rapid ramp-up and ramp-down in times of high demand or low-supply and in particular would complement variability of PV and wind power.	• Operating in load-following mode would significantly decrease the economic competitiveness of non-traditional reactors due to lowered capacity factors and thus higher per-unit-electricity costs. ○ With high fixed capital costs, return on investment is achieved through high capacity factors and continuous operation, as is done for traditional base-load reactors. • Non-traditional reactors operating in load following mode will likely be outcompeted by grid-scale stationary battery storage.
Ability to consume or recycle waste	• A few non-traditional reactors, such as SFR or MSR burner-breeder reactors, are designed to reprocess and then re-use spent fuel in a so-called closed loop cycle thus significantly reducing nuclear waste accumulation.	• Non-traditional reactors can only use a fraction of spent nuclear fuel as new fuel. • Though it is not possible to generalize due to the high number of disparate designs, some non-traditional reactor concepts, such as LWR SMRs, will produce even more waste than traditional LWRs [9]. • Fuel reprocessing facilities are presently few and far between and would require high capital investment for immense infrastructure roll-outs. • Fuel reprocessing facilities inevitably increase proliferation risk. • Volume of waste is not the only relevant variable to consider. The size of geological storage required for waste burial depends on heat production and waste composition. Complicated forms of fuel waste from some non-traditional reactors require more processing attention resulting in higher waste volumes [9].
Provision of high-temp process heat for secondary uses (i.e. hydrogen production)	• Non-traditional reactors operating at hotter than usual temperatures provide high temperature “waste” heat that can be used as a secondary energy resource for industrial applications (i.e. hydrogen production, steel production).	• Potential industrial users have shown little to no interest in this provisional application [8,37]. ○ They are weary of safety concerns associated with co-locating nuclear plants near their industrial facilities. ○ They do not want assume the cost or responsibility associated with nuclear waste.

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[23] The first CAP 1400 large demonstration project was recently completed in the fall of 2020 as intended to be deployed in large numbers across the country [40,41].

	• This secondary provisional resource would elicit further investment from industrial users.	
Efficient uranium utilization	• Non-traditional nuclear reactors use HALEU fuel which has higher levels of enriched uranium. This results in higher power outputs per volume of fuel and thus more efficient material utilization. • Some non-traditional reactors plan to use depleted uranium stockpiles as fuel in a once-through breed-and-burn reactor, thus further increasing efficiency of uranium use.	• High fuel enrichment increases security concerns. • "Burning" or reusing spent fuel requires reprocessing, which involves recycling and thus exposure of nuclear-weapon-usable material.
Improved safety	• Non-traditional reactors will be significantly safer than traditional reactors. They offer higher safety measures such as passive cooling. • SMRs poser lower safety risks because of the smaller volume of radioactive material present in the core reaction.	• Non-traditional reactors introduce new safety issues that will require extensive testing and analysis. The technology itself is too early in its development stage to be certain of all possible safety issues. • SMRs often involve multiple reactor modules at one site in order to lower costs by way of shared infrastructure elements. Multiple units at a given site increase the risk of common-mode failures or cascading chains of failures. • Additionally, a greater number of SMR complexes that may be constructed in a local, de-centralized manner means a greater risk of potential accidents as well as a greater proliferation threat.
Reduced risk of nuclear proliferation	• Non-traditional reactors plan to reprocess spent fuel for secondary use, thus reducing the total volume of processed uranium in the system.	• Non-traditional reactor designs would still require large quantities of HALEU fuel for operation. Annual HALEU fuel demand for a reasonably sized non-traditional reactor fleet could be hundreds of times greater than the current demand. • Both reprocessing facilities and HALEU fuel enrichment facilities will require new infrastructure. This infrastructure will not only increase the number of processing facilities in the US, but also abroad as US companies would likely seek to export advanced fuel cycle infrastructure, thus posing a high global proliferation risk.

4. Conclusion

In order to avoid the most severe effects of climate change, a transition to future low- or zero-carbon power systems must develop quickly. This will require coordinated policy efforts between and within nations, as well as a diverse portfolio of clean or low-carbon technologies that will facilitate the transition. Non-traditional "advanced" nuclear power reactors represent one such technology in this portfolio—they offer, in theory, higher ensured safety, environmental sustainability, lowered cost and lowered proliferation risk. This analysis, however, finds that many of the non-traditional NLWR designs presently under consideration do not in fact demonstrate these advantages or do not offer obvious improvements over traditional LWRs significant enough to justify their many risks. Summarized aptly in the UCS study, "*given the urgency of the climate crisis, rigorous evaluation (of advanced nuclear reactors) is needed to avoid wasting time or resources in the pursuit of high-risk energy concepts*". While the UCS study concludes that a fully vetted analysis is required to be certain of the potential downfalls of investing both time and capital in advance nuclear, this analysis finds additionally that such an investment may ultimately be futile. Today, non-traditional advanced nuclear reactors are unavailable in our arsenal of readily deployable low-carbon technologies and it is unlikely they will become available in the near future. Outcompeted by renewable energy technologies such as wind and solar power in the baseload grid service application and likely outcompeted by large-scale battery energy storage as well as other low-carbon flexible resources in the ancillary demand response grid service application, non-traditional nuclear reactors face a number of rather strong competitors. NuScale, an "advanced" reactor company furthest along in the regulatory process, will only begin construction of a test reactor in 2027—large-scale commercialization will likely require many more years. For other non-tradition reactor design concepts looking to follow NuScale's path, the outcome has been hardly different: though experts have been researching for decades, success has been minimal. Accordingly, betting on an immature technology class with a variety of operational, safety, cost, sustainability, and nuclear proliferation concerns seems both unwise and misguided. US policymakers may instead consider prioritizing the support of mature low-carbon technologies that are ready to be deployed today and more likely to keep pace with the recently increased climate commitments that reflect the urgency of the crisis.

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