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New paradigm for civil nuclear energy. Perspectives from the hierarchy of energy sources and fundamental safety

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Contents

Abstract. **This paper is a review and treatise extended in scope and based on a presentation made at the Uspekhi Forum on Climate Change and Global Energy. Following a brief overview of the history, status, and outlook of civil nuclear energy to present the key problems and challenges, this energy source is placed in a primary energy hierarchy on Earth with all classes of energy systems based on fundamental forces to reveal its unique characteristics that set civil nuclear energy qualitatively apart. A new paradigm is outlined with a distinct set of safety categories, design principles, and production methods that differ from conventional nuclear power, which leads to a global energy system solution for much broader development and deployment at scale in time to help mitigate climate change. Based on concepts and methods from studies of emergent properties in complex adaptive systems, we use a scaling method to analyze nuclear reactor safety and economics, and explicitly relate reactor unit scale, safety limits, and production volume to cumulative cost and capacity. Simultaneous improvement in and optimization of nuclear safety and economics are leading to small modular reactors (SMRs) and micro reactors (MRs) as exemplar technologies of the new paradigm. We show that select SMR and MR designs with deterministic fundamental safety should be manufactured, which can achieve substantial cost reductions as production volumes increase, following Wright's law observed in the majority of proven technologies. The new paradigm offers distinct and testable predictions, some of which have been partially tested, and some of which have surrogate tests from successful technologies and industries, which are also endowed with substantial transferable capabilities and capacities for implementation. The scaling principles and results should be generally applicable to other energy systems and the majority of manufactured goods.**

Keywords: nuclear energy, paradigm, primary energy hierarchy, fundamental safety, manufactured systems, economies of production volume, unit scale, small modular reactors, micro reactors, global energy solution

1. Introduction

As the world gradually recovers from the global COVID-19 pandemic that severely disrupted our societies and economies

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beginning over a year ago, mitigating climate change is coming back into focus. Many countries and regions are calling for and starting green recoveries. Transitions to low-carbon energies are accelerating in many parts of the world, exemplified by extraordinary growths of renewable energies, energy storage, and electrification of transportation.

At this critical juncture in history, 10 years after Fukushima and 35 years after Chernobyl, it is essential and timely for the global nuclear industry in particular, governments and civil societies in general, to ask whether nuclear energy should or can contribute more meaningfully to meeting ambitious climate goals and facilitating energy transitions in time, and if so, how.

Because one main objective of the *Uspekhi Forum* is cooperative finding of time-constrained and globally-scalable solutions to a planetary man-made problem with supreme urgency, and some diverse issues, concepts, developments, and organizations covered here are highly complex, relatively new and still emerging, this review chooses its scope, substance, and style with noticeable differences from reviews of more established and mature scientific fields and research problems, which will be clarified below.

The main body of the review and treatise is structured in sections that follow a logical progression of discovery, diagnosis, and design through problems, needs, approaches, and solutions. Section 2 provides a broad theoretical underpinning for the emergence of a new paradigm; Section 3 overviews briefly the status, history, and outlooks of civil nuclear power in the context of mitigating climate change; Section 4 explores the problems and challenges, and reveals the origin of long-standing dilemma of nuclear safety and economics; Section 5 outlines a new paradigm for resolving the dilemma through fundamentally safe and manufactured nuclear energy modules; Section 6 runs partial tests and offers testable predictions of the new paradigm, using practical experiences, universal laws, incorporation of unit scale economies, limitation on unit size imposed by inherent safety, and surrogate tests that also showcase transferable capabilities and capacities for the delivery of the solutions; Section 7 summarizes the main findings, and references a benchmark based on an ambitious and comprehensive roadmap for reaching net-zero carbon emission by 2050.

Readers familiar with nuclear power and industry can skip Sections 3 and 4, and go directly to Sections 5, 6, and 7. Section 6 is a systematic and comprehensive treatise on the potential resolution of the dilemma of improving safety and escalating costs in nuclear power throughout its history.

All information reviewed comes from open public sources, including published reports and announcements from the related agencies and organizations, peer-reviewed journals, books, media and industry publications, and open-source databases. The specific analysis and synthesis of some paradigmatic concepts and their origins have been presented and discussed in various forms and contexts in academic institutions, national laboratories, industry associations, and think tanks.

2. Scientific paradigm and theoretical underpinning

In his 1962 book on the structure of scientific revolutions, Thomas Kuhn defines a scientific paradigm as "universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of practitioners," i.e., what is to be observed and scrutinized; the kind of questions that are supposed to be asked and probed for answers in relation to this subject; how these questions are to be structured; what predictions are made by the primary theory within the discipline; how the results of scientific investigations should be interpreted; and how an experiment is to be conducted, and what equipment is available to conduct the experiment [1].

Kuhn perceived sciences as going through alternating periods of normal science, and revolution when model of reality itself undergoes sudden drastic change. The underpinnings of paradigmatic experiments are shared preconceptions, made prior to — and conditioning — the collection of evidence. These preconceptions embody both hidden assumptions and elements that Kuhn describes as quasi-metaphysical (or trans-scientific, as discussed below). Its relevance and significance to assessing the scale and scope of civil nuclear energy as a timely solution to mitigating climate change are illustrated and supported by extension of natural sciences to sciences of the artificial in the following.

The interdisciplinary study on the future of nuclear fuel cycle, published by the Energy Initiative of MIT (Massachusetts Institute of Technology) in 2011, may be viewed as an example that shows urgent needs and great potential for a paradigm shift in the nuclear energy field [2]. The study reexamines the premises and hypotheses of the mainstream strategies and ideas, and changing conditions and environment, presents highly systematic, innovative and forward-looking analyses, insights, conclusions and recommendations. It provides broadly valuable basis and evidence for high level selections and decisions on technology development pathways and strategies.

Based on then-limited knowledge and understanding of resource availabilities and reactor technologies, also constrained due to urgency of wartime and postwar military needs, the assumptions for planning and designing early nuclear fuel cycles and future of nuclear energy were "(1) uranium resources are extremely limited, and (2) a high conversion ratio is required to meet future needs." Such assumptions dominated the development pathways and strategies in mainstream nuclear power technologies and fuel cycles around the world for more than half a century. One of the most important and outstanding assessments from the MIT study is that both assumptions are false. This revelation helps open doors to more novel and creative thinking and innovative development in civil nuclear energy, or a new paradigm.

Such fundamental reflections and changes of long-held perspectives and conventional wisdoms are rising in other nuclear power countries. A representative and comprehensive summary can be find in a recent paper on critical notes of history, state, problems, and prospects of nuclear science and technology from Russia [3].

This author called for a paradigm shift for nuclear reactors from economies of unit scale to economies of production scale, moving from construction heavy to manufacturing centric [4]. It is based on a study of costs for nuclear power plants, with the most comprehensive available data from US nuclear power buildup. It confirms the historical experiences from the majority of leading countries in nuclear power, and shows that there had been some significant dis-economies of unit scale, i.e. the larger the plant power capacity became, the longer it took to construct, and the more it costed per kilowatt capacity installed.

This effort is a part of an emerging global movement toward small modular reactors (SMRs) long in making but yet to be fully realized. Such a line of recognition, thinking, and action has gained increasing awareness and acceptance in nuclear energy field and industry, in particular as manifested by rapidly rising global interests, programs, projects, policies, plans, and public and private investments surrounding SMRs and micro reactors (MRs) [5–10].

The need for shifting from on-site construction to factory manufacturing has been broadly recognized ad accepted. There are industry studies showing substantial lack of efficiency and lagging productivity growth in construction, and ways to solve systemic problems (see, e.g., [11, 12]). Some studies have analyzed cost reduction and production expansion through adoption of more efficient platforms, such as shipyard manufacturing, and analyzed the work and costs that are not needed, thus can be avoided, and repetitive work and costs that can be substantially reduced in a controlled environment for implementation and continuous learning [13].

Much of the current development of SMRs and MRs is based on potential for more predictable reductions of production cost and delivery time through factory manufacturing, improved safety in operations, increased flexibility for deployment, more diverse applications in more markets and regions, and other innovative goals and objectives. They are also generally positioned for small scale applications in niche markets that are constrained either by local demand levels or upfront capital outlays. There are commonly accepted perceptions that with the apparent loss of economies of unit scale, specific costs of SMRs and MRs will be high, and their roles and contributions are limited (see, e.g., [5]). They are mistaken and will be clarified and corrected here.

It has been recognized by some of us that certain designs have potential to assure deterministic nuclear safety at the fundamental levels from the smallest scale practical, and not mere reduction of already extremely low, but hardly testable, probabilities of severe accidents, creating a new paradigm for civil nuclear energy. Such designs are suitable for broad deployment at scale rapidly, thus appropriate for using a serial or mass manufacturing platform, which is far more efficient than the on-site construction platform with minimal or no productivity growth for the past half century and more. Fundamentally safe SMRs and MRs can improve economics steadily in the new paradigm, with predictable cost reductions as production volumes increase, following Wright's law observed and validated in most successful technologies and industries.

This new paradigm will reveal mistakes, deficiencies, and distortions in some long-standing assumptions, perceptions, conventional wisdoms, design principles, and positioning of various types of reactors, especially with regard to unit power rating and system economic efficiency in the context of this review. In particular, common mistaken perceptions and positioning of SMRs and MRs have held back much needed commitments and investments to realize their true potentials, prolonging the decades-long stagnation and decline of commercial nuclear power, exacerbating the difficulties and challenges for global energy transition to mitigate climate change, and damaging the long-term prospects of sustainable and equitable development. The new paradigm will resolve a long-standing and seemingly-intractable dilemma between nuclear safety and economics.

There are important benefits from adopting this new paradigm. Using factory manufacturing to produce fundamentally safe reactor modules sets up new institutional arrangements that restrict access to and dispersion of nuclear technologies and special materials on the production side while expanding accessibility and availability for more and diverse peaceful uses of nuclear energy. This will change prevailing practices from safety-risk forced needs to transfer technologies and special nuclear materials to owners and operators of power plants. It has the potential to resolve another dilemma between promoting nuclear energy for peaceful uses and restricting access to technologies and materials for security and nonproliferation, more fundamentally and systematically. Specific viability and potential depend on designs of reactors, fuels, and fuel cycles.

A key inspiration for civil nuclear energy centered on fundamental safety came from Dr. Alvin M. Weinberg, a visionary pioneer at the very beginning of nuclear power [14–16]. Among his early participations in and central contributions to developing nuclear reactors for production and propulsion from the 1940s to 1950s, Weinberg proposed Pressurized Water Reactor (PWR) from many competing designs, with recognition that its ultimate success as the most common design worldwide was due less to any superior characteristics of water, but rather to the decision for nuclear submarine propulsion that later excluded other possibilities. As the Director of Oak Ridge National Laboratory from 1955 to 1973, Weinberg led the first institutional effort to focus on a civilian version of meltdown-proof Molten Salt Reactor (MSR), away from military origin in nuclear-powered aircraft.

Weinberg calculated that with many possibilities for each component of a reactor — fuel, moderator, absorber, and coolant, one could identify about a thousand distinct reactors. According to Freeman Dyson, he was the only nuclear pioneer who supported a wide universe of reactor designs. Weinberg also led early systematic studies of radiation effects on living things and how to survive radiation damage, and evaluation of alternatives for meeting future energy requirements, covering diverse issues related to carbon dioxide and global warming [17].

In 1972, Weinberg published a landmark article, "Science and Trans-Science," in which he presented insight on and analysis of many issues arising from interactions between science or technology and society, and clearly delineated the boundary between science, and those that can be asked of science but cannot be answered by science as trans-science, or transcending science [18, 19].

The pioneering work of Weinberg on nuclear power provided a visible origin and a starting framework for the field of fundamentally safe civil nuclear energy, which has been proven highly prescient and more pertinent now than ever. Conventional nuclear power has been stagnant and declining for three decades, especially in advanced economies, while combating climate change and broadening equitable growth demand more clean and low-carbon energy this century. His deep insight on science and trans-science helps clarify that many issues related to climate change and global energy are critically important but trans-scientific, so we need to and can effectively and efficiently review, assess, and resolve them accordingly. For a leading scientific journal dedicated to advances in physical sciences, such a subject scope is an extension but necessary for relevance on such high level topics of broad significance.

This view is supported and advanced by seminal works of other visionary thinkers. They include "Sciences of the artificial" [20] by Professor Herbert A. Simon, winner of Nobel Memorial Prize in Economics and best known for theories of bounded rationality and satisficing [21, 22]; "More is different" [23, 24] by Professor Philip W. Anderson, winner of Nobel Prize in Physics, who first made one of the most influential calls for establishing a new paradigm in physical sciences, a shift away from purely reductionist hypothesis, and built on broken symmetry and nature of hierarchical structure of science; and Professor Frank Wilczek, winner of Nobel Prize in Physics, who concludes that we now know the fundamental laws of nature with sufficient accuracy and precision for all practical engineering [25, 26].

Such scientific philosophies and principles provide further guidance and spirit behind this review and treatise. Their specific relevance will become clear later when applications using results from complexity studies, many from Santa Fe Institute (SFI), facilitate the emergence and establishment of a new paradigm of fundamentally safe civil nuclear energy embodied in manufactured modular systems. SFI is internationally regarded as the formal birthplace and a leading center of excellence on interdisciplinary study of and creative thinking in complex adaptive systems, and counts Anderson and Simon among its essential intellectual origins and guiding lights [27].

A visionary and highly acclaimed representative work from SFI, Dr. Geoffrey West's transdisciplinary book Scale, is beginning to turn many issues traditionally considered trans-scientific into realm of science, or science of the artificial [28]. West and his colleagues have developed a framework for finding universal laws based on optimizing fractal geometry of networks that supply energy, resources, and information to, and remove wastes from complex adaptive systems. The main properties of such generic network are space filling, invariance of terminal units, and optimization.

Some of the groundbreaking insights pertinent to this review include super-linear scaling of properties with corresponding super-exponential growth toward finite-time singularity, and constantly accelerating needs for paradigm shifts to sustain growth in sociological systems. This is in contrast to sublinear scaling, economies of scale, and bounded growth in biological and most purely physical systems.

On energy, he points out that the fossil fuel regime had turned our planet into a more closed system, which is thermodynamically unsustainable, as opposed to using renewable energies in an open system. On climate change, exponential scaling of organism metabolism implies that a 2 °C increase in average global temperature will increase the pace of almost all biological lives by 20–30%. This is far too much change in too short a time for natural evolution to adapt.

From a direction opposite to usual scientific discovery and theory building, which is empiricism that starts from nature, Dr. Adrian Bejan proposed and established a constructal theory to go from principle to nature. Bejan, a professor of mechanical engineering and prolific author, explicitly called out engineering as the science of systems and processes with purpose. Similar to entropy being introduced by Rudolf Clausius to formulate the second law of thermodynamics to account for coupled thermomechanical behavior, he proposed a new principle in construction of geometric form with a new concept, objective or purpose [29].

Bejan considers the design and optimization of engineered systems and discovers a deterministic principle for generation of geometric form in natural systems. Shape and structure spring from constant struggle for better performance in both engineering and nature. This is the basis of constructal theory: the objective and constraints principle used in engineering is the same mechanism from which geometry in natural flow systems emerges.

Based on his new theory, Bejan derived purely theoretically the famous empirical proportionalities between metabolic rate and body size to power $3/4$ and between time period and body size to power $1/4$. This is the same end result from West's study on scaling, but instead built up segment by segment of a tree-shaped network and optimized to distribute imperfection uniformly across domains of gaping differences. We will see such exponents emerge later in the new paradigm.

It is fascinating to view West's approach to bridge gaping differences of simplicity and complexity in his development of universal laws in complex adaptive systems, from Bejan's constructal theory perspective. Almost all laws of physics embody simplicity, but the real world is vastly complex and constantly changing. Since Newton's laws, Maxwell's equations, Einstein's theory of relativity, and many others, can all be formulated and elegantly derived from the principle of least action, West conceived that coarse-grained dynamics and structure of complex adaptive systems can be formulated and derived from the same. He went on to construct the scaling theory by finding objective and constraints of network, and optimizing global performance.

Such transdisciplinary ideas and works from creative physicists, engineers, and mathematicians, coupled with explosive growth in big data from all facets of social activities, are beginning to provide first-principle based mechanistic models and theories with universal laws supporting development and refinement of growth economics theories. The Endogenous Growth Theory, as represented by seminal works of Professor Paul Romer, winner of Nobel Prize in Economics, involves a break from competitive market structure by ad-hoc exponent in growth of technology stock or level always being 1 (linear scaling, exponential growth, constant return) or smaller (sublinear scaling, limited growth, diminishing return) [30, 31].

We will use such creative perspectives and profound insights to review, assess, and develop possibilities and potential of a new paradigm for civil nuclear energy. In particular, we will take advantage of exponential or super-exponential growth in sociological systems to develop and deploy new paradigm nuclear energy at scale in time to mitigate a man-made climate crisis. Economies of unit scale, rooted in biological and physical systems, and forming basis of existing paradigm, will not be sufficient to solve problems created by (super-)exponential technologies and economies. We need to solve problems on higher levels of thinking and with more powerful approaches than those that created the problems in the first place.

The first half of review will touch upon those issues that may be deemed trans-scientific, or in domains of not yet fully established sciences of the artificial, but will limit the scope to near the interface with the scientific, to the extent necessary to understand possible interactions, constraints, limits, and outcomes, and what science can answer or achieve through engineering and design. We will not cover the well-established and understood domains of nuclear science and reactor physics either, but rather go back to basic energetics with a first-principle based system approach viewing all energy systems together for commonalities and differences. In the process, some new taxonomy on design principles and fundamental safety will be introduced, helping to facilitate constructive dialogues and cooperative development of the new paradigm.

The second half is an outline of the structure and key aspects of this new paradigm in a constructal-theoretic approach. Instead of using the objective and constraints principle to understand how geometry emerges from natural flow systems, we will engineer a new civil nuclear energy paradigm to mitigate climate change at scale in time as the global objective, and fundamental nuclear safety, economics, sustainability, and other salient requirements as constraints. This paradigm will be conceived and designed to bridge the vast spans from millions time higher energy level and intensity of nuclear interactions to that of chemical and thermal interactions, expand possibility and utilization space of nuclear energy from limited baseload electricity in large grids to diverse applications, industries, and markets. Partial tests are performed, and new predictions are made for future tests. Due to limitation of scope and length here, this part is truncated and constrained to a level sufficient to illustrate the scaling methodology and application to integrating nuclear safety and economics.

3. Status, history and outlook of commercial nuclear power

Civil nuclear power industry and market have been relatively segregated from other industries and markets, highly visible and limited in scope, closely monitored and fairly constant, thus can be reviewed with high degrees of fidelity qualitatively and quantitatively. Since this review is intended to assess its potential for mitigating climate change in the coming decades, nuclear energy will be viewed together with all other forms of energy as much as possible, and trends compared on decadal basis.

3.1 Status

For a comprehensive overview of the many ways nuclear energy contributes to society, the upcoming four volume Encyclopedia of Nuclear Energy is timely and valuable [32]. It includes topics such as generating clean electricity, improving medical diagnostics and cancer treatment, improving crop yields, improving food shelf-lives, and crucially, nuclear energy as an alternative energy source proving essential in the management of global warming.

The most comprehensive source of data on commercial nuclear power worldwide is IAEA's Power Reactor Information System (IAEA PRIS) [33]. It contains all relevant information and statistics for the world, each country, every reactor type, and detailed histories. IAEA publishes annual reports on nuclear power reactors in the world.

Worldwide in 2020, there are 443 nuclear power reactors in operation with 393,084 MWe total net installed capacity; 50 reactors under construction for 53,163 MWe; and a grand total of 18,837 reactor-years of operation since the very beginning [34].

IAEA also has a fairly comprehensive database in Advanced Reactors Information System (IAEA ARIS) [35]. It lists 10 types of reactors in 12 categories. Some are integral or small modular designs very different from large conventional monolithic designs, with 78 individual designs in total, at various stages of development, on hold, under design, licensed, construction, or in operation.

Of these advanced reactors, there are 22 PWRs (Pressurized-Water cooled), 4 BWRs (Boiling-Water cooled), 5 HWRs (Heavy-Water cooled), 3 SCWRs (Supercritical-Water cooled), 3 iPWRs (integral PWR), 4 GCRs (Gas Cooled), 3 GFRs (Gas cooled Fast Reactor), 10 SFRs (Sodium fooled), 12 LFRs (Lead or Lead-Bismuth cooled), 8 MSRs (Molten-Salt cooled), 26 FRs (mostly overlapping with SFR, LFR, and GFR), and 48 SMRs (including all types of reactors). There are many fast reactors under development, most of them having been around for decades. The most prominent, however, is the prevalence of SMRs, 48 out of 78 listed. One recent design of SMR, KLT-40s by Russia, the world's first floating mini nuclear power plant, was built, delivered, started, and connected to grid from 2007 to 2019 (more on this later).

Except for the light- and heavy-water cooled advanced reactors, which are often categorized as Generation III or III$^+$ systems, most of advanced reactors in ARIS are Generation IV nuclear energy systems. These designs are being developed with eight technology goals in four broad areas: sustainability, economics, safety and reliability, and proliferation resistance and physical protection, to use fuel more efficiently, reduce waste, be economically competitive, and meet stringent standards of security and nonproliferation goals.

The original technology roadmap for Generation IV Nuclear Energy Systems was developed during 2001–2002 by over 100 experts (this author included) from ten countries, IAEA, and OECD NEA [36]. The team evaluated 130 reactor concepts contributed from around the world with the goals in mind. Generation IV International Forum (GIF) selected six reactor technologies for further research and development. They include GFR, LFR, MSR, SCWR, SFR, and VHTR (Very High Temperature Reactor). The roadmap was updated in 2014, and foresaw demonstration of some designs within 2020s, with commercial deployment beginning in 2030s [37].

Parallel to Generation IV program, IAEA established International Project on Innovative Nuclear Reactors and Fuel Cycles [38] in 2000 to help ensure that nuclear energy remains available for contributing to meeting global energy needs until the end of the 21st century. It is a membership-based project for long-term planning and collaboration on innovations in reactors, fuel cycles, and institutional approaches that promote sustainable development of nuclear energy. Using INPRO Methodology, it organizes activities in four major tasks — global scenarios, innovations, sustainability assessment and strategies, and dialogue and outreach [39].

China has just completed the cold test and is near the startup of a prototype High Temperature Reactor (HTR-PM) as a first step towards development of VHTR. Russia, China, and India are developing and building sodium fast reactor designs for near-term demonstration. France has cancelled its SFR prototype program, but continues cooperation with Japan for industrial demonstration. Russia also has plans to construct lead and lead-bismuth cooled fast reactors during the 2020s.

In recent years, US has reinvigorated civil nuclear energy development through multiple legislations, regulatory reform, and advanced reactor demonstration and risk reduction programs [40]. In 2020, US Department of Energy

Table 1. Worldwide history of reactor construction starts and connections to grid in the past five decades.

Decade	1970 – 1979		1980 – 1989		1990 – 1999		2000 – 2009		2010 – 2019	
Year	Starts	Connection	Starts	Connection	Starts	Connection	Starts	Connection	Starts	Connection
0	37	6	20	21	5	10	7	6	16	5
1	18	16	17	23	2	4	1	3	4	7
2	28	16	19	19	3	6	6	6	7	3
3	30	20	14	23	4	9	1	2	10	4
4	38	26	13	33	2	5	2	5	3	5
5	38	15	19	33	0	5	3	4	8	10
6	43	19	8	27	1	6	4	2	3	10
7	23	18	13	22	5	3	8	3	4	4
8	23	20	7	14	3	4	10	0	5	9
9	27	8	6	12	4	4	12	2	5	6
Decadal total	305	164	136	227	29	56	54	33	65	63
Annual average	30.5	16.4	13.6	22.7	2.9	5.6	5.4	3.3	6.5	6.3

announced selections of public-private partnerships to build two advanced reactors, SFR and GCR, that can be operational within seven years; five risk reduction programs in MSR, GCR, molten chloride cooled fast reactor, heat-pipe cooled micro reactor, and light-water cooled SMR; and three advanced reactor concepts in inherently safe advanced SMR, fast modular rector, and horizontal compact HTGR [41]. A national test facility, Versatile Test Reactor (VTR) is being developed and designed, led by Idaho National Laboratory, to provide research capabilities, and targeted for operation to begin in 2031 [42].

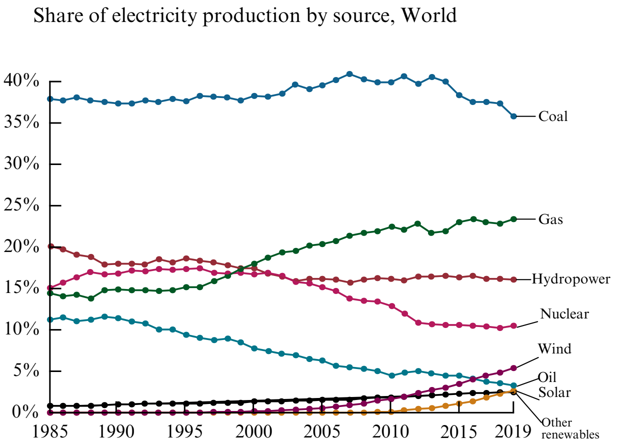
In parallel to advanced reactor technology development and design, there are RD&D programs to develop accident tolerant fuels, HALEU (High-Assay Low Enriched Uranium) fuels, and build up production and supply capacities [43].

In addition to information included in IAEA databases, which are contributed from member states, there are other innovative development, mostly conducted by startups and funded by private capitals in US, followed by a few in Europe, Asia, Russia, Canada, and others. A US think tank, Third Way, has been keeping track of many of them [44]. The majority of these designs are also SMRs.

3.2 History

For history, let us first look inside nuclear industry. The annual numbers of power reactor construction starts and connections to the grid for the past five decades are listed in Table 1 [45], with decadal total and annual average included. This establishes the historical baseline.

An important feature to note here is the gradual decrease in annual starts after 1979, year of Three Mile Island accident, reinforced by 1986 Chernobyl catastrophe, and immediate drop-off post Fukushima disaster in 2011, a few years after new construction starts finally began to rise again after over two decades of stagnation and decline. The severe global impact of nuclear accidents and strong correlation around the world, epitomized by the saying that a nuclear accident anywhere is an accident everywhere [46], and as a proto 'Black Swan' in financial industry and popular culture [47], are a distinct feature and a severe weakness of the current paradigm, indicating a very fragile and brittle system lacking some essential resilience, and presenting substantial systemic risks.



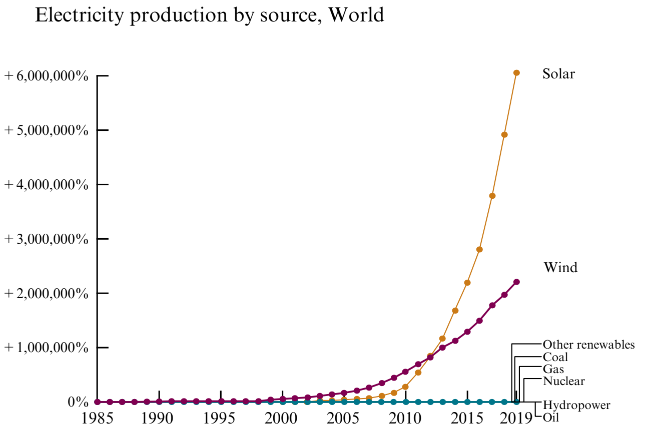
Source: Our World in Data based on
BP Statistical Review of World Energy & Ember
OurWorldInData.org/energy • CC BY

Figure 1. Share of electricity production by source around the world during 1985–2019 (Our World in Data).

It is helpful to view such trend together with other energies for broader perspectives and to assess relative performance and significance. Since the first and most impactful target for decarbonization is the electricity sector, we will start from there.

Figure 1 shows that the global share of electricity generated from nuclear has been declining, together with those from coal, oil, and hydro, while shares from gas, wind, solar, and other renewables are rising. The nuclear share peaked at 17.45% in 1996, and fell to 10.43% in 2019 [48].

Figure 2 shows the growth of electricity by source from 1985 to 2019. This is where some trajectories show utterly shocking patterns — solar share has risen over 6,000,000%, wind over 2,200,000%, other renewables 756%, gas 335%, coal 152%, hydropower 114%, nuclear 85.1%, and oil



Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2021)
Note: 'Other renewables' includes biomass, waste, geothermal, and wave and tidal energy.
OurWorldInData.org/energy • CC BY

Figure 2. Relative growth of electricity production by source since 1985 (Our World in Data).

−22.37%. This is a solid proof and an extraordinary triumph, among other things, of highly efficient and rapidly improving manufacturing paradigm following Wright's law that brings the cost of solar cells and wind turbines down on very predictable paths and rates (examined in more details later). Although lower in growth rate in comparison to these renewables because of the much higher starting level, share of gas power grew rapidly from 1995 to 2010, enabled first by much improved industrial gas turbines mass produced in factories, then major breakthrough in hydraulic fracturing that brought about the unconventional oil and gas revolution. The stagnation and decline of nuclear power, especially in comparison to renewables and gas, are clear.

On a decadal basis, the growth rates for electricity by source for last three decades are shown in Table 2. It shows that solar growth is accelerating at extraordinary rates; wind growth appears to have peaked even though it is still very high, so are other renewables; coal and gas growths have slowed; hydropower growth is steady; oil has never been a significant source of electricity and continues to fade; while nuclear growth essentially disappeared in the last two decades.

Within the mix of primary energies, the nuclear share peaked at 6.62% in 2001, and has slowly decreased to 4.27% by 2019. As in the electricity mix, nuclear is still the second largest source of low carbon source, after hydropower, but may be overtaken by wind and solar in 2020s. Nuclear energy has essentially only provided baseload electricity in large grids, with little contribution in industrial and transportation sectors.

Renewables make up 11.4% of low-carbon sources of global primary energy in 2019. Together with 4.27% from nuclear, the low-carbon total is 15.7%, while the remainder, 84.3%, still comes from fossil fuels, with oil 33.1%, coal 27%, and gas 24.3%. The global decarbonization challenge is truly daunting, yet it is not impossible — there are countries with very high shares of low-carbon energy sources, such as Iceland, 79%; Sweden, 69%; Norway, 66%; France, 49%; and Switzerland, 49%. Of these, France, Sweden, and Switzerland have substantial contributions from nuclear, with 71.26% of electricity in France from nuclear in 2019. They can serve as models for low-carbon energy transitions.

Table 2. Decadal growth rates of electricity production by source.

Source	1990 – 1999	2000 – 2009	2010 – 2019
Solar	135.95%	1727.76%	2111.36%
Wind	484.07%	780.90%	309.45%
Other renewables	51.67%	72.31%	68.93%
Gas	44.92%	59.33%	29.93%
Coal	26.15%	36.26%	11.91%
Hydropower	20.69%	22.36%	24.08%
Nuclear	26.19%	4.60%	1.14%
Oil	−7.16%	−15.89%	−9.05%

The extraordinarily high growth rates of solar and wind, and very high rate of gas turbines, show clearly that mass produced energy systems can grow much faster than constructed power plants despite (much) smaller units. They, along with plane making and ship building, serve as models for a new paradigm of civil nuclear energy.

3.3 Outlooks

Having this big picture of current status and recent history in mind, we now turn to outlooks with emphasis on the role and potential for nuclear energy in mitigating climate change. We will focus mainly on those issued by international organizations central to climate change and energy production.

In 2018, IPCC (Intergovernmental Panel on Climate Change) published a special report on global warming to 1.5 °C, with all considered scenarios requiring more nuclear power [49]. Specifically, the four pathways (P1–P4) examined by IPCC show increases of nuclear power relative to 2010, by between 59–106% by 2030, and between 98–501% by 2050. Pathway P3, based on continuation of historical technological and societal development, requires the most significant rise (+501%) in nuclear generation by 2050. This will demand nuclear power to re-accelerate drastically from low growth and stagnation in the last three decades.

IEA (International Energy Agency, OECD) publishes the highly anticipated and influential world energy outlook every year. In the 2020 outlook, the stated policies scenario for nuclear would generate 210% more during 2019–2040 than 2000–2019 [50].

An earlier IEA report in 2019 on nuclear power in a clean energy system has called out the significant contribution nuclear can make to achieving sustainable energy goals and enhancing energy security, alongside renewables, energy efficiency, and other innovative technologies [51]. This represents a part of changing perceptions of and attitudes toward nuclear, within nuclear industry, broader energy industries, and societies at large. Nuclear energy is not in competition with other low-carbon sources and technologies, but should be considered together in global energy transition and mitigation of climate change. At the same time, increased flexibility of nuclear power is needed to improve reliability and security of low-carbon energy systems.

The same report points out that nuclear power has avoided about 55 Gt of CO_2 emission over the past 50 years, nearly equal to 2 years of global energy related CO_2 emissions. (In 2020, IAEA reported a reduction of 74 Gt during 1971–2018, or equivalent to cumulative emissions from the entire power sector from 2013 to 2018, second to 98 Gt contribution from hydro.) This is a highly valuable contribution made by nuclear long before renewables besides hydropower had become sufficiently mature and economical for broad deployment at scale.

However, based on assessment of status and challenges in US, European Union, and Japan, the nuclear fleet in advanced economies, which has had substantially higher shares in electricity generation than world's average, could face a steep decline. In this Nuclear Fade Case, nuclear capacity operating in advanced economies would decline by two-thirds by 2040, from about 280 GWe in 2018 to just over 90 GWe in 2040. This poses possible electricity security threats, and clean energy transition becomes more difficult and very expensive.

The outlook for nuclear energy has been steadily improving in the last few years, especially since the signing of Paris Agreement, and with the IPCC special report calling for 1.5 °C target. NEA (Nuclear Energy Agency, OECD) published a report on the role and potential for nuclear energy in combating climate change [52]. In a 2 °C scenario, gross nuclear electricity generation capacity is projected to grow from 390 to 930 GWe by 2050, +138%. This scenario would require annual grid connection rates of over 12 GWe in the 2010s, to well above 20 GWe in the 2020s. While this was achieved in 1970–1980s, it would have been a substantial step up from the trends since mid-1990s. The recently announced 14th 5-year development plan in China has revised national policy toward actively and orderly growing nuclear power, with 6–8 units to start annually, which is a very concrete step toward its pledge of carbon neutrality by 2060.

IAEA updated its study on climate change and nuclear power recently [53]. It is one of the most comprehensive, systematic, and in-depth institutional reports on this topic, containing several key scientific and technological findings relevant to the new paradigm, thus valuable to be covered more extensively here. The report starts with a synthesis of over 400 recent long term scenarios of energy demand from international, governmental, non-governmental, private sector, and scientific organizations that illustrates the challenges and opportunities of reducing emissions while supplying energy for economic and social development. Electricity is central in decarbonizing energy, and needs to play a larger role to support decarbonization of transport and industry, while other low carbon energy carriers — such as hydrogen and heat — will play an increasing role in fully decarbonizing these sectors.

The increasing importance of electricity brings into focus the technology options for low-carbon generation. While all of them, nuclear, hydro, wind, and solar produce the lowest GHG emissions on a lifecycle basis, they have more varied impacts on material requirements with associated effects on environment, ranging from low for nuclear, hydro, and natural gas combined cycle power to high for wind and solar power. The vast differences will have significant ramifications when they are deployed at large scales.

The scenarios projecting strong increases in nuclear capacity highlight several potentially important enabling factors: (a) a strong mitigation target, and related consistent policy signals; (b) control of nuclear costs and access to finance; (c) a moderate degree of social acceptance; and (d) recognition of the value of nuclear power to stable operation and management of the electricity system or grid.

The transition towards a future low-carbon energy system comprising diverse technologies and resources requires a radical transformation of how energy services are produced, provided, and used. The electricity system will become increasingly complex and highly integrated, with more distributed generation and storage as well as tighter coupling with transport and broader energy sector. The growing shares of variable renewable energies will make residual demands more volatile and unpredictable, requiring more short term and seasonal storage.

The growing volatility in residual demands and resulting market prices has significantly increased risks for investment in capital intensive low carbon technologies. It also prompted nuclear operators to operate plants flexibly, and developers to consider flexible co-generation of low-carbon hydrogen and heat while running nuclear reactors at full power constantly.

Several elements are proposed to support or incentivize the transition to a reliable, low-carbon energy system in liberalized markets: (a) competitive short-term electricity markets for efficient dispatch; (b) framework for the adequate provision of capacity, flexibility, and infrastructure for transmission and distribution; (c) measures to foster long-term investment in low-carbon technologies, (d) internalization of system costs; and (e) carbon pricing. Large energy infrastructure projects, including nuclear, remain high risk for investors, and need some forms of government support and market measures to manage and share risks. However, nuclear power plants have shown to be relatively resistant to weather events, with limited forced outages in most cases despite a high frequency of extreme weather events in some regions.

Some additional elements can unlock the mitigation potential of nuclear power. Nuclear power projects require large capital investments and long construction times, typically seven years (and much longer and more varied in some countries and regions). Investment costs can be contained effectively through multi-unit constructions allowing plant developers, vendors, work crews, and regulators to gain experience over time. Use emerging financing and risk sharing models for large, complex, and capital intensive nuclear projects. Build and maintain robust supply chains capable of delivering equipment, systems, and services with the highest quality levels. Extend operational lifetimes of existing NPPs. Develop and deploy advanced and emerging nuclear energy technologies, including small modular reactors for markets and applications less suited to other low carbon technologies (including conventional NPPs) owing to geographical, technical or financial constraints (we will show later that this limited positioning for SMRs is mistaken).

The report acknowledges that a culture of transparency and openness is essential for addressing legitimate concerns of stakeholders regarding nuclear power, including safety, nuclear waste, and nuclear energy's role in climate change mitigation.

It is apparent that many of the major issues and key elements covered in this report, similar to most studies on such topics, are trans-scientific. The scientific parts are mostly focused on matters external to nuclear reactors and power plants, such as lifecycle carbon emissions, material requirements and impacts on environment, reliability and stability of low carbon energy systems, deployment viability of SMRs, etc. The nuclear power technology itself, and the products and services it provides, appears mostly fixed. As such, the report can serve as a summary of the existing paradigm and a starting point to introduce and assess the new paradigm, with the trans-scientific conditions and trends serve as external forces and evolving constraints that will help bring about needed changes in civil nuclear energy technologies, products, and services. The additional outlooks reviewed below serve similar purpose and functions.

In the context of low-carbon energy systems, MIT Energy Initiative published a report on nuclear energy in a carbon-constrained world [54]. It explores the potential of nuclear energy in reducing total system costs in deep low-carbon scenarios, and reveals that nuclear energy with controlled or reduced costs can become a major component. The study models select countries and regions with different energy resources, including some areas in US, EU and China, analyzes and compares select scenarios for various levels of decarbonization, and obtains a series of insightful and constructive conclusions. The study points out that one key constraint on nuclear energy growth is high capital cost, and recommends several solution approaches, including a shift away from primary field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants, toward reactor designs that incorporate inherent and passive safety features.

There are a number of models and simulators developed for scenario analysis and strategic planning. The En-ROADS simulator developed by Climate Interactive, Ventana Systems, and MIT Sloan, is a transparent and freely-available policy simulation model online [55]. It has been grounded in the best available science, and calibrated against a wide range of existing integrated assessment, climate and energy models. It quickly becomes clear through simulation that without significant increase of nuclear energy, or advances in carbon removal technologies, most other measures including high growth of renewables, efficiency, and electrification, would not be sufficient for the more ambitious 1.5 °C target.

For this review with its international background and context, there is one outlook worthy of special mention. Professor Siegfried S. Hecker is a former director of Los Alamos National Laboratory and the author/editor of a two-volume book, “Doomed to Cooperate: How American and Russian Scientists Joined Forces to Avert Some of the Greatest Post-Cold War Nuclear Dangers” [56]. In 2016, he created, and has been leading since, a U.S.–Russia Young Professionals Nuclear Forum to encourage dialogues on critical nuclear issues of concern to both countries. The forum was organized within Center for International Security and Cooperation (CISAC) at Stanford University, and partnered with Moscow Engineering Physics Institute. One of the forum meetings was on whether or not an expansion of nuclear power is necessary to help mitigate the danger of climate change. The findings of young professionals are captured in eight articles featured in a special presentation in *Bulletin of the Atomic Scientists* [57].

Weinberg pointed out that one must establish what the limits of scientific facts really are, where science ends and trans-science begins. He viewed engineering as trans-science, especially in fields which are developing rapidly, where incomplete data is often the norm and engineering judgement is used as a guide. In principle, one exhausts all scientific elements and answers every question which can be answered scientifically before dealing with the trans-scientific residue. There are two institutional mechanisms to resolve trans-scientific issues: the ordinary political processes and legal adversary procedures.

Additionally, there is another way to resolve unanswered questions of public or environmental risk caused by new technology: to perfect the technology so as to minimize risk. This is the focus and priority of the new paradigm.

After more than seventy years of research, development, and deployment of civil nuclear power, many more practical experiences, facts, data, and knowledge have been accumulated and understood, especially with the three major nuclear accidents, their severe consequences, and public and marketplace responses as valuable data for future development, engineering, design, build, installation, and operation. Some of the early trans-scientific issues can now be answered more scientifically, or considered resolved trans-scientifically through institutional mechanisms informed by real-life experiences, or accidents as unintended experiments. This review and treatise will assess such matters, while continue to perfect technologies and systems to minimize known risks, and guard against emerging risks.

4. Problems, challenges, and origin of nuclear safety and economics dilemma

4.1 Current problems highlighted in development goals

In many ways, the goals of Generation IV Nuclear Energy Systems indicate key deficiencies, problems, and risks of the current technologies and systems, as viewed comprehensively by the nuclear field and industry (Table 3).

Decades of experiences have shown clearly that meeting all goals simultaneously is extremely challenging and time consuming, as it is also evidenced by decades-long timelines for development, demonstration, and deployment that the nuclear institutions and industries have planned and set up.

Table 3. Goals for generation IV nuclear energy systems as key indicators of barriers and challenges.

Sustainability-1	Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilization for worldwide energy production.
Sustainability-2	Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
Economics-1	Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.
Economics-2	Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.
Safety and Reliability-1	Generation IV nuclear energy systems operations will excel in safety and reliability.
Safety and Reliability-2	Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.
Safety and Reliability-3	Generation IV nuclear energy systems will eliminate the need for offsite emergency response.
Proliferation resistance and physical protection	Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

A recent editorial from the leading scientific journal *Nature* on the Anniversaries of the Fukushima and Chernobyl disasters is representative of perspectives and sentiments of the general scientific community [58]. Successive disasters have depleted the public optimism that accompanied the Eisenhower's speech on Atoms for Peace [59]. Today his speech is a reminder that nuclear power shares a common ancestor with weapons of mass destruction. Both factors have stymied nuclear energy's great promise as a source of fuel.

While deaths from nuclear power disasters are very limited and the extent of health risks still uncertain, or in dispute, the costs of these damages are very high, ranging from over US$200 billion by Chernobyl, to between $470 billion and $600 billion by Fukushima, and still rising overall with ongoing stoppage or pre-mature shutdown of other reactors. The wide-spread and long-lasting damages to local and regional environment and ecosystems, and affected populations, economies, and societies are devastating.

It has becoming increasingly studied and known that on the fatality per unit of power generated, nuclear has the lowest rate by a large margin compared to other conventional powers, even some renewables [60, 61].

But the high costs and severe consequences from small incidents to major disasters, repeated failures for most nuclear power countries to secure long-term waste disposal solutions, persistent public concerns and oppositions, long delays of regulatory approvals and construction completions, and rising cancellations of projects and pre-mature closures, demonstrate that the other substantial risks to various stakeholders have not been adequately addressed, reduced, or eliminated.

The add-on-patchwork approach to addressing them incrementally have led to much increased complications and costs that have significantly weakened market positions and reduced industry's potential, while not eliminating some of the most pernicious fundamental risks. As we will see later, some solutions lead to more concentration of risks, and nominal reductions in already very low probabilities of severe accidents and damages cannot be verified and validated scientifically, or are too expensive to ascertain except through major accidents, worsening multitude factors in risk perceptions by the public.

It is productive to pause here and review the three major paradigms in risk perceptions, which help highlight the complex challenges facing nuclear technologies, but also point to potential directions for constructive and effective solutions. We will mainly use the key results from Dr. Paul Slovic, a leading scientist in the emergent risk science with systematic research on risk perceptions posed by extreme events and impacts on technologies, in particular nuclear power, and the related literature, for this purpose here [62–65].

Slovic points out that while industrialized nations have expended great effort to make life safer and healthier, many in the public have become more, rather than less, concerned about risk. Public perceptions of risk have been found to determine the priorities and legislative agendas of regulatory bodies. Polarized views, controversy, and overt conflict have become pervasive within risk assessment and management. The increasing dissatisfaction on risk management can be traced, in part, to a failure to appreciate the complex and socially determined nature of the concept of risk.

Research has found that the public has a broad concept of risk, qualitative, and complex, that incorporates considerations such as uncertainty, dread, catastrophic potential, controllability, equity, risk to future generations and so forth. In contrast, experts tend to see risk through probability of harm or expected mortality. The vastly different perspectives lead to many conflicts over risk, and corresponding risk statistics and communications often do little to change people's attitudes and perceptions.

Risk is a hazard, probability, and has consequences and threat. Risk perceptions connect peoples' emotions and reasons, and are studied in three major paradigms: axiomatic — consequences and impact; socio-cultural — effects of group and culture level variables; and psychometric — emotional reaction that affects judgments.

In the psychometric paradigm, one leading factor stands out — dread risk, defined at its high end of perceived lack of control, dread, catastrophic potential, fatal consequences, and inequitable distributions of risks and benefits. Nuclear weapons and nuclear power score the highest here. Another important factor — unknown risk, is defined at its high end by hazards judged to be unobservable, unknown, new, and delayed in their manifestation of harm. Chemical and DNA technologies score particularly high in this factor, while radioactive waste and nuclear reactor accidents also score quite high. Such perceptions have key impacts, such as social amplification of risk, as demonstrated by the three major nuclear accidents and the severe fallouts impacting the worldwide nuclear industry, and national energy policies and development plans.

There are technical and process-oriented solutions to risk conflicts, but they are yet to be sufficient for many at the present. Value conflicts and pervasive distrust in risk management cannot easily be reduced by technical analysis. Addressing risk controversies primarily with more science is likely to exacerbate conflict. Some of the present social and democratic institutions breed distrust in the risk arena, especially when managing risks within an adversarial legal system that pits expert against expert, contradicting each other's risk assessments and further destroying public trust. But paying serious attention to participation and process may lead to more satisfying and successful ways to manage risk in the long run. Risk science is evolving as a branch of the emerging sciences of the artificial, with close proximity and strong interaction with natural sciences. It is essential to a new paradigm for civil nuclear energy being developed and implemented.

In addition to the very stringent and unique demands from technological, construction, financial, economical, and institutional requirements [66], IAEA's dual role in monitoring and inspecting nuclear power plants, and trying to ensure that a country is not diverting fissile materials for weapons use, further exemplifies the high barriers to adoption of nuclear energy. This aspect is made more explicit and extensive on the national levels, for example, in a report published by Nuclear Energy and National Security Coalition organized by Atlantic Council Global Energy Center [67]. The continued low take-up of nuclear power indicates that some countries think that the benefits are outweighed by the risks.

4.2 Future challenges revealed by market competitions

While new power reactors continue to be planned and built in China, India, and a few other countries, they are mostly a part of their respective national programs and not market actions. With more economies around the world moving toward free markets or regimes where markets are increasingly the deciding factor, the myriad challenges facing the current paradigm for nuclear energy are becoming increasingly harder to overcome.

Compared to other emerging modern energy systems, the existing mainstream nuclear power plants have proven very difficult to improve their economics consistently over time. While serial constructions of the same designs on the same sites have led to reduced capital costs and shortened completion times in later units, such effects have not been accumulated or spread throughout the industry and over time (see, e.g., [4, 68, 69]). This, combined with other headwind factors, has contributed to the Nuclear Fade Case in high-income countries [51]. It is very troubling for an energy source that is normally clean, seemingly futuristic, and very low carbon, and its production technologies and systems, to lose appeals and shares in advanced economies.

Even more alarming, due to rapid and predictable cost decreases in some renewable energy technologies, such as solar photovoltaic and wind turbine, and explosive growths of these intermittent and variable sources, the critical needs for grid stability and supply reliability have led to increased uses of fossil fueled power. In some cases, such as Germany's Energiewende, this has led to increased electricity costs and slower reduction in carbon emissions at the same time, making it unlikely to achieve energy decarbonization by 2050 [70]. This troubling trend is exacerbated by phasing out existing nuclear power.

Increasing energy storage, especially with batteries, has become a top go-to solution for the time being, and greatly enhanced by electrification of transportation through electric vehicles. This solution pathway has many advantages for clean and low-carbon energy transition and increasingly demonstrated potential for exponential growth. However, due to their much lower energy densities, higher resource demands, and likely very large scale impacts on major systems and materials cycles on Earth, full energy transition based solely on these solutions may present a different set and very challenging issues. This will become more evident when we review the primary energy hierarchy and the major systems and material cycles on Earth below.

The many layers and redundant additional safety, emergency response, and containment systems mandated by lessons from nuclear disasters, demands by public and regulators, not only increase complications and costs to the existing nuclear power plants, but also significantly reduce the potential for improvement and slow down technological advances. Emerging studies and models (see, e.g., [72]) reveal the effects of design complexity on the evolution of cost — the more complex the design, the slower the rate of improvement. When connectivity among system components varies, bottlenecks can arise where a few components limit progress, and can determine whether progress is steady, or whether there are periods of stasis punctuated by occasional large changes. This point is particularly pertinent when it comes to fuel and coolant of nuclear reactors.

Using historical data and trends to extrapolate into future, which can be more credible and reliable for the near future, instead of the need-based scenarios for mitigating climate change, the outlook for civil nuclear energy is rather somber if business-as-usual persists, even with improved opinions and acceptance from some corners that used to be anti-nuclear. It is true that simple extrapolation of history does not take into account the role and potential of new technologies and disruptive innovations, but neither is their emergence self-ordained or assured, especially since timely reversals of many current trends are necessary. As Romer points out, steering is more important than stepping on gas when it comes to driving innovation and properly anticipating outcomes [30, 31].

In a recent study by Institute of New Economic Thinking at Oxford Martin School [71], costs of four different scenarios for global energy system from 2020 to 2070 are evaluated. Using empirically validated technology forecasting method based on extensive historical data from multiple industries [69], the study finds that a nuclear scenario is substantially more expensive. The rapid transition scenario, deploying solar photovoltaics and wind turbines quickly with batteries for short-term storage, and hydrogen-based fuels for long-term storage and non-electrifiable applications, has the highest net present saving compared to a no-transition scenario, and a slower transition scenario. This study is limited to costs, so potential restrictions and impacts on resource, environmental, and ecological matters, and needs for grid stability, supply reliability, and system resilience, are not included.

The outlook as a timely global solution to climate change becomes even more clouded when we review the states and plans of developing advanced nuclear energy technologies and systems. It has been alluded to previously on the decades-long development timelines for Generation IV nuclear energy systems. We will take another look from a paradigmatic perspective.

4.3 Origin of nuclear safety and economics dilemma

The current mainstream nuclear power technology is based on water cooling, and grew out of the early needs for military uses in production of special nuclear materials and nuclear propulsion. The choice was made based more on time pressure and limited resources than superior characteristics of water. It was likely enhanced by the compactness of such designs prized for mobility and saving of materials, and wide familiarity with and broad availability of water and steam based technologies, components, and equipment. The dual functions of water as coolant and moderator helped simplify designs in the early years, before safety problems and consequences were well understood. Admiral Hyman Rickover decided on the PWR route for nuclear navy. The convergence of such factors created satisficing solutions that quickly gained unsurmountable advantages when peaceful use of nuclear energy was called for, and locked in a path within a dominant paradigm for nearly three quarters of a century, crowding out other options.

More specifically, the most prevalent design of commercial power reactors around the world today and for the near future, PWRs, came from direct adaptation of design at Oak Ridge National Laboratory as a nuclear submarine power plant. The fully operational unit was located at Idaho National Laboratory, and follow-on work was conducted by Westinghouse Bettis Atomic Power Laboratory. The first purely commercial nuclear power plant at Shippingport Atomic Power Station was originally designed as a PWR for a nuclear aircraft carrier, reaching criticality in 1957. Later design modifications are mostly in scaling up power ratings, and adding more and more safety, emergency response, and containment systems and equipment, whether active, passive, or hybrid, often with redundancy, in the defense-in-depth model. One PWR suffered a partial meltdown in the Three

Mile Island accident in 1979 through loss of coolant, essentially ended growth of new construction in US for over three decades.

The RBMK reactors in Chernobyl came from the Soviet program to develop a water-cooled power reactor with dual-use potential for plutonium production. They were mainly designed by Kurchatov Institute of Atomic Energy and NIKIET. The first of these, Obninsk AM-1, started and ran from 1954 to 1959. Using a minimalist design with light water for cooling and graphite for moderation, it was possible to use natural uranium for fuel. The simple design allowed an extraordinarily large reactor cheap enough to be built in large numbers and simple enough to be maintained and operated by local personnel, making it the national reactor of Soviet Union. But the RBMK design flaws include a fundamental safety defect due to its high positive void coefficient, which can lead to a runaway condition for neutron production and reaction in a thermal feedback loop through water boiling and evaporation, and subsequent steam and hydrogen explosions. The lack of sufficient safety and emergency response systems, and full physical containment, amplified and extended disastrous consequences and impacts. Such combinations eventually led to the world's largest nuclear catastrophe at Chernobyl in 1986.

The BWR concept was developed later than PWR and became the second most common type of reactors. It was a collaboration between General Electric and several US national laboratories, in particular Argonne, after a series of BORAX experiments proving the safety principles of BWR. It was found in early development that quickly boiled water in reactor could shut it down, indicating a useful self-moderating property in emergency. In 2011, due to loss of coolant and hydrogen production by zirconium alloy fuel cladding with high temperature steam after a giant earthquake and resulting tsunami, three BWR units suffered catastrophic hydrogen explosion and core meltdown after automatic shutdown in Fukushima.

In responses to nuclear disasters and public demands, nuclear regulatory frameworks become more rigid, highly prescriptive, with strong preference toward established designs of large monolithic nuclear power plants. This ratcheting trend, combined with and enhanced by the industry's singular pursuit of economies of unit scale through increasing reactor power, locked nuclear technologies into a vicious cycle. To improve safety and economics in the same paradigm with already minuscule probabilities of core damages and large releases, more systems and higher costs are necessary, which have led to increasing total power in an attempt to spread and reduce specific costs, but have led to increased construction times and costs, and increased consequences of severe accidents beyond design basis, which in turn demand more safety and emergency response systems and containment, and on and on.

The scaling-up in such development with associated safety risks requires multiple careful steps, from zero power, experimental, prototypic, commercial demonstration reactors to deployment. With each step needing a decade or more time, total cycle times of technologies and system designs became multi-decadal. The safety concern and resultant slowdown have deprived nuclear technologies and systems from very many diverse and rapid innovation opportunities available to other technologies and industries, especially those exponentially growing disruptive innovations made possible by networking effects and combinatorial explosions.

They also led to decades-long stagnation and decline of the first nuclear era. Weinberg pointed out that safety and emergency systems almost dominated the whole nuclear power technology [18, 19], years before the Three Mile Island incident in 1979. That dominance has only increased ever since, to a point where people outside the industry with astute observation and high-tech industry experiences, such as Bill Gates who has been investing to develop advanced nuclear energy technologies, would wonder how such kinds of technologies could compete and survive in marketplaces, as successive 'generations' of technologies and products provide essentially the same services (baseload electricity) with more complexities at higher costs. To some visionary pioneers of nuclear power, a second era of nuclear is called for, and inherent safety is key to restarting nuclear energy growth and expansion [14].

If pursuit and adoption of nuclear energy technologies and systems are determined by reasons and strategies other than efficient economic uses, then concerns and risks for security and proliferation rise substantially (see, e.g., [73]), further restrict the essential role and vast potential, and hinder fundamental advances and rapid expansion of civil nuclear energy in combating climate crisis.

5. A new paradigm for civil nuclear energy

A second era of nuclear calls for a new paradigm for civil nuclear energy. It needs to provide fundamentally safe, market competitive, and investment friendly products and services that have diverse applications, broad appeals, straightforward and flexible deployment and operation, and minimal security and proliferation risks. Most importantly, it needs to enter markets soon, build momentum continuously, and scale up deployment quickly, exponentially if possible.

5.1 Primary energy hierarchy

To understand and appreciate the special position, potential, and peril of nuclear energy, we need to review the primary energy hierarchy briefly. Many challenging problems in the present designs and operations of nuclear energy systems stem from some fundamental mismatches of extremely powerful nuclear force to surrounding materials formed with relatively weak chemical forces, and misallocation of resources and efforts due to outdated and mistaken assumptions. While the basic science is simple and straightforward, engineering practical solutions with proper designs is much harder and leaves much room to improve.

There are several forms of primary energy that we use, including fossil fuels, nuclear power, and renewable energies. Each has its own distinct characteristics, unique advantages and disadvantages, suppliers and users, proponents and detractors. Systematic understanding of their roles and objective evaluation of their current and potential contributions and impacts remain a difficult challenge, especially when it comes to accelerating global energy transition to mitigate climate change.

To give these studies and debates some uniform scientific framework and metrics, and avoid too narrowly focused and often biased arguments and decisions, a primary energy hierarchy based on physical origins and natural or artificial transformations is used here, with a set of metrics that place all of them on some common platforms to start more in-depth and specific assessments. In the context here, this will increase the domain of science and reduce that of trans-science, or

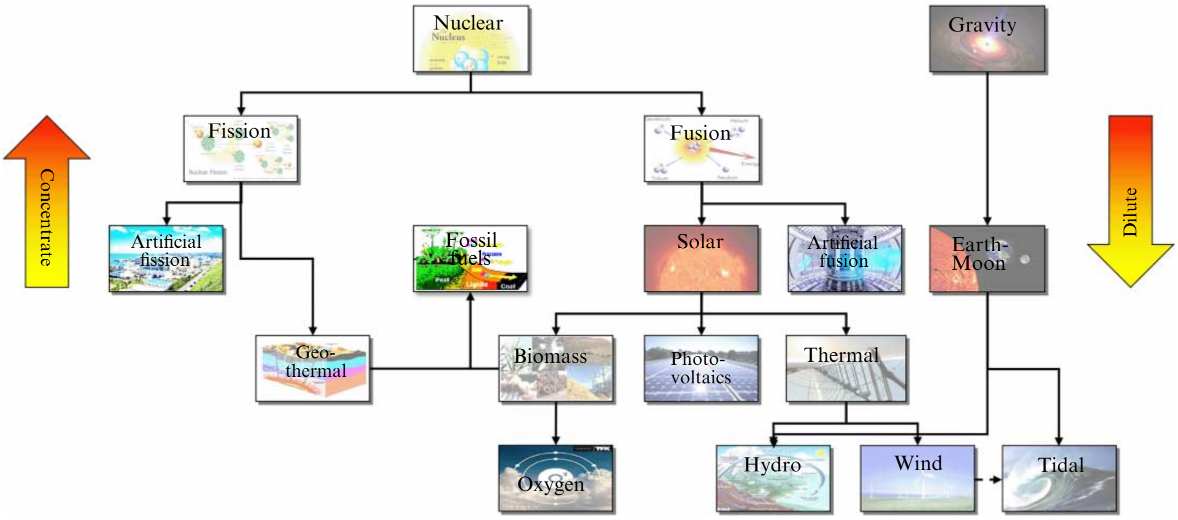


Figure 3. Primary energy hierarchy on Earth with origins and transformations.

alternatively, making trans-science more of a science of the artificial.

The energy hierarchy places the origins of primary energy on Earth at nuclear fusion and fission, and gravity, with all forms we encounter and use as tiered natural or artificial transformations through physical and chemical processes (Fig. 3). The metrics are surface energy flux, a measure of land use with implication on environment and ecosystems; carrier energy density, a measure of transportability or geographical restriction; proven reserve, an indicator of availability of non-renewable energies; and total surface flux, a corresponding indicator of renewable energies. The specifics are beyond the scope here, but I hope that listing of such concepts will facilitate common understanding of the issues.

All primary energies on earth can be traced to two physical origins: nuclear and gravitational.

The nuclear origin can be categorized into fusion and fission. The fusion energy radiating from the Sun manifests itself in a variety of forms. Biosphere converts received solar energy mainly through photosynthesis, transforming it into bio-energy. Shaped by millions to billions of years of crustal movements and associated thermal, biological, physical, and chemical processes, bio-energy is transformed into fossil energy, stored in coal, petroleum, natural gas, and other unconventional fossil fuels. For other hydrocarbons of non-bio-origins, their formations are likely driven by nuclear decay heat in Earth's core.

Solar energy captured and transformed via photovoltaic (PV) process is solar PV energy. Solar heat captured and utilized is solar thermal energy, with applications in low temperature heating and high temperature steam generation of electricity, or concentrated solar power. These are artificial forms of direct capture and transformation, and can be classified as secondary utilization of fusion energy, or first order use of solar energy on Earth.

The natural transformations and eventual utilizations of solar thermal energy result in other forms of primary energy. Thermal and gravitational interactions cause water to vaporize, transport, and precipitate, transforming into hydro energy; make air rise, move and fall, transforming into wind energy; and drive open water to ripple, circulate, rise, and fall, transforming into wave or tidal energy. These forms can be classified as secondary or tertiary uses of solar energy on Earth.

Oxygen is often neglected as a source of primary energy. Generated through photosynthesis, it is absolutely essential in providing bio-energy to life, necessary in combustion of chemical fuels and contributes substantial shares of energy released. This omission likely shares the same cause of long neglect of carbon dioxide emission as a waste product from power generation because they are not directly visible but ubiquitously available.

Hydrogen is often touted as a carbon-free energy. It is not, however, a primary energy, but a molecular carrier that stores energies used to produce it. It should be considered on the same level as electricity, batteries, and other fuels and storage systems that are artificial or secondary.

In this hierarchy, energy is greatly diluted moving down each level of transformation, with corresponding drastic reduction of carrier energy density or flux. Since gravitational force is very weak at small scales, the primary energies resulting from transformations via gravitational interactions, e.g. hydro, wind, tidal, and wave energy, are highly diffused, by many orders of magnitudes, from hundred to hundred thousand times, compared to total solar irradiance of approximately 1360 W m^{-2}. Their efficient capture and utilization require massive scales in terms of resources needed, especially land surface covered.

All of the above are various transformations of received solar fusion energy on Earth. Since such cycles are short in time and replenished by the Sun continuously, they are renewable.

The exceptions to such dilution are fossil fuels. Geological time and crustal movement have processed and concentrated bio-energy transformed from solar energy, and made fossil fuels very concentrated rich sources of energy. In the primary energy hierarchy, this natural transformation concentrates, rather than dilutes, by millions of times in comparison to renewables.

Fossil fuels are in principle renewable as well, but the renewal rates and cycles are far too slow and long for civilizations to be treated that way. A fundamental problem and challenge of heavy anthropogenic uses of fossil fuels is rapid draw down — several hundred years uses of resources accumulated over tens to hundreds of million years, depleting energy reserves quickly and, more importantly, changing natural systems and materials cycles far too quickly for natural evolution to adapt, including that of carbon, the main building block of life and a key component of heat balance of planet Earth.

The only primary energy with sole present Earth origin is nuclear energy. Geothermal energy is a highly dilute natural transformation through decay heating, a secondary source contributing about half of Earth's heat flux. The artificial form we use today is nuclear fission energy, manifested mainly through electricity generated from power reactors. Since this is direct transformation of nuclear reaction, based on extraordinarily strong nuclear forces, nuclear energy has a carrier density that is over a million times that of all chemical energy carriers, i.e, fossil and bio-mass energy, and many more orders of magnitudes denser than all other renewables not based on chemical transformation of molecules. It is immediately apparent that a system architecture for nuclear energy tailored for this unique character should be distinct from that for other forms of energy.

On the cosmic scale, fissile and fertile elements for nuclear energy originated through rapid nucleosynthesis in supernovae or merger of neutron stars, then enriched in continental crust. While their abundances on Earth or in solar system are lower than that of hydrogen, oxygen, carbon, silicon etc, similar to rare earth elements, and much higher than precious metals, their total energy content is high. There are about 40 trillion tons of uranium on Earth, and 4 billion tons in seawater at concentrations around 3.3 ppb. Seawater uranium is selectively extractable as demonstrated at lab scale, and maintained at that level through contact with the crust [74–77]. As a reference, the global nuclear power industry, with 400 GWe total capacity generating over 10% of electricity, consumes about 67,500 tons of uranium a year, and the measured reserve in 2019 is 6.1 million tons.

There is no shortage of uranium now or in the long run, and the market price based on thermal energy output is also much lower than or similar to other fuels, even at the lowest level of fuel utilization in thermal spectrum reactors (water or gas cooled). The evidence requires a thorough rethinking of a key assumption in the established paradigm of nuclear energy and associated reactor design principles and methods — scarcity of uranium and need to optimize its utilization to improve performance and sustain growth in the near- to midterms.

5.2 Earth's major systems and material cycles

There are four major sub-systems or spheres in the integrated Earth system — geosphere, atmosphere, hydrosphere, and biosphere. They are interconnected by flows of energy and materials. The major energy flows are powered by an internal source (radioactive decay heat) and an external source (solar radiation). Energy is transferred via radiation, convection, and conduction. The key materials flow through major bio-geo-chemical cycles are carbon, oxygen, hydrogen, water, nitrogen, phosphorus, and sulfur — all essential for life.

The substantial modifications by human activities of these systems and cycles are driving rapid changes in Earth's environment, ecosystem, and climate. If we are to develop and deploy global solutions to mitigation climate change on fundamentally sustainable pathways, we need to reduce the impact of such systems and cycles, or decouple certain aspects from them, especially in the most fundamental force driving change, energy.

For examples of the needs and impacts of primary energies on resources and environment, let us review their waste streams. The global energy-related carbon dioxide emissions total at 33.4 Gt in 2019, and 31.5 Gt in 2020 due the pandemic. Detailed statistics and models are widely available from various credible sources (see, e.g., [78]).

The global used nuclear fuel discharged from reactors total at about 0.4 Mt from the beginning of nuclear power, with about one-third having been reprocessed [79]. A large power reactor (1 GWe) produces about 25–30 tons used fuels per year. The U.S. generates about 2 kt each year, totaling 83 kt since the 1950s, and all of it could fit on a single football field at a depth of less than 10 yards, for 20% of electricity [80]. While there are continuing research to explore, develop, and refine solutions to waste management and disposition, dry cask storage of used fuel has proven to be a highly practical, safe, and economical satisficing solution for the interim. Many options are being studied and emerging. In any case, due to the vast amount of energy at high levels still remain in used fuel and high-level wastes, they are still capable of producing substantial work if we can find suitable applications and technologies to utilize them, especially if they accumulate to sufficient amounts for economic development and deployment. Time and investments are needed and will be more available if civil nuclear energy is thriving again and producing high values to the economies and societies.

The data for renewables is changing quickly. As an illustrative example, decommissioned PV modules could total 1 Mt of waste in U.S. by 2030, or 1% of world's e-waste [81]. This shows substantially more in terms of volume and weight as compared to used nuclear fuel, but the fact that they belong to e-waste shows that the management and disposition can be conducted in the same broad category, making them more acceptable and manageable. The problems and recycling efforts are being studied (see, e.g., [82]).

Not only do they not emit carbon dioxide or other greenhouse gas during their normal operations, the key elements or materials used and produced for nuclear power and some renewables — uranium, silicon, lithium etc, are not in the Earth's bio-geo-chemical cycles. Their production and consumption are thus likely to have lower impact on ecosystems, if properly separated, contained, and recycled to close loops when technologically viable and economically efficient.

In this sense, renewable energy directly from Sun without nature's conversions, such as solar photovoltaics, or controlled and contained nuclear energy, are external to ecosystems, and their uses can be sustainable. Other energy sources and uses are internal to and close the ecosystems, thus cannot be sustainable based on the second law of thermodynamics.

From this system perspective, not only do the causes and impacts of carbon emission become easier to grasp and understand, the potential solutions and likely impacts and sustainability are also emerging more naturally. The historical energy solutions, going from renewables of past to fossil fuels, enabled and supported successive Industrial Revolutions, and are now creating climate crisis, provided backward tests and proofs.

Following such lines of scientific exploration and discovery, using perspectives of systems and cycles, we can make certain predictions on sustainable development. For instance, while using renewable energies and energy storages will contribute significantly and quickly to decarbonization, sole reliance on them will affect Earth's systems and cycles more in a direction of unsustainable changes, as demonstrated by hydropower, which is both renewable and storage (see, e.g., [83]).

Deeper penetrations and higher proportions of intermittent and variable renewables in energy systems require more resources, generate wider impacts, and present higher risks to system stability and reliability. To ensure continued human progress toward living in harmony with Nature, not at whims of Nature, there are viable and valuable technological solutions such as batteries for short-duration storage, and hydropower, hydrogen or other molecules for longer-term storage.

Among all renewable energy technologies and systems presently available or under development, solar PV stands out as the most sustainable large scale global solution since it is the most direct capture and conversion of solar energy from photons to electrons, and most efficient due to advanced materials based on fundamental interactions; it uses materials farthest removed from Earth's systems and cycles relevant to biology and ecology; and its material cycles can be closed with abundant external solar energy. By extension, some batteries represent likely the most efficient and sustainable short-duration energy storage solution.

5.3 Nuclear energy and safety reassessed and reimagined

Building on such basic logic, scientific knowledge, and historical progress, nuclear energy can become and will be one of the most sustainable global energy solutions that opens up vast expanses for exploration, discovery, growth, peace, and prosperity, by many orders of magnitude. We will systematically assess its possibility and potential in the following.

Figure 4 shows the orders of magnitude differences of primary energy levels, ranked in decreasing energy released per reaction from left to right. It also includes the levels of energy barrier for the reactions to overcome and thermal energy level for respective operating conditions.

The band of bond strength of materials (functional, structural, or containment) demarcates practical energy systems. All systems based on electromagnetic or gravitational interactions — fossil or chemical fuels (including hydrogen and bio-mass), solar PV, fire (including solar thermal), wind, and hydro, have released energy and reaction barriers often well below the band of bond strength. This means that such energy systems can function, be supported and contained at all times, even when accidents may alter the integrity, states or compositions of materials temporarily.

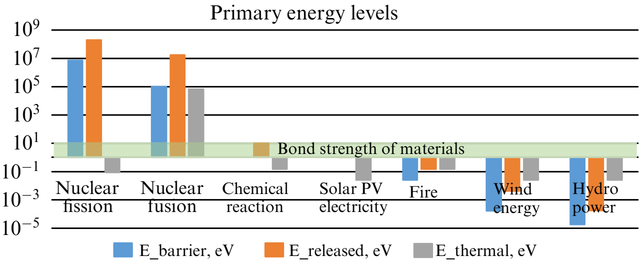


Figure 4. Primary energy levels — reaction barrier, released, and thermal — per reaction per atom or molecule.

While released energy and reaction barrier for fission are million times higher, nuclear fission can start and proceed in conditions well under that band of material bond strength. A natural proto-reactor also existed in Oklo, Gabon, West Africa. This is the most fortunate circumstance by nature, allowing us to design, build, and operate fission reactors using materials and systems that are available and not radioactive. Due to extremely high energy neutrons and radiations, surrounding materials are altered via microstructural damages, nuclear activation, and transmutation over time, which are entirely new in comparison to non-nuclear systems but manageable for some durations.

The more serious limitation, however, is that with extremely large amount of energy released, even as much lowered decay energy after chain reactions are stopped, and tremendous energy stored in loaded fuel, fission energy systems can damage or breach any materials given enough power density, total power, and lasting time. Because intense radiations and invisible radioactivity (but easily detectable by sensors) can pose severe acute or chronic damages to all biological materials and life, such failures should be deterministically excluded in the built civil energy systems and practical applications, and not merely at very low and non-testable probabilities or frequencies. This is especially necessary if failure consequences are high and extensive. Fortunately, this is possible, and is emerging to become cost competitive in a new paradigm. The main challenge is not in further advances in nuclear physics, but in engineering reactors and plants that can safely and economically bridge the vast expanse between MeV level from fission and eV level for materials.

It is noted that nuclear fusion is the only reaction that cannot start nor proceed in conditions under the band, but far above by many orders of magnitude. While stellar fusion is initiated and maintained under extremely high temperature and pressure with confinement by massive gravity at the scale of stars, we need to create such conditions through man-made magnetic or inertial confinement, or some alternatives such as magnetized target fusion and inertial electrostatic confinement, as well as new variations of stellarator. None of these conditions or proto-systems exist in nature. They pose entirely different categories of scientific problems and technological challenges.

The fission power reactor design approaches prioritized fuel utilization and energy efficiency at the beginning. As safety problems and accident consequences began to emerge and became better understood through experiments, tests, operations, and accidents, new safety and emergency response systems, containment structures, exclusion areas, and emergency planning zones were added and multiplied, regulations tightened, and public demands for safety of and oppositions to nuclear power grew.

The initial priorities, partly based on the mistaken assumptions about resource scarcity [2], and influenced by the pursuit of economies of scale in thermal power plants in that era [84], combined with the increasing demands on safety, created a feedback loop to increase reactor power and complexity with increased capital costs and construction times [4]. This has led to increasing price for nuclear power on inflation adjusted basis, which is unique among over 60 technologies studied with historical data [69]. Coal power price has been rising and falling in a flat range, the only other technology without consistently falling prices. This is a clear sign that nuclear power plants were being designed and built similarly as coal fired power plants, because they share many similar auxiliary systems and equipment.

The key difference is that the pursuit of economies of unit scale in nuclear disproportionally increases the complexity and cost due to increased safety risks and regulatory requirements. The difference in nuclear power price from all other technologies is that the large size and high complexity of monolithic plant make it only suitable for on-site construction, similar to coal power plant. All others are manufactured in factories, with predictable cost reduction with increasing production volume, following Wright's law, or sometimes cast in time and known as Moore's law [68].

The manufacturing sector has seen consistent productivity gains over the years, while the construction sector remained stagnant or in decline [11, 12]. In U.S., the productivity measured in gross value-added per hour worked in manufacturing is over 8 times higher in 2010 compared to 1947, overall productivity is over 3 times higher, but that of construction rose to near double before the 1970s, then decreased continually to no gain by 2010.

Such differences have not only led to increasing total costs for nuclear power, but distorted cost structure allocating resources to efforts and systems not needed in fundamentally safe reactors with standard designs. The increased safety impact and regulatory scrutiny force all other auxiliary systems and activities to become more complex and costly, even though such effects may not be apparent by only looking at the numbers. This has often led to a mistaken conclusion that since the explicit cost share of nuclear island is not dominant at about 28%, and that of reactor is even smaller, there is not much to gain by improving the reactors. Because nuclear reactors are at the centers of such power plants and the main source of energy and radioactivity, almost all materials, equipment, and systems become much more costly, often by a factor of several, even for lower functional performance or less advanced materials and components.

Estimates show that the cost of materials in a nuclear power plant is only a few percent of the capital cost. This is vastly different from most manufactured products, which can make up to 70% of the total cost, and indicates that nuclear power economics has a lot of space for improvements in a new paradigm.

Following paradigmatic questions and answers (not covered here, but basically around why we use civil nuclear energy, how best to avoid the known problems, and achieve market competitive economic efficiency with more deterministic safety), we arrive at a high level system solution architecture for resolving the seemingly intractable dilemma between nuclear safety and economics.

Advances in natural and artificial sciences can now improve nuclear safety at fundamental levels not possible or selected in the past. The much increased knowledge about reactor safety and accidents, fallibility of humans and institutions, and unacceptable consequences of catastrophic failures, coupled with general increase in risk aversion in modern societies, and emerging low-carbon energy technologies and systems, demand fundamental nuclear safety, as deterministic rather than probabilistic exclusion of large releases of radioactive materials.

Fundamentally, large amounts of concentrated and highly radioactive materials do not exist nor can they emerge naturally in Earth's systems and cycles. The extremely high density of nuclear energy based on strong and weak interactions present forces that chemically formed and bonded materials cannot resist or contain for long at high concentrations or in large amounts. We can and should use and contain them for peaceful purposes by distributing and diluting energy and radioactivity to levels that will provide useful work but not enough to breach containment in any scenarios with credible initiating events.

Nuclear power was first discovered scientifically, engineered technically, and utilized commercially in just a few decades in the early- to mid-20th century. The system, although fundamentally based on natural forces and laws, is almost entirely artificial, was designed and selected under time and need constraints with incomplete, sometimes mistaken, information and understanding. On the other hand, organisms, humans, and societies have not had enough time to evolve adequate coping strategies and mechanisms against high levels of radiation, nor have nuclear energy industry and institutions had much time to try and test sufficient combinations and configurations to become sustainably competitive and realize extraordinary potential.

Human reliability analysis, as a part of probability risk assessment (PRA) used and adopted by the nuclear industry and regulator (see, e.g., [85, 86]), shows that the failure probability from human factors is not insignificant, and can sometimes dominate the total probability when the plant's mechanical failure probability is designed to incredibly low levels (but not verifiable in the canonical scientific fashion but relying on trans-scientific judgment calls).

The very fortunate gift of nature that fission can start spontaneously under readily achievable conditions not only makes nuclear energy possible, but present a real threat from catastrophic accidents when sufficient fissile materials come together out of control. As a consequence, not only should we not allow radioactive materials to disperse and contaminate, we also have to ensure that fissile materials stay in subcritical conditions at all times unless under tight control and maintained at criticality during operations. This means we should not allow reactor cores to lose substantial structural integrity under any credible circumstances for peaceful uses. If such failures do occur in some designs of special purposes, e.g. compact systems for mobility, continued or extended uses of already built power plants, effective mitigation and full containment should be within design basis via thorough implementation and adequate margins and redundancy, relying on processes based entirely on irrefutable natural laws [87].

Based on the above considerations, safety levels of nuclear energy systems can be defined as follows.

Level I. Fundamental safety: no runaway chain reactions, no fuel or core damage, no large release of radioactivity, no radiological consequences outside plant. Or simply, reactivity and radioactivity safety are both deterministically assured by design at all times.

Level II. Radioactivity safety: no fuel melt, low probability of fuel damages, core damages, or core meltdown, no self-organized configurations for re-criticality, no large unmitigated releases of radioactivity, and limited radiological consequences outside plant.

Level III. Probabilistic safety: small probability of fuel and core damages, core meltdown, or large early releases, potential for BDBAs (beyond design basis accidents), with possible large scale releases of radioactivity and extensive radiological consequences outside plant (the safety level in the current paradigm).

From the perspectives of science and trans-science, or sciences of the artificial, we recognize that the high energy density of nuclear fuel and critical mass are given by nature, can be determined scientifically but cannot be altered, while the power density and total power of a reactor are artificial, and are of our choosing. We made some design choices in the past, and were able to make peaceful uses of nuclear power for a substantial share of low-carbon electricity for nearly three quarters of a century, accumulating all the knowledges and advances along the way. But experiences have shown those choices are no longer adequate or valid for our societies and markets at the present, nor for a more sustainable future.

We can and should make new and different design choices now based on the current states and foreseeable advances of natural and artificial sciences to keep up with major progresses and needs of our time. Given the constraints of time and resources, we should start with satisficing choices that can quickly revive civil nuclear energy with long runways and great expansion spaces ahead, set high expectations and aspirational goals, gather momentum and grow at scale with sufficient speeds for ambitious climate goals for the next several decades. We can then have more time and resources to further advance sciences, and engineer toward increasingly more optimized, comprehensive, and sustainable solutions step by step through innovative combinations.

This is a rational use of the Bayesian approach to update design choices based on discovery and revelation of new information. Unfortunately, the nuclear industry has been too conservative when faced with mountains of new evidence emerging constantly, and too slow to adjust designs to reflect new knowledge. The returns from many incremental and additive improvements have long diminished to none and turned negative.

A note of clarification is needed here in the choice of using fundamental safety rather than the commonly known and accepted term of inherent safety. A system or a process has inherent safety if it has a low level of danger if things go wrong. But what is a low level? We have seen reactor designs with extremely low probability of core damages and large releases of radioactivity that claim inherent safety. Apparently, asset losses or environmental degradations were accepted as low level dangers with such design methods. Fundamental safety, as defined above, clarifies that total asset losses and extensive radioactive contamination are excluded by design, and is achieved by ensuring integrity of structures and containment at the fundamentally smallest scale possible by carefully taking into account the fundamental interactions and forces at work.

5.4 A new paradigm with fundamentally safe and manufactured nuclear energy modules

This new paradigm will conduct specific tests and develop exemplar technologies and systems that answer paradigmatic questions, with new system perspectives and objectives, restructured configurations for reactors, plants, applications, industries, supply chains, and markets, and much expanded value propositions. They include:

(1) Robust fuels:

- containment integrity preserved under all reasonably conceivable upset conditions for most fissile materials and fission products, in cradle-to-grave forms to start if achievable;
- no credible mechanism or pathways for large leaks of radioactive materials in severe accidents.

(2) Meltdown-proof reactors:

- core integrity preserved under all reasonably conceivable upset conditions and credible initiating events;
- assured safety of public, environment, and assets;
- flexible operation with poly-generation capable of versatile applications to broaden market reach.

(3) Differentiated designs:

- minimized access to special nuclear materials and technologies, physically and institutionally;
- separate performance objectives suitable for civilian uses only, and exclusion of dual-use functions and features.

(4) Manufactured systems:

- standard modular designs suitable for serial or mass production, including broad sourcing of materials and components from general supply chains;
- modules made in factories, transported to and assembled on site with readily available equipment and infrastructure.

(5) Constructed systems:

- deterministic exclusion of failures to contain radioactive materials in all credible severe accidents (external containment as designed now, or source containment with new fuel forms);
- high-efficiency construction platform adopted with corresponding technologies, human capitals, institutions, and supply chains (full adoptions are tantamount to transforming construction industry into manufacturing industry).

(6) Products and services, or value propositions:

- flexible power, from baseload to peaking;
- industrial process heat, green hydrogen, desalination and others;
- daily, seasonal, annual, and decadal (as strategic reserve) energy storage.

The fundamental safety-based reactor design principles (in contrast to safety features added after design-to-failure-limit), based on the key differences of nuclear energy from chemical energy, can be outlined as:

- first, after reactor shutdown, residual heat can be removed indefinitely without damaging the fuel;
- second, reactivity coefficient is negative or close to zero in all operating and transient conditions;
- third, select safety levels acceptable to owners, users, investors, and applications.

Such adjustments imply the following:

- limit reactor power density and total power, decrease from the current levels;
- large power designs, with much relaxed core parameters, must assure inherent safety that cannot be compromised by malfunctioning equipment or human intervention;
- design, build, and operate reactors as power generators both during normal operations and after shutdown, and as energy storage systems with years or decades long lives, with attendant safety and utility considerations and measures.

The paradigm shift can lead to significantly reduced or eliminated risks, and improved benefits and rewards. Conventional nuclear power plants have very unfavorable financial profiles with large upfront capital costs, long times before revenues, and increasingly unprofitable margins when emergent competitions can lower costs predictably and quickly. Most importantly, their risk and reward profile is prone to Black Swan events, namely they have limited upside during normal operating periods, but very deep catastrophic downside that could far outweigh their total economic values.

New paradigm reactors designed to Levels I or II safety can invert that highly unfavorable risk reward profile. Their downside risks are limited to normal industrial incidents and damages, but their high reliability and stability in providing plentiful clean and low-carbon power, heat, propulsion, or hydrogen, with long-term energy storage built in, can generate very high rewards. Nuclear energy will transform from brittle and hard-to-use, to resilient and easy-to-use, eliminating the fat tail risk distribution leading to Black Swan accidents, and possibly become antifragile [88].

For instance, during natural disasters when other power plants, fuel supplies, or grid connections are disrupted and unavailable, or demands surge, new paradigm nuclear energy systems can provide essential power and heat because they can continue to operate for very long time due to extremely large amount of energy stored in loaded fuels, and proximity to end uses. In the global transition toward low-carbon energy, if divestures from and closures of coal or gas fired power plants gather momentum to pass beyond some tipping points, generations and supplies could collapse suddenly. New nuclear that is fast to deploy and flexible to operate can come in quickly to replace the heat sources and continue to use existing infrastructure to serve existing needs, preventing excessive stranded assets and unmet customer needs. In addition to studies in such prospects, NuScale Power and TerraPower (backed by Bill Gates and Warren Buffet) are both planning to deploy their new SMR designs to replace coal power plants or on former sites.

Borrowing words from Nassim Taleb, new paradigm nuclear energy systems have potential to be antifragile, able to gain from disorder.

Given the adjusted design principles with Level I or II safety, nuclear power plants can eliminate exclusion and emergency planning zone, and reduce safety boundaries to within plant facility. This reverses the historical trends of increasing power density and total power, or making reactors more compact, while adding and enlarging containment structure, exclusion areas, and emergency planning zones. These are two counter-acting design efforts and built systems that cancel each other out, a doubly wasteful endeavor. The new design principles will help align risk and reward distribution among various stakeholders — developers, investors, owners, and users, vs residents and businesses nearby, and general public. It also helps to restore effective surface power density of nuclear power, which is drastically reduced by need for large exclusion areas and emergency planning zones, to a point that is now below that of renewables.

For current and new power reactors in the near future, their designed power density and total power are too high to deterministically exclude core meltdown. However, their fuels can be replaced with robust containment of radioactivity, not mere accident tolerance, to improve safety from Level III to Level II. This will keep most existing nuclear power plants utilized to their full lifetimes, or extend operations more at lower costs in shorter times for necessary upgrade or replacement than currently possible.

Separation of performance objectives for civil nuclear energy can follow successful examples of other technologies. They include passenger vehicles vs armored vehicles, commercial airliners vs fighter jets, cruise ships vs aircraft carriers, launch rockets vs ballistic missile, etc. But as discussed previously, the prevalent commercial power reactors mostly were direct adaptations from military and production reactors, carrying significant security and proliferation risks in their designs. A clear separation should and can be implemented immediately going forward. In fact, it was explicitly called for by Eisenhower in his Atoms for Peace speech [59], "It is not enough to take this weapon out of the hands of the soldiers. It must be put into the hands of those who will know how to strip its military casing and adapt it to the arts of peace." We should all heed to this prescient call.

The nuclear materials are known for potential of dual uses. When they are designed into fundamentally safe reactors, they can generate clean electricity with no carbon emission, provide high quality process heat, and make green hydrogen, leading to peace and prosperity. But designed otherwise, they can suffer catastrophic accidents, produce radioactive used fuel not fully protected and contained, and leave opening for diversion and proliferation, leading to war and disaster. We can choose to design new civil nuclear energy systems in a new paradigm that ensures fundamental safety with manufactured systems to compete successfully in marketplaces.

6. Tests and predictions of the new paradigm

We are now equipped and ready to test the validity, efficacy, and efficiency of the new paradigm. We will use some newly completed and commissioned power reactors as test cases, and then rely on thought experiments and surrogate tests to make some predictions to be tested in the future.

6.1 Partial tests through practical experiences

First, Akademic Lomonosov floating nuclear power plant (FNPP) started in December of 2019 offers the most recent test for one type of SMRs. This one-of-a-kind plant (according to Rosatom) uses 2 KLT-40S reactors, 35 MWe each, developed and designed to provide heat and power, based on well-proven icebreaker reactors using ship-building technologies [89]. Rosenergoatom, the Electric Energy Division of Rosatom, is responsible for its implementation.

The two-circuit plant incorporates vessel-type PWRs with forced coolant circulation in primary loops. The fuel uses uranium enriched below 20% in dispersion smooth-pin type elements in zirconium-alloy cladding, and fuel assembly includes burnable poison (gadolinium) rods to compensate for excess reactivity early on. The core has negative power and temperature reactivity coefficients within the entire range of operating parameter variations during lifetime. The plant employs active and passive safety systems, including an electrically-driven automated system and a passive system using gravity to insert control rods into core in emergencies [90].

Given such design and safety measures with peer-reviewed probabilistic safety assessment, Rosatom claims that the chances of a serious accident happening to the FNPP are less than 10^{-7} per reactor-year, lower by 2 orders of magnitude from 10^{-5} accepted in the earlier plants.

The refueling interval is 3 years, and used fuels are stored in pools on deck. The whole plant will be towed every 12 years back to its construction wharf and overhauled. The service life is 35–40 years.

The total cost reportedly rose from an initial estimate of around US $232M to US $740M by 2015. Before construction began in 2007, the announced start date was October 2010. It was completed and transferred, towed 5,000 km via the North Sea Route to its final destination, a small Arctic port town of Pevek, and started in 2019. It will supply electricity and heat to settlements and mining companies in the Chukotka region.

Because of the severe overrun of budget and long delay of schedule, Rosatom has reportedly decided not to go forward with this design, and is considering a modified version of RITM-200, the icebreaker reactor. Is this a failed example of the new paradigm outlined here?

According to its design, KLT-40S has assured reactivity safety, but not deterministic radioactivity safety. It has Level II Safety as discussed previously. As such, hybrid redundant safety and emergency response systems and full containment are deemed necessary by Russian standards and IAEA recommendations.

It was built using ship-building technologies in a dedicated wharf, conceptually much more productive than construction on site. Yet the first plant suffered badly or worse in terms of cost overruns and schedule delays as many constructed monolithic plants. Are they first-of-its-kind problems or system design problems?

Upon closer examination and deeper thinking, we can find multiple significant inefficiencies in design and build. For a reactor of this power rating, hybrid redundant safety systems add too much in complexity and costs. It is possible that one passive safety system could be sufficient, as demonstrated by, at least conceptually, several PWR and BWR designs with much higher power ratings, such as AP1000, ESBWR, or NuScale SMR.

For a plant designed for stationary use, designing in a floating platform and local infrastructure constructed to prevent and reduce marine-based risks, added complexity and costs for functions hardly needed and rarely used.

Towing entire plant back and forth between build and use sites over long distances for refueling and overhaul will add significant logistic complexity, costs, and times, and potentially deprive customers of services for long periods of time. In a more specialized and efficient architecture, new and used fuels need to be transported, along with some components and supplies for operation, maintenance, and repair, but not the rest of plants. Therefore the functions and systems used for transportation and transit containment can be used to serve multiple plants and sites, increasing duty factors and reducing system costs.

Such inefficiencies with low to extremely low duty factors for costly transport and safety related functions and systems seem to have doomed the market prospects of such designs. Yet if we analyze this design in a new paradigm, we can also uncover substantial potential for improvement and growth, as demonstrated later.

Other notable industrial demonstration SMRs near completion of constructions are HTR-PM (HTGR) in China, and CAREM (integral PWR) in Argentina. They will provide additional tests soon. Construction of Linglong One small reactor, cooled by light water, has just started in China.

NuScale Power [91] received the first ever U.S. NRC SMR design approval for its plant. The power modules, based on advanced PWR technology and fuel, generate 77 MWe each in a 12-module plant for a total of 924 MWe. It will be first built in Idaho Falls in 2020s, with first power from first module in 2029. Since it is not yet built, it is premature to assess its economics. But similar analysis for KLT-40S can be applied in concept, and different conclusions may be drawn due to notable differences in design and implementation.

Second, AP1000 first started in 2018 offers a test case for a very different kind of modular plant design, which still relies heavily on construction on-site.

AP1000 is designed and marketed by Westinghouse Electric Company (see, e.g., [92]). It is a leading generation III^+ PWR with 1,117 MWe net power output, and improved use of passive safety and many design features intended to simplify design, lower capital cost, and improve economics. According to Westinghouse, AP1000 has up to 85% fewer components compared to its generation II PWR, and a theoretical maximum core damage frequency of 5.09×10^{-7} per plant per year.

In 2006, Chinese government selected AP1000 as its future national nuclear power plant model after a 2-year international bidding process. In 2008, construction of the first 4 units, 2 each at Haiyang and Sanmen, owned and operated by 2 national nuclear power companies, was started by Westinghouse and its Chinese partner, State Nuclear Power Technology Corporation (SNPTC). The first unit was to be completed by 2013 at that time.

A number of events and problems caused long delays and cost overruns, including the Fukushima nuclear disaster in 2011, and many issues typical of first-of-its-kind designs and megaprojects, including constant design changes, inexperienced workforce, not-yet-established supply chains, and malfunctioning equipment from scaling up far beyond experiences. The first unit was started in 2018, with a reported cost of US $1.46B over its original US $5.84B budget. In 2019, a second unit was shut down shortly after starting up due to malfunction of a reactor coolant pump. Such multitude of mishaps severely damaged the market prospect of AP1000, and many planned sites have switched designs.

Construction of four more AP1000 were started in the U.S. during 2012 and 2013, 2 each at Vogtle in Georgia and Sumner in South Carolina. Cost overruns and schedule delays eventually forced the owners to abandon the Sumner project in 2017. Estimated capital costs for the Vogtle project rose from the original US $14B to about US $25B in 2018. After repeated schedule delays, more delay was announced recently, pushing the completion time from the originally expected 2016 and 2017 to 2022. Westinghouse filed for bankruptcy protection in 2017 due to $9B losses from these 2 projects, and forced its parent company Toshiba to write off billions in losses and sell valuable assets and businesses.

The highly claimed passive safety system, simplified and modular design and construction of AP1000 have not revived the fortune of the existing paradigm of nuclear power. However, it does offer several valuable lessons in what a new paradigm must not do.

The AP1000 passive safety system is much improved over active systems in generation II designs. Yet its compact core design with high power density and total power leave little margin for error. The resources and efforts expended to enhance plant performance, especially in economics, are offset by more of the same used to prevent it from failures by being designed and operated so close to limits, and then mitigating and containing consequences if accident sequences become unstoppable. The 72 hours without need for operator intervention after accidents in AP1000 represent a tremendous improvement over the minutes or hours in older designs, yet an AP1000 could have failed or irreversibly damaged during Fukushima, when offsite power was not available for 11 to 15 days. This risk, embedded in designs with Level II or III safety, could be a trade-off based on potential benefits, and alignment among stakeholders. So far, it appears that this is not broadly accepted in marketplaces, but limited mostly to a few national government decisions, state-owned enterprises, or utilities in regulated markets.

Its modular design and construction have not been proven effective or efficient. In building complex systems necessary for general purposes with complex structures performing complex functions, modularity serves a valuable purpose to simplify and accelerate design and implementation by isolating sub-functions in modules with well-defined inputs, outputs, and interfaces. It is economically efficient if replicated and used many times.

In contrast, power plants perform relatively standard and very specific function to supply electricity, or electrons, normally over grid connections, which can be accomplished by many simple systems. Highly complex power systems are intrinsically not efficient because every component or system can create losses while adding costs. Very large power plants with large components cannot be manufactured in high volumes and shipped to most sites without large scale transportation infrastructure and means, and are not needed because of the total demand limitations.

When rapid replication in high volumes is not possible in reality, modular construction is reduced to building module factory on site, used only once or twice. It is highly inefficient and wasteful. Similar concepts have been tried in various countries by a number of companies, and evidence so far has been discouraging.

While such partial tests in practice have not proven the validity of the new paradigm yet, they do highlight some significant deficiencies of the current paradigm.

6.2 Wright's law and significance for the new paradigm

The effects of production volumes in manufacturing, and return-to-scale in generation systems on technical performance and economic efficiency can be assessed quantitatively using Wright's law and module or unit scale economy. It is briefly outlined and applied here, starting with production volumes.

During the 1920s, Theodore Wright, an aerospace engineer, found that for every cumulative doubling in the number of airplanes produced, manufacturers realized a constant cost decline in percentage term, or about 15% [93]. A key impetus for publishing the study, first started in 1922, was a sponsored program to develop a small two-seater plane that could be marketed at a very low price, assuming a quantity of ten thousand units could be produced. This, as we will show below, is a key insight and a basic law needed in a new paradigm for civil nuclear energy.

One variation of Wright's law, cast in time instead of production volume (mistakenly but applicable when latent demand far outstrips supply, and capital investment follows accordingly), became the most famous law to understand future. In 1965, Gordon Moore looked at the number of transistors on the circuits manufactured at Fairchild Semiconductors and noted that they had doubled in number every year. He predicted this exponential development to continue for at least 10 years, while halving computation costs for every doubling of transistor density. It became known as Moore's law, and has been in effect much longer. Since 1971, the number of transistors on a circuit has indeed doubled every two years, and went from 1 to an incredible 19.2 billion.

Wright's law can be expressed mathematically as

$$c = c_1 N^{-w}, \tag{1}$$

where c is cumulative average cost (or time) per unit; N is cumulative number of unit produced; c_1 is cost (or time) required to produce first unit; w is inverse slope of cost function in log-log graph, derived from reduction percentage per doubling, which is 0.15 for 10% reduction every doubling, and 0.23 for 15% reduction. For Moore's Law, halving cost for every doubling, $w = 1$. All cost numbers here are inflation-adjusted.

Now let us take the KLT-40S example, with specific capital cost c_1 = US \$10.57/W (\$740M/70MW). This is not competitive in current marketplace. But if the price target is set at \$4/W, similar to that of gas turbine power plants, it will become competitive because of the much higher duty factor (about 2 times) and low cost of fuel with very low share in total power cost, before carbon emission is even priced in. We can see how many units Rosatom needs to produce to break even and become profitable.

For simplicity, we will use static calculation of costs (all inflation adjusted) and returns to illustrate the main point, and select 10% cost reduction per doubling, conservatively at the lower end of range achieved in over 60 technologies.

Following Wright's law, by unit number 1,024, or after 10 doublings of production volume, the KLT-40S product line will become profitable with a cumulative average cost of US \$3.69/W, a 65% decrease from the starting cost. The total installed capacity would be 71.68 GWe, with a total cost of US \$264B, and a net profit of US \$22.5B. The cumulative losses would mount first, peak at unit number 256, US \$9.87B, then decrease quickly afterwards. A well-capitalized large corporation can realistically pull this off.

Applying the same to AP1000 in US, with c_1 = US \$11.19/W (\$25B/1117MW), breakeven would be reached by unit number 1,024 with a cumulative average cost of US \$3.90/W. So far this looks about the same to KLT-40S. However, the total installed capacity would be 1,144 GW or 1.144 TW, with a total cost of US \$4,463B, turning a total profit of US \$112B at 3%, and a peak cumulative loss of US \$234B by unit number 256. This may appear rather unrealistic even for the largest and wealthiest nations in the world. But a committed and sustained national or international decarbonization initiative can readily realize this, when trillions are at stake.

This scenario is improved substantially using the much lower cost achieved in China, with c_1 = US \$6.54/W. The total cost to reach 1,144 GW is US \$2,606B, with cumulative average cost US \$2.28/W, profit US \$1,969B at 76%, and cumulative loss peaked in unit 2, after a mere 1 doubling, at US \$3.474B — if this many plants can be sited, approved, and built.

In practice, learning cannot be consistently or broadly achieved in the current paradigm of construction. Cost reduction from learning and experience dissipate and disappear with new projects on different sites using different management and workforce. No one site can or should build and operate more than a few GW-class units, for safety concerns and regulatory restrictions, local oversupply and price depression, and heavy burdens and losses on transmission. Thus, even though cost reductions were achieved in a number of national nuclear programs and on multi-unit sites, for up to 20–40% in later units if constructed nearly in parallel with the same designs, economies of unit or construction scales have not been achieved historically in nuclear power industries worldwide. Such evidence also provides some basis for expected cost reductions in the new paradigm.

A more economical and likely more viable pathway may be producing and installing many more KLT-40S (after some improvement of total system efficiency). Extending Wright's law, by unit number 16,384, or after 14 doublings of production volume, the total installed capacity would reach 1,147 GW, similar to the AP1000 scenario above. The total cost, however, is nearly half as much at US $2,294B, with cumulative average cost of US $2.42/W, turning a total profit of US $1,814B, or 65%, a drastic improvement over the AP1000 pathway of only 3% profit by this point, reflecting much faster learning and improvement of much smaller units.

At this scale of deployment, probabilities of core damage accidents will become material. Using KLT-40S, with a 40 year service life each, 1,024 plants will accumulate 40,960 plant-years, and 4.1×10^{-3} accident for the entire fleet during their lifetimes. The source term is substantially smaller since each unit is only 70 MW, as opposed to the typical 1,000 MW commercial power reactors marketed and installed now. For 16,384 plants, the total probability of severe accidents increases to 6.6×10^{-2}, or 6.6%.

For AP1000, with a slightly higher core damage probability, a fleet of 1,024 reactors in 60 years of lifetime may have 3×10^{-2}, or 3% chance of severe accidents. The source term is much larger.

At these large numbers, if implemented and realized, the probabilistic safety assessment will be verified and validated more scientifically.

SMRs thus demonstrate substantial advantages of improving both safety and economics simultaneously for nuclear energy over large power plants, at substantially lower costs and higher profits, with higher system-level safety and much smaller accident consequences.

Extending this approach further, we will assess a pathway with 10-MW micro reactor (MR) plants. We will first give it a poorer start in economics, with $c_1 = \text{US}\,\$15/\text{W}$, but qualitatively different safety profile, with zero chance of core damage or large release assured by Level I fundamental safety through design. They can be deployed in single units, or large clusters, depending on local demands. There is no need for exclusion areas or emergency planning zones, even for very large plants with many modules — if no module needs them, then none are needed for any number of modules.

By unit number 114,400, or between 16 and 17 doublings of production volume, the total installed capacity is 1,144 GW, similar to the KLT-40S and AP1000 scenarios assessed previously. The total cost is US $2,943B, with cumulative average cost US $2.55/W, profit US $1,633B, at 55.5%, and peak cumulative loss US $14.5B at unit 2,048 after 11 doublings of production. Chances of severe accidents are zero. This has the potential to build up a great new industry with annual revenues over several hundred billions USD in under two decades.

If the starting point is improved to $c_1 = \text{US}\,\$10/\text{W}$, similar to KLT-40S and AP1000, through improvement after demonstration, then the outlook becomes much brighter still. The total capacity would still be 1,144 GW, but the total cost is dropped to US $1,962B, with cumulative average cost down to US $1.70/W, profit up to US $2,614B, at 133%, and peak cumulative loss of US $1B at unit 128 after 7 doublings of production.

If 15% cost reduction per doubling of production can be achieved, in the middle to high end of historically achieved range for other technologies of similar scale and complexity, then it becomes an energy miracle. The total cost to reach 1,144 GW capacity is further reduced to US $1,132B, with cumulative average cost down to US $0.65/W, profit up to US $3,444B at 304%, and a peak loss of only US $1.06B at unit 64 after 6 doublings of production. Timely decarbonizing majority shares of global economies in many sectors are within reach.

More detailed, systematic, comprehensive, and dynamic analysis can be performed following the approach outlined above. The overall qualitative conclusion is clear. A viable pathway for a global energy solution to mitigate climate change at scale and in time has emerged. It is enabled and manifested by mass manufactured modular systems designed with assured fundamental safety in a new paradigm for civil nuclear energy.

Such a new paradigm allows for much more rapid incorporation of advances in technologies and materials, much quicker entries into new applications and markets, and much faster and predictable reductions in costs and expansions of capacities. The smaller units allow all links in supply chains and infrastructure to establish, scale up in parallel and continuously, and benefit from positive and profitable reinforcement feedback loops. Simply put, it will grow and evolve an ecosystem organically. This could be truly a great innovation steered by proven effective and efficient laws in desired directions, yet engineered piecemeal for continued discoveries and advances to avoid potentially catastrophic disruptions due to inevitable problems and challenges arising from imperfect knowledge, limited skills, and human fallibility.

6.3 Incorporation of unit scale economies

We can further refine and improve several specific aspects and approaches in this new paradigm. We can assess two aspects in unit scale and design scope. To limit the scope of this review and treatise, we will focus on unit scale.

Economies of production scale have been pursued almost singularly at all costs for decades in all sectors of manufacturing. Wright's law and Moore's law clearly demonstrate that extraordinary power. But what sets the optimal or preferred unit scale?

In power engineering, if we view electrons as the unit of production from power plants, then it would seem logical and rational to build plants as large as possible. This makes sense when other limits are too far removed from constraining scaling up unit, for instance, available capabilities, capacities, resources, and infrastructure for manufacturing, supply, transportation, assembly, and construction; demand distributions and transmission losses; institutional and societal risk tolerance and acceptance; political wills and equity calculations, etc. There are intrinsic limitations on how far increasing returns to scale can go before diminishing and decreasing returns set it. In case of energy systems, acceptable levels of safety will also limit how large or powerful a system can or should be.

Within such constraints, there are basic scale economies stem from intrinsically scaled needs for materials. For thermal power plants, the central energy release and conversion reactions are volumetric, meaning that they occur throughout the volumes containing them. The surface to volume ratios are thus scaled with a 2/3 exponent in volume (or power) for spherical structures (tanks), and 1/2 exponent for cylindrical structures (cylinders, pipes). Such scaling leads to generalization of overall equipment cost

$$c_1 = c_0 V^s , \tag{2}$$

where c_0 is a coefficient specific to designs, V is the effective volume of equipment or system, and $s \approx 0.6$ is the scale exponent. This is known as the '0.6 rule' in engineering cost estimation [94]. For energy systems, this can be expressed as $c_1 = c_0 (P_{\text{unit}}/P_{\text{density}})^s$, where P_{unit} is power rating of each unit, and P_{density} is effective power density (averaged over entire unit volume, not just the energy release volume).

On closer inspections of industrial data, scale exponents vary from 0.21 to 1.26. Exponent less than 1 favors enlarging equipment or systems. Exponent at 1 indicates there is no scale benefit. Exponent greater than 1 means dis-economies of scale, favoring smaller equipment or systems. It is noted here that earlier steam turbines have a scale exponent far smaller than 1 (close to 1/4), leading to very strong incentive to build them as large as possible, and likely influenced the plant designs for coal and nuclear power heavily.

Based on historical data on capital costs of nuclear power plants, especially those of US and other developed countries, the exponent is greater than 1 [4]. This is empirical evidence that increasing power ratings of commercial power reactors had long gone over into regime of dis-economies of scale, in addition to increasing radioactive source terms and consequences during and after accidents. Earlier studies of economies of scale for U.S. firms producing electric power found that, while there were significant scale economies in 1955, the bulk of U.S. electricity generation was by firms operating in the essentially flat area of average cost curve by 1970 [95]. Pursuit of economies of scale had long reached limits both for technological systems and economic organizations.

There are some subtleties worth noticing. In contrast to volumetric reactions and corresponding technologies and systems, there are reactions taking place only or mostly at interfaces. Typical interfacial technologies and systems include filtration, evaporation, condensation, conduction, radiation, steam generation, photo-electric, electro-chemical, or catalytic processes underpinning photovoltaic cells, batteries, fuel cells, catalytic converters, superconductors, 2D displays, etc.

Reaction rates or throughputs in such systems are proportional to interfacial or cross sectional areas, and maximal scale exponent is 1. In practice, they are slightly smaller than 1 because of edge effects and need for structural support and protection, favoring larger units. Engineering and design for such technologies and systems focus on making nonfunctioning structures as thin as practical, and volumes (substrates) as small as possible, pushing scale exponent closer to 1. Again, an important limit here, especially in batteries and other energy storage and generation systems, is power density and its impact on safety.

It is also worth noting that since there is little economy of unit scale, many such technologies and products have relied on production scale to improve economics, and consistently, sometimes predictably (Moore's Law), achieved cost reductions and performance enhancement at the same time. The inability or no need to make very large units early on, or intrinsic market needs to make many small or right-sized units, helped such technologies to expand and evolve very quickly following a powerful Wright's law by replications on massive scales.

Things become more complicated and confusing when there are unit scale economies. Trade-offs are needed. Singular pursuit of economies of unit scale can be detrimental to the underlying technologies and systems [4]. It was found that the respective maximal installed unit size can predict market lifecycles for nearly all predominantly volumetric power generation technologies and systems, following logistic growth curves. This universal law gives us a quantitative tool to spot trends and predict future development [84].

For thermal power systems, besides chemical or nuclear reactions taking places in volumes, heat exchanges and steam generations take place mostly at interfaces. If volumes (correspondingly power density and total power) are too large than available surfaces, systems will overheat and fail. Volumetric energy systems are intrinsically limited in unit scale as well, not always the larger the better.

Within limits imposed by safety, manufacturability, transportability, or constructability, empirical data show varying exponents, often rising when unit scale increases. This indicates that there is diminishing return with increasing scale, and there may be some unit scale for better economics and improved safety. This consideration is different from right-sizing, which is choosing unit scale based on end uses.

Thus, unit scale exponent can vary in a range, and is not always much smaller than 1 which favors scaling up.

We can now combine unit scale and production volume to assess and predict optimal or superior pathways. The total cost of producing a design to achieve a total power capacity target P_{total} is $c_{\text{total}} = c N_{\text{total}}$, where $c = c_1 N_{\text{total}}^{-w}$ is cumulative average cost per unit; $c_1 = c_0 V^s$ is the cost of first unit based on scale economics; and $N_{\text{total}} = P_{\text{total}}/P_{\text{unit}}$, $V = P_{\text{unit}}/P_{\text{density}}$, where P_{density} is effective power density of entire plant (not just the reaction volume, see below).

Substituting in Wright's law and scale economies, we can derive the following scaling laws for the total cost:

$$\begin{aligned} c_{\text{total}} &= c_0 V^s N_{\text{total}}^{-w} N_{\text{total}} = c_0 \left(\frac{P_{\text{unit}}}{P_{\text{density}}}\right)^s \left(\frac{P_{\text{total}}}{P_{\text{unit}}}\right)^{1-w} \\ &= c_0 P_{\text{density}}^{-s} P_{\text{total}}^{1-w} P_{\text{unit}}^{-1+w+s} , \end{aligned} \tag{3}$$

and cumulative average cost:

$$c_{\text{avg}} = \frac{c_{\text{total}}}{N_{\text{total}}} = c_0 P_{\text{density}}^{-s} P_{\text{total}}^{-w} P_{\text{unit}}^{-1+w+s} . \tag{4}$$

It is useful to transform Wright's law into time domain to help solve time-constrained problems, such as reaching certain climate goals by mid-century.

To highlight the key dynamics in the simplest terms, we assume a constant growth rate g for production volume and installed capacity over time with a fixed unit size P_{unit}, which underpins exponential growth, $N(t) = N_0 \exp(gt)$, where N_0 is the starting number of units. Assuming Wright's law is in effect from the first unit in an explicitly designed and constructed manufacturing paradigm, $N_0 = 1$. The cumulative average cost is:

$$\begin{aligned} c(t) &= c_1 N^{-w}(t) = c_0 V^s \left(N_0 \exp(gt)\right)^{-w} \\ &= c_0 \left(\frac{P_{\text{unit}}}{P_{\text{density}}}\right)^s \exp(-wgt) = c_0 P_{\text{density}}^{-s} P_{\text{units}}^{s} \exp(-wgt)\,, \end{aligned} \tag{5}$$

$$\begin{aligned} c_{\text{total}}(t) &= N(t)c(t) = c_1 N^{1-w}(t) \\ &= c_0 P_{\text{density}}^{-s} P_{\text{unit}}^{s} \exp\left[(1-w)gt\right]\,, \end{aligned} \tag{6}$$

$$P_{\text{total}}(t) = N(t)P_{\text{unit}} = N_0 \exp(gt) P_{\text{unit}}\,. \tag{7}$$

To reach a total installed capacity goal P_{total} in a fix period t_{p}, $N_{\text{total}} = P_{\text{total}}/P_{\text{unit}} = N_0 \exp(gt_{\text{p}})$. It follows then the growth rate is

$$g = \frac{1}{t_{\text{p}}} \ln\left(\frac{P_{\text{total}}}{P_{\text{unit}}}\right), \tag{8}$$

$$\begin{aligned} c_{\text{total}}(t_{\text{p}}) &= N(t_{\text{p}})c(t_{\text{p}}) = c_0 \left(\frac{P_{\text{total}}}{P_{\text{unit}}}\right)\left(\frac{P_{\text{unit}}}{P_{\text{density}}}\right)^s \\ &\times \exp(-wgt_{\text{p}}) = c_0 P_{\text{density}}^{-s} P_{\text{total}}^{1-w} P_{\text{unit}}^{-1+w+s}\,. \end{aligned} \tag{9}$$

This last expression for the total cost is the same as the one derived before (Eqn (4)).

6.4 Power and efficiency of the new paradigm

Now, keeping in mind that $s > 0$, and $w > 0$ for cost reduction as production volume increases in most cases ($w < 0$ for historical capital costs for nuclear power plants), it becomes clear that:

(1) higher effective power density for unit (not just in reaction volume), subject to safety constraint, lowers total system and average cumulative unit costs — economies of power density;

(2) higher total power target, subject to balance with needs, lowers average cumulative system cost (with exception for past and current commercial nuclear power plants, constructed and not manufactured) — economies of production volume or target scale;

(3) in open-ended growth of fixed unit size at a constant growth rate g, cumulative average cost decreases at a rate of wg, while the total production cost growth rate is $(1-w)g < g$ for $w > 0$, below production growth rate (with exception for past and current commercial nuclear power plants, $w < 0$) — economies of learning and experience;

(4) effect of unit scale on total system and cumulative unit cost depends on exponent $-1 + w + s$:

(a) if $-1 + w + s > 0$, then smaller units cost less — dis-economies of unit scale;

(b) if $-1 + w + s = 0$, then all unit sizes cost the same — Scales (unit-scale & production-volume) invariant economies;

(c) if $-1 + w + s < 0$, then larger units cost less — economies of unit scale.

The general relationship between unit scale (US) and production volume (PV), with associated geometric scaling exponents, are shown in Fig. 5. It is important to note that these quantitative relationships should hold for the majority of manufactured products and systems, and are not limited to nuclear energy. The fastest growing technologies and industries reside in the area where economies of production volume dominates. Other successful technologies and industries reside in the areas where economies of unit scale prevails while also benefiting from economies of production volume. Unfortunately, conventional nuclear power plants are outside these areas with $w < 0$ (increasing cost with rising production or construction volume) and $s > 1$ (higher specific cost for larger unit). This singular anomaly can be corrected in the new paradigm outlined here.

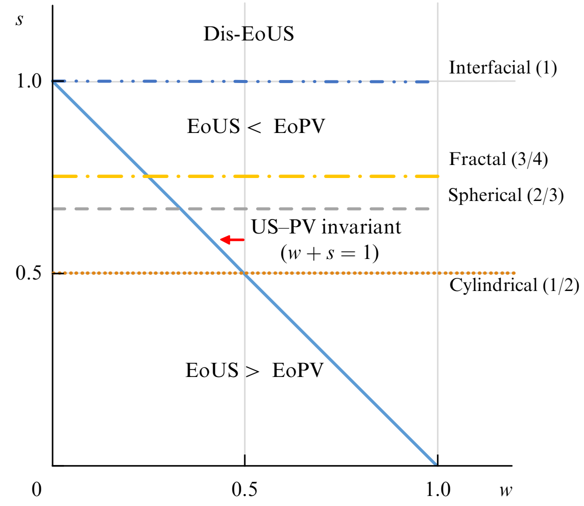


Figure 5. Exponent phase-space for unit scale s and production volume w. Area above $s = 1$ has dis-economies of unit scale (dis-EoUS); line $w + s = 1$ is scales invariant (unit-scale and production-volume); in area above scales invariant line and below $s = 1$, economies of production volume dominates over economies of unit scale (EoUS < EoPV); in area below scales invariant line and s = 1, economies of unit scale dominates over economies of production volume (EoUS > EoPV). Geometric scaling exponents are $1/2$ for cylindrical shape; $2/3$ for spherical; $3/4$ for fractal (volume-filling and scale-invariant); and 1 for interfacial.

Other costs of energy systems, including that for fuels, fixed and variable operation and maintenance, and potentially carbon emissions, need to be incorporated to get the full picture. However, the above scaling argument can help bring the key issues more into scientific domain based on first-principles and universal laws in artificial systems. It is particularly applicable to nuclear energy systems since fuel cost shares are very low. Only under one particular condition (4c) can economies of unit scale be realized on production volume level over time.

For a generic energy system following the 0.6 rule, or $s = 0.6$, $-1 + w + s = -0.4 + w$. If $w = 0.4$, or 24.2% cost reduction per doubling of production, which is quite high and difficult to achieve in practice for large systems, then all unit size would cost the same. Most likely, $w < 0.4$, $-1 + w + s < 0$, then larger units cost less and are more economically efficient based on capital costs.

But since exponent w has been achieved consistently in the range of 0.15 to 0.23 or higher, or cost reductions of 10% to 15% or more per doubling of production, $-1 + w + s = (-0.85 \sim -0.77) + s$. For $s > 0.77 - 0.85$, which has been observed in historical data from nuclear power plants, $-1 + w + s > 0$, then smaller units will be more economical (and safer as well). In fact, in generic thermal power systems where energy release and transport are volumetric, but heat exchange, steam generation, condensation are interfacial based, the compound exponent is closer to 1 than 0.6, then smaller systems are more economical in general.

If $s = 1$, meaning no unit scale economies, then $-1 + w + s = w > 0$, and smaller units cost less overall. The gain comes purely from learning and experience through replication in production.

For power systems with unit scale exponent s ranging from 0.6 to 0.77–0.85, cost reduction via increasing production becomes the deciding factor — more cost reduction favors smaller systems, less cost reduction favors larger systems. In any case, it rests on trade-off and balance, rather than going only one way.

System-wide optimized natural and artificial networks that transform and transport energy have the scale exponent of 3/4, corresponding to fractal-like space-filling networked structures as explained by theories from West and Bejan [28, 29]. Then $-1 + w + s = -0.25 + w$, and the demarcation boundary is $w = 0.25$, or 15.9% cost reduction per doubling of production volume. Economically, if production can be improved to achieve more than 15.9% cost reduction per doubling, then the smallest units limited by underpinning technologies are overall more economically efficient.

Extending such optimization to entire manufacturing ecosystems, and considering production costs as manifested values of embedded energy, resource, and information during transformation and transportation, then efficiency gains in scale will naturally lead to corresponding cost reductions. Such systems are self-similar across all scales, which would lead to $-1 + w + s = 0$. Since $s = 3/4$, then $w = 1/4$, the same as the allometric scaling properties observed and derivable from network and constructal theories. They have constant returns that enable and support exponential growth, with no singularity at finite time, and are infinitely sustainable if available space and energy for growth is infinite. It is, in this respect, optimal allocation and distribution of resources, functions, performances, and imperfections. In reality, all systems capable of evolution are dynamic, with spatial or temporal dislocations and distortions driving constant improvements and re-allocations among all possible configurations at all scales, in competition with other systems.

This illustrates that under the ultimate constraint of energy conservation, all aspects of matter (resources) and information (economics) need to be included in full system description and global optimization. When some aspects are limited for the moment that constrain the overall system, then optimization will lead to hierarchical structures and processes that are topologically static and scale range limited, thus unsustainable for intelligent systems or species, becoming evolutionary dead-ends. In such closed systems, optimization is limited to more uniform distribution of imperfections across scales, and opportunities for system-wide improvement are scarce. Local optimizations are pursued instead, which often lead to system inefficiency when some components or subsystems are optimized at excessive expenses of others, distorting resource allocations. There are possibilities and spaces to grow by extending downward in scale into smaller and smaller scales, but the abilities of such system to perform work at larger scales may diminish because more internal structures and processes at smaller scales may use more energies and resources to sustain. Ultimately, downward scaling is limited because it will become so far removed from human scale that it becomes useless or meaningless. Symmetry breaking emergence will, over the long run, scale upward and outward, in particular for human interests and values.

In open systems where limits are removed or pushed far out, efficient systems are still hierarchical, but they are dynamic and all scales can improve and evolve simultaneously. Local over- or under-optimizations can be adjusted for overall optimization and improvement of system, instead of distributing imperfections across scales.

It follows then during earlier stages of (near) open-ended growth, since smaller units can generally have higher growth rates through faster learning and expansion of mass production, they can overtake larger units in total capacity in time — the larger the difference in growth rates is, the shorter the time it will take. This is being demonstrated in real time by explosive growths in solar and wind energies (wind turbine has strong economies of unit scale, so its growth has been benefitted from both economies of unit scale and production volume).

There is another potentially very important scaling to assess, the total resource requirement. For simplicity, we will assume that materials used are proportional to total structures, hence scale similarly to costs. It follows then,

$$M_{\text{total}} = M_{\text{unit}} N_{\text{total}} = m_0 \left(\frac{P_{\text{unit}}}{P_{\text{density}}} \right)^s \frac{P_{\text{total}}}{P_{\text{unit}}} = m_0 P_{\text{total}} P_{\text{density}}^{-s} P_{\text{unit}}^{s-1} \,. \qquad (10)$$

The advantage of having high power densities for reducing resource needs, hence impacts on environment, becomes clear, and quantifiable. This power density, however, is the effective density averaged over entire space or area occupied for power generation, and is not the density of fuel, core, or boiler. Here M can be interpreted as either materials used, or land occupied, or some appropriate combinations of both.

This is why nuclear energy systems must reduce or eliminate exclusion areas. Kashiwazaki-Kariwa Nuclear Power Plant in Japan, the world's largest, has an effective surface land power density of 1,130 W m^{-2}, from 8 GWe total power over 1.5 km radius exclusion area. This is about the same as solar irradiance on top of Earth's atmosphere, at 1,361 W m^{-2}. If emergency planning zones of 10 miles radius, or 16.1 km, are included, the density will drop by another 116 folds to a mere 9.8 W m^{-2}. This is on par with large hydropower, but much lower than commercial solar PV, already achieved 175 W m^{-2} peak electric and still increasing. The comparison is improved substantially in favor of nuclear when capacity factors, grid stabilities, supply reliabilities, and energy storages are taken into consideration, but still not superior.

A brief excursion here is taken to illustrate this effect with the historical precedents. The estimated maximum energy efficiency of photosynthesis is 26%, which is nature's way to capture, use, and store solar energy. But actual percentage stored in total dry biomass is much less, and 1–3.5% is exceptionally high. This sets the level of surface power density received by and stored in biomass at about 11 W m^{-2} at the very high end. In reality, annual biomass yield is approximately up to 60 MJ m^{-2}, or 1.9 W m^{-2} thermal power if released over the same time (at the same level of current global radiative forcing). Most of the solar energy captured is utilized to grow and maintain the biological systems.

In contrast, a coal seam with average thickness of 15 m and recovery rate of 95% has 400 GJ m^{-2} of stored energy. If it is extracted and used to generate power in 1 day, it is 2.4 million times more power intense than biomass. This kind of orders of magnitude increases of available fuel sources, and corresponding reductions in land uses and much higher energy intensity are the fundamental key factors that enabled and supported the First and Second Industrial Revolutions. They pushed the proven energy resource limits out by several orders of magnitude (conservatively at two orders based on proven reserves at current consumption level, three orders or more than pre-industrialization levels), increased the intensity by several times for heating (compared to biomass), several hundred thousand to million times for propulsion (compared to bio, hydro, and wind), enabled powering increasingly more aspects of economies and societies with electricity, and reduced direct impact on environment by hundreds of times in today's energy intensive economies, using over 30 times more total energy globally than at the beginning of 19th century.

Utilization of such vast stores of highly concentrated and intense energy in fossil fuels required and allowed for corresponding large scale centralized exploration, extraction, transportation, processing, and distribution. End uses can be supported with large scale networks of roads, railways, electric grids, gas pipelines, oil tankers, and fueling stations. Scale economies and network effects are large and apparent in such a total system architecture. Fossil energy industries and ecosystems are very effective and efficient, until wastes and emissions begin to distort and damage Earth's systems and cycles. Because using fossil fuels has turned human's energy system into a terra-based closed system, the earlier advantages and economic values are quickly turning into severe disadvantages and liabilities with existential consequences, including climate crisis. In any closed systems, orders will gradually disintegrate and disorders will eventually prevail. Closed systems cannot be sustainable.

Turning back to using renewables such as solar, wind, hydro, and biomass solves the closed-system problem. The modern versions of renewables are substantially more efficient than the natural renewables of the past. In particular, solar photovoltaic has the highest efficiencies in capture and conversion of solar energy into electricity, the most efficient and clean form of general power. This is possible because transformation and transport take place at surfaces of functional materials at microscopic level through fundamental electromagnetic interactions without going through myriad emergent phenomena and systems. Solar PV is likely the most sustainable because it has the least overlap with Earth's systems and cycles of biological importance, especially if surface land use is reduced by combining with other necessary uses. It is in essence the direct capture and conversion of solar fusion energy without the need to create and maintain fusion reactions.

Wind, hydro, and biomass are secondary and tertiary transformation and transport of solar energy, and are much more tightly coupled to Earth's systems and cycles, thus their impacts can be substantial at large scales, which may lower their potential for sustainability. This is not only evidenced by the results from large scale uses of hydropower with negative local impacts on ecosystems and weather over long terms, deforestation for fuel and food (bio-energy) production in pre-industrialization societies, but it is also supported by the fact that solar PV had been first used in space. The ability to use some energy in space is an ultimate test and true indicator that it is not tightly coupled to Earth's systems and cycles, thus much more sustainable. However, mere sustainability of this kind is not sufficient for developing economies and societies. Energy intensity matters — higher intensities enable structures and processes that are impossible at lower intensities, creating possibility and potential for transcendence.

For systems with scale economies, $s < 1$, larger units do save more resources. It is not always economically more efficient system-wide as discussed previously. There is a need for trade-offs in the near term under certain constraints of resource availability and impact extent, especially in a closed system when energy sources and materials are mostly internal to Earth's systems and cycles important to life. Such constraints can be reduced or removed if energy sources and materials are mostly external, and sufficient energy returns on investments can be used to close material cycles for energy production and consumption, and keep them separate from systems and cycles essential to life. In that case, smaller energy systems, subject to lower limits set by underpinning technologies themselves, can be more economically efficient from system perspectives, which may sometimes differ from unit perspectives.

Thermal power systems can achieve higher efficiencies and lower losses in larger systems, since heat is an emergent phenomenon, and power generation involves energy release through reactions, transfer, and conversion. This factor favors larger systems, in particular when fuels comprise large fractions of costs and wastes (including emissions). This, however, has not been the case for commercial nuclear energy, and cannot be for the safety and economic reasons presented here.

In any case, thermal power systems are not always the larger the better in generating units. Because of inevitable losses in transmission and transformation for distribution and utilization, there are system constraints that need optimization to uniformly distribute uses, losses or inefficiencies across all scales, which will determine the proper unit scale.

For comparison across different energy systems, especially upfront capital intensive ones, including duty or capacity factors in the above relations will reveal another aspect affecting economic and resource efficiencies. Since the economic values are directly proportional to such factors, they inversely affect costs. We can include them in costs to obtain effective costs, as $c_{\text{eff}} = c/DF$, where DF is the duty factor (or capacity factor). Higher duty factors lead to lower effective costs.

There is another important system level efficiency needed for accurate comparisons. For a model system with N independent functional modules (not coupled modules with different functions to complete overall system function, as a monolithic system), if duty factor for a single module is DF_{unit}, the system duty factor can be higher if scheduled outages can be coordinated so only a small number $n < N$ are offline at any time. The effective system duty factor is

$$DF_{\text{eff}} = \frac{NP_{\text{unit}} - n(1 - DF_{\text{unit}})P_{\text{unit}}}{NP_{\text{unit}}} = 1 - \frac{n}{N}(1 - DF_{\text{unit}})\,. \tag{11}$$

If $N = n = 1$ (single module, or monolithic), $DF_{\text{eff}} = DF_{\text{unit}}$. If $N \gg n$ (large clusters of reliable modules), $DF_{\text{eff}} = 1$.

Small reliable modules are thus more efficient and available than large monolithic units. This conclusion is only applicable to dispatchable generation modules. It does not apply generally to solar or wind systems where duty factors are mostly determined by nature based on availabilities of respective driving forces, and not by design. In such cases, duty factors can be decomposed into two — one on availability of external drive, one on availability of individual unit, and used for comparison accordingly.

A note here is needed to allay potential concerns about applying such scaling methodology to the design and construction of a new paradigm of energy systems. There are multiple aspects to cover for a comprehensive scientific resolution. For general interest of this readership, some perspective and insight from leading physicists may help clarify the applicability.

Professor Robert B. Laughlin, winner of Nobel Prize in Physics, and Professor David Pines, a visiting scholar at Los Alamos National Laboratory and an external professor of Santa Fe Institute among his illustrious career, wrote in an influential paper critiquing The Theory of Everything, "The emergent physical phenomena regulated by higher order principles have a property, namely their insensitivity to microscopics, that is directly relevant to the broad question of what is knowable in the deepest sense of the term" [96].

In fission chain reaction, typical prompt neutron lifetime is on the order of 10^{-4} s for thermal (slow-neutron) reactors, and 10^{-7} s for fast reactors, with corresponding mean free path from 0.02 cm to 2 cm. Within that temporal and spatial scales, MeV and higher level nuclear energy is converted into eV and lower level thermal energy. The emergent phenomena and properties of fission reactors on larger scales do not depend sensitively on the microscopics of fission reactions and properties, with many orders of magnitude scale separations. Specifics of nuclear reactor physics and reactor engineering, and associated thermal hydraulics can be found in representative monographs of leading scholars [97–99].

These results, condensed by the scaling forms combining scale economies of unit and production volume with duty factor explicitly included, comprise the general predictions of the new paradigm. They are already testable in some aspects using examples from other technologies and industries, and can be specifically tested when some SMRs and MRs go into commercial production and deployment in the near future. It is to be noted here that such laws and predictions are based on and used for the artificial, and will only be realized if human efforts are expended to implement and deliver solutions in such system-wide optimized approach. They will not occur naturally. If not implemented accordingly, the results can be suboptimal. The stagnation and decline of the current civil nuclear power, while not providing positive tests of the new paradigm predictions, nevertheless have provided ample evidence over decades that significant deviations from such laws and principles can lead to failures in marketplace over time.

6.5 Generation unit scale limited by inherent safety

Next, we will use the same scaling method to establish some relationships within and safety-based limits on energy systems.

For simplicity, spherical systems are chosen for illustration. Cylindrical systems follow similar scaling. Keep in mind that analysis performed below can be applied at any levels in hierarchical energy systems. If such scaling fails at some levels in some systems, it usually signals that there are system deficiencies or distortions that can be improved or corrected.

Assuming a uniform power density $P_{\text{coredensity}}$ (different from the effective P_{density} used before) in a sphere for reaction (chemical or nuclear) to convert energy stored in fuel to heat, and isotropic heat removal to outside, the temperature distribution in sphere is simply $T(r) - T(0) = -(P_{\text{coredensity}}/6k)r^2$, where r is the radial coordinate and $r \leqslant R$, the radius of sphere; and k is the effective thermal conductance. Heat transfer may be through conduction, convection, radiation, or combinations of any.

In operating systems, thermal energy is actively removed and interface temperature is controlled at fix values. Then in the center of sphere where temperature is maximum, $T(0) = T(R) + (P_{\text{coredensity}}/6k)R^2$, $T(R) = T_{\text{coolant}}$ (all notionally for simplicity), which is usually maximized to increase thermodynamic efficiency of conversion cycle.

To keep $T(0)$ below the failure limit of fuel or structural materials with some margin, or $T_{\max}$,

$$P_{\text{coredensity}} R^2 < 6k(T_{\max} - T_{\text{coolant}})$$

or

$$P_{\text{unit}} = P_{\text{coredensity}}\,\frac{4}{3}\,\pi R^3 < 8k\pi R(T_{\max} - T_{\text{coolant}}) = p_0 V^{1/3} \Delta T_{\max}\,. \tag{12}$$

This means that as the system total power increases, the radius of sphere needs to increase proportionally to keep the same margin to failure. Conversely, if the physical size is kept the same as total power increases, then margin of safety decreases. Since higher T_{coolant} can provide higher quality heat or thermal to electric conversion ratio, increasing $T_{\max}$, or improving fuel (including its containment, whether encapsulation or cladding) robustness at high temperature, can raise safety limits for power density and unit power.

More nuanced analysis to include dependence of k on power when highly turbulent forced circulation is the main heat transfer mode appears to reach a similar conclusion. It makes sense that if such scaling is effective at the smallest scale, where conduction is the only heat transfer mode, then optimized hierarchical networks should have the same or similar scaling for entire systems to be scale invariant, or most efficient overall [28, 29].

This scaling has some critically important implications. On a unit level, $c_1 = c_0 V^s$, $s = 0.6 - 1$ for well-designed systems, $P_{\text{unit, max}} = p_0 \Delta T_{\max} V^{1/3}$, then the specific capital cost $c_{\text{p}} = c_1/P_{\text{unit, max}} = (c_0/p_0 \Delta T_{\max}) V^{s-1/3}$. Since $s - 1/3 > 0$, this requires minimizing volume or unit power to minimize specific cost for each type when all other factors are kept the same. This is when safety and economics can be optimized or satisfied at the same time. There are some limits on how small systems can go based on technical feasibility and necessary basic needs, which are not covered here.

The specific capital cost is inversely proportional to $\Delta T_{\max}$, implying fuels with higher failure temperatures can lead to lower costs and better economics.

If under any credible conditions, whether in normal operations, transients, abnormal or accident situations, $P_{\text{unit}} > P_{\text{unit, max}}$ may last long enough to damage or fail fuel, core, or vessel, then additional safety and emergency response systems, and containment (SERSC) will be needed. These are in essence, added equipment and systems of very low duty factors at the best, thus economically inefficient, or in some accident scenarios, can impede access and prevent more effective and efficient mitigation. Such are the designs and states of past and present commercial power reactors. It is much better to avoid such conditions in designs to start with.

This particular point needs to be further analyzed for nuclear energy. Unlike other energy systems, when fission chain reactions are stopped in a nuclear reactor, fission energy release drops off immediately, but substantial decay heat will be generated and last for very long times. Because nuclear fuels have over 100,000 times higher energy density than chemical or fossil fuels, even minuscule fraction of that energy released over long time can accumulate to extraordinary amount.

To put such statements in more quantitative terms, we will use the Wigner–Way formula for decay heat rate and integrated thermal energy. Note it is based on statistical approximation and only useful for decay times for a few days or shorter. It is very conservative for longer decay times, substantially underestimating total decay heat:

$$P_{\mathrm{d}}(t) = 0.0622 P_0 \left[t^{-0.2} - (t_0 + t)^{-0.2} \right], \tag{13}$$

where $P_{\mathrm{d}}(t)$ is thermal power generation due to beta and gamma rays; P_0 is thermal power before showdown; t_0 is time, in seconds, of thermal power level before shutdown; t is time, in seconds, elapsed since shutdown.

Decay heat immediately drops to 6.22% in one second after shutdown, and continues to decrease to below 1% over an hour. While this may seem small in comparison to full power, it is not insignificant for large power reactors. For instance, a current 1,000 MWe or 3,000 MWth reactor will generate over 180 MWth at one second after shutdown, and over 30 MWth after one hour. These are much larger than most diesel power generators, and it is why multiple of them are needed on-site in case of emergencies or accidents.

Even more extraordinary is that over days to months, cumulative decay heat can add up to a few to tens of thousands seconds equivalent thermal energy generated by the full power reactor. If there is not sufficient heat removal or leakage, this will melt not only metals but also ceramics. In Fukushima, most emergency diesel generators and their fuel tanks were washed away by tsunami, causing three reactors to melt down within a few days, even though they were shut down automatically during the earthquake.

Such catastrophic disasters can be deterministically eliminated by designs that limit power density and total power. These designs will not need multiple trains or layers of redundant SERSC, and are able to improve nuclear energy safety and economics simultaneously.

To design reactors that are walk-away safe indefinitely, there are several distinctly different directions and pathways besides limiting power density and total power. Some involve assured retention of coolants, e.g. in pool-type reactors, and structurally enhanced natural convection driven decay heat removal into surroundings, or very large thermal masses or supplies of water to cool and evaporate as heat sinks. Some select coolants with low stored physical or chemical energy to limit complication and amplification of accidents. Others use coolants with relatively low cooling capacity, so losses of coolant circulation power or even coolants after reactor shutdown cannot cause excessive overheating and meltdown. There are also designs using liquid fuels so they are molten to start with. Relative advantages and disadvantages depend on specific designs, purposes, and performances in practical implementations.

For reactors that cannot be walk-sway safe indefinitely on their own, they should be designed with passive decay heat management equipment and systems to handle post-shutdown times as if they were active power systems with lower output. Hopefully, the additional complexities and costs can be offset by other improvements and savings. This is not the optimal entry design, unless additional SERSC are mandated by regulations despite of the fact that none is needed in fundamentally safe systems anyway. It could become a slippery slope.

If existing and emerging designs can be assessed and implemented from the new paradigm perspective, then more effective and efficient combinations can be explored and tested with smaller quanta of investment, shorter periods of development, and substantially higher returns and larger contributions when successful designs are selected through competition and optimization, guided and assured by universal laws governing nature and the artificial world. At the beginning of the first nuclear era, there was an explosion of ideas and approaches, resulting in the fastest entry and establishment of an entirely new source of primary energy in human history. A second nuclear era with deterministic fundamental safety and competitive market economics will be a giant leap forward.

6.6 More tests and realizations through emerging SMRs and MRs

In 2010, there were more than 12 leading SMR designs around the world, including 6 PWRs, 3 HTRs, and 4 LMRs [6]. Of these early SMRs, KLT-40S has been realized, HTR-PM and CAREM are near completion, and NuScale SMR received NRC design certificate and will start construction in a few years. Some larger ones were canceled, e.g. mPower, PBMR, or put on hold.

Cancellations and slow progress on large SMR designs provided partial proofs for new paradigm predictions. These designs, with unit power ratings in or over 300–450 MWe range, are still mostly in construction paradigm, and very difficult to gain substantial advantages from much more efficient manufacturing paradigm. They do not have Level I fundamental safety by design, so regulatory requirements are not qualitatively different from those for very large monolithic plants. Their entry investments are large, development periods long, market potential limited, and economic competitiveness lacking, thus are examples that a new paradigm should avoid.

By 2020, there are over 69 SMRs and MRs, including 25 land-based PWRs, 6 marine-based PWRs, 11 HTGRs, 11 FRs, 10 MSRs, and 6 MRs [5]. They are being developed and demonstrated all over the world (Fig. 6), with a rich diversity that signals potential for breakout growth and expansion in the near future.

Several companies have publicly announced development plans and projects for micro reactors (MRs) under 10 MWe by IAEA classification. Oklo, a U.S. startup, submitted an application to U.S. NRC in 2020 for a custom combined license for its 4 MWth, 1.5 MWe compact fast reactor, Aurora [100], to be first built and operated at Idaho National Laboratory. Global First Power in Canada, a joint venture between Ontario Power Generation and Ultra Safe Nuclear Corporation (USNC), has advanced a 15–30 MWth, 5–10 MWe micro modular reactor (MMR) project to environmental assessment and host agreement at Chalk River, a site owned by Atomic

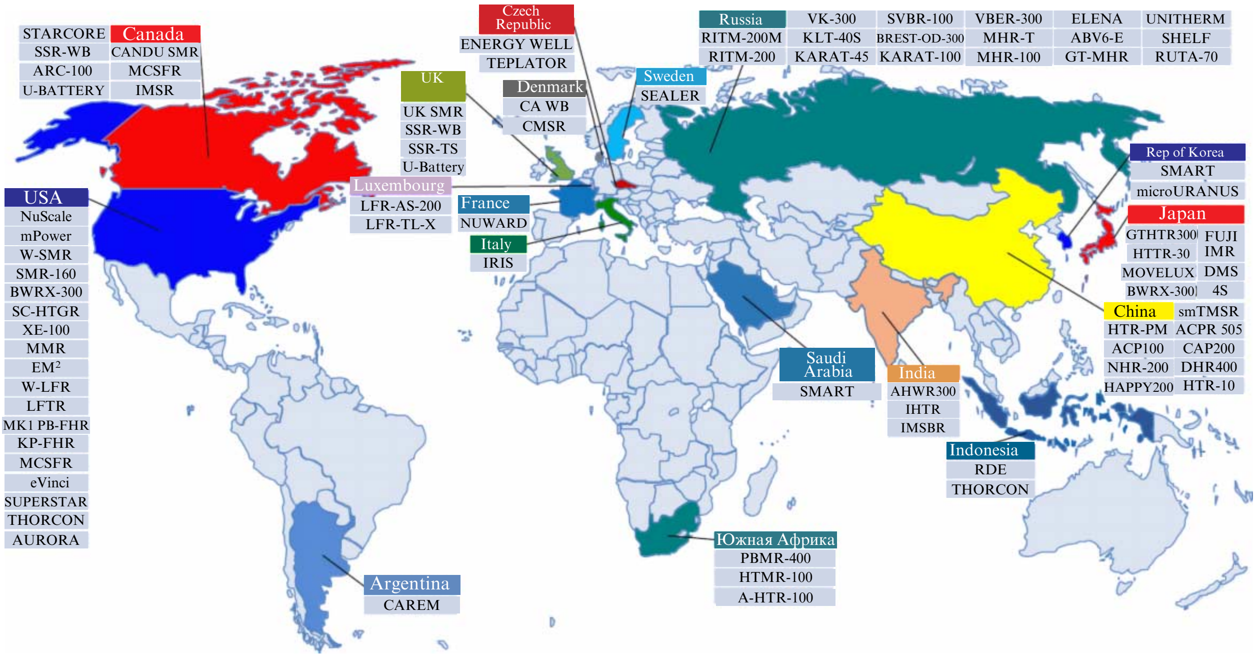


Figure 6. Small modular reactors and micro reactors in development or demonstration around the world.

Energy of Canada Limited and managed by Canadian Nuclear Laboratories [101].

US DOE has just announced the MARVEL project to build one MR at Idaho National Laboratory as a test bed to offer experimental capabilities not currently available, help researchers and end users understand how MRs can integrate with other technologies, and help accelerate deployment [102].

Many massively deployed energy technologies are micro systems. They are exemplified by diesel gen-sets, from a few to thousands kW per unit, with annual global installation of a few hundred GW; and ICE (Internal Combustion Engines, mostly for autos, or wheeling power plants), typically 50–100 kW each, with annual worldwide production and sales of a few TW (in contrast, total global installed electricity generation capacity is over 7 TWe in 2019, with annual additions in 200–300 GWe range). Overall system economics and resource efficiencies are likely the deciding factors for massively produced and deployed power reactor modules.

These emerging SMRs and MRs will provide more complete tests and proofs, and broad realizations for this new paradigm of civil nuclear energy.

6.7 Surrogate tests and transferable capabilities and capacities

For the most ambitious goal in IPPC's 2018 report [49], nuclear power needs to grow 501% by 2050 over 2010 level of 375 GWe to 2,250 GWe, or nearly 75 GWe every year for 30 years from now on (all current installed capacities will be retired by then). Most other scenarios forecast much lower total capacity additions, by a factor of 2 or more. We already outlined pathways to 1,148 GWe previously to illustrate Wright's law, separately using a small modular reactor, a large reactor, and a micro reactor. If we could start now, the constant annual growth rate for 10 MWe modules to reach 2,258 GWe by 2050 would need to be 41.4%, and 33.4% for 100 MWe modules. Recalling the growth rates in Table 2 for all power generation technologies, such rates, although quite high by themselves, are rather ordinary in comparison to others and should be readily achievable. Increasing the module power while staying within the fundamental safety limit will reduce the growth rate needed.

If a new paradigm of civil nuclear energy capable of manufacturing and installing power reactor modules numbering in several thousands or even many tens to hundreds of thousands in the next three decades seems incredible, we should see what are possible in other more successful technologies and industries.

We will start by assessing a wildly successful technology with a killer product, industrial gas turbine for power generation. Before significant advances in materials, design, and manufacturing were made from mid-1980s to mid-1990s, aeroderivative gas turbines based on existing aircraft gas turbine engines were sometimes used as peakers for electricity generation. Since the mid-1990s, heavy-duty industrial gas turbines using single crystal turbine blades and other advanced materials have pushed up combustion temperatures and conversion efficiencies far above previous possible ranges (see, e.g., [103]). Gas fired power generation became the fastest growing thermal power source in many parts of the world. Even in recent time with slowing orders from market saturation, gas turbines still add 36–60 GWe every year, with 360–500 units, averaging 110 MWe each. The installed cost in 2018 is \$4.2/We [104]. Three leading manufacturers, GE, Siemens, and MHPS, produce the majority of industrial gas turbines. Global gas power generation have been growing in a range of 30–60% every decade since 1990 (see Table 2). In the decade around year 2000, US alone added well over 200 GWe gas power capacity, increasing the total installed power generation by nearly a third. The rapid growth of fracking for shale gas and oil, effectively transforming mining with low duty factors for drilling, into de-facto underground chemical processing (manufacturing) with high duty factors, and has changed the global energy landscape and accelerated shift away from coal.

The potential for gas turbines in a carbon-constrained world is becoming more limited. While GHG emission from gas power is substantially lower than that from coal power, it nevertheless is far too high for climate goals. Gas is being promoted as a bridge fuel, complementary to renewables.

Gas turbines likely comprise a class of energy systems with the strongest economies of unit scale that are also benefited greatly from economies of production scale. Gas combustion, energy conversion in multi-stage turbines, and power generation through co-axial generators are mostly volumetric, with no internal interfacial reactions. They are factory manufactured in series and transported on-site to be installed in plants, with minimal construction needed. They do, however, need pipelines to supply fuels constantly. Natural gas resources are not evenly distributed around the world, so gas pipelines or LNG tankers and terminals are necessary infrastructure for transmission and distribution. As analyzed and predicated over a decade ago, the market lifecycle for gas turbines based on maximal installed unit size is approaching an end for this generation of technology [84].

That same study predicted that there was a need and a window for the emergence of new power generation technologies and systems for large-scale deployment within the next decade or so. As it turned out, solar photovoltaics broke out into explosive growth around that time, increasing installed capacity by over 20 times each in the first two decades of 21st century, and still going strong. Photovoltaic cells have very weak unit scale economy, mostly in edge effects, so their development and deployment are not confounded by economies of unit scale. Instead, they have been effectively and efficiently conducted through pursuit of economies of production volume, achieving the most extraordinary growth in the history of energy technologies and systems. The intrinsic limitations due to low power density and low duty factor from variable and intermittent natural source constrain its potential in the long run.

Commercial airliners are essentially flying power plants with propulsion power in a range of 20–100 MW. They are complex and safety critical with tight regulations, sharing some key features and risks with nuclear reactors with additional very demanding mobility functions and associated risks. In 2020, one of the worst year for air travel and aircraft makers in decades due to the global pandemic, the largest four manufacturers, Airbus, Boeing, Bombardier, and Embraer still delivered a total of 972 units. The aggregate demands of global commercial aircraft markets in the next 2 decades are projected to be about 40,000 units [105, 106]. If average power is 50 MW, then total new capacity will be 2,000 GW for 2 decades, demonstrating that manufacturing nuclear energy systems to meet climate goals can be viable if a new paradigm is adopted soon.

Ships are effectively sailing power plants. Ship building is one industry and shipyard is the production platform consistently used in studies to reduce costs for advanced nuclear reactors. Large tankers are similar in scale and complexity with nuclear power plants. KLT-40S is a test product of this transferable capability and capacity with a deadweight tonnage of 33,980 t. There are about 98,140 commercial vessels registered around the world, with average gross tonnage of 21,010 t. The new building deliveries in 2019 total 65,911 kt, or about 3,000 units. Global shipyard industry is highly competitive and has substantially increased productivity in recent years, with a total capacity of 1,500–3,500 units per year, currently operating at 50% capacity [13, 107]. If a fraction of them are mobilized and transitioned toward manufacturing SMRs and MRs, adding tens to hundreds GWe nuclear power capacities annually is feasible, at least from the module production perspective.

These industries not only provide positive surrogate tests for the new paradigm, they also carry substantial transferable manufacturing capabilities and capacities for fundamentally safe SMRs and MRs that are designed for mass production and wide deployment.

The issues related to nuclear fuel and waste can be resolved similarly. Uranium extraction and processing are typical mining and chemical processes that follow the Wright's law very well, so scaling up production while the reactor modules are in the proof phase can be synchronized with careful planning and appropriate investment. With dry cask storage proving to be an effective and economical interim waste management solution, and significant advances in drilling technologies and systems in general, suitable waste disposal means can be developed in time as well. We need to keep in mind that since the fuels and products of nuclear fission reactions are outside the main bio-geo-chemical cycles for life, and the most readily accessible use is providing power and heat, these fuel cycle production activities cannot be adequately developed and deployed unless the energy production part of the value chain is well established. This recognition sets up the development priority.

7. Conclusions

We face extraordinary global challenges in mitigating and adapting to man-made climate change. The first half of this forum brought attention to several impending disruptions that are far more ominous and immediate than the general consensus in the public. Climate and ecosystems are coupled complex nonlinear dynamic systems, and changes may seem gradual and insignificant over long periods of time. Yet complex dynamic systems can undergo sudden drastic changes when internal or external drives or imbalances reach over some tipping point or bifurcation stage, as evidenced by five mass extinction events and many smaller ones on Earth in the past. As intelligent species, we cannot and will not wait for this to happen without foresight and preparation to forestall, mitigate, and adapt.

It has become clear that decarbonizing global energy has the highest priority and viability, and can make the most significant contribution in near to mid-terms. While renewable energies with energy storage are growing rapidly and showing great potential for significant contributions, it is also increasingly clear that sole reliance on them for deep decarbonization in time is not realistic [108]. Fusion research and development have seen tremendous recent surges of interests, investments, and ventures to find innovative approaches and solutions in addition to the mainstream Tokamak exemplified by the international project of ITER and national projects around the world. While it has a bright future, its timely deployment to be a significant part of the solution before mid-century is highly uncertain at the present.

After this paper was mostly finished and in circulation for comments and revisions, IEA published an agency report on reaching net-zero emission by 2050 and limiting the rise in global temperature to 1.5 °C [109]. This is one of the most comprehensive and ambitious roadmaps issued so far in the world, and calls for a total transformation of the energy systems that underpin our economies. Despite the current gap between rhetoric and reality on emissions, the roadmap shows that there are still pathways to reach net zero by 2050. The pathway IEA focuses on relies almost exclusively on renewables, especially solar and wind, with assistance from hydro and nuclear as essential foundation for transitions. The roadmap calls for two-thirds of total energy supply in 2050 from wind, solar, bioenergy, geothermal and hydro energy. Solar PV capacity increases 20-fold between now and 2050, and wind power 11-fold. Scaling up solar and wind in this decade would reach annual additions of 630 GWp solar PV and 390 GWp wind by 2030. Electric vehicles (EVs) go from around 5% of global car sales to more than 60%, and public charging points for EVs rise from around 1 million today to 40 million, with annual battery production for EVs leaps from 160 GWh today to 6,600 GWh in 2030 — the equivalent of adding almost 20 gigafactories each year for the next 10 years. While seemingly feasible, IEA acknowledges that the pathway remains narrow and extremely challenging. It provides a well-documented reference to benchmark the nuclear solution outlined here.

Nuclear fission energy, while already generating the second largest share of low-carbon electricity in the world, has been in a more controversial position and its future very clouded. Most climate change mitigation scenarios recognize that nuclear energy needs to be in the solution, and the more ambitious the climate goals are, the higher its share needs to reach. There have been significant turn-around of attitudes toward nuclear energy from communities that had been anti-nuclear. Many governments have plans to grow and expand nuclear power. There has been substantial recent resurgence of private and public investments, programs, and ventures in research, development, and demonstration of advanced nuclear energy technologies and systems. But these efforts have been constrained by some common mistaken presumptions, perceptions, and positioning. Nuclear power has been in decades-long stagnation and decline, and the field and industry appear unable to gather and sustain positive momentum to re-accelerate development and deployment. A long-hoped for nuclear renaissance, or the coming of a second nuclear era, is yet to realize.

It is against this background and challenges that a new paradigm of civil nuclear energy is proposed here to review and assess the history, status, and outlooks, and outline a globally scalable and timely system solution. This approach, rooted in assuring fundamental nuclear safety by design while improving economics through manufacturing of power modules, has the potential to break out the stagnation and meet the most ambitious climate goals. It is built upon existing nuclear science and available proven technologies, guided by universal laws discovered, theorized, and validated in most successful technologies and industries. It can utilize many existing manufacturing capabilities and capacities from adjacent industries, and extend lifetimes or reduce stranded assets of many carbon-intensive energy systems and infrastructure.

The global energy production and consumption emits about 73% of greenhouse gas through electricity, heat, and propulsion. The sector shares are: industry, 24.2%; transport, 16.2%; buildings, 17.5%. While some portions of transport and buildings are being electrified, many parts of industry and transport do not yet have low-carbon alternatives. Green hydrogen has been proposed as an energy carrier solution, which needs large supplies of low-cost and low-carbon primary energies to produce. Industrial process heat is a large part that electrification is not well suited due to inefficiency and waste in extraneous transformation and transmission. These are areas where nuclear energy can shine — if the long-standing dilemma between nuclear safety and economics can be resolved, used fuels and waste managed and disposed, and security and proliferation risks controlled and minimized. The new paradigm has so far demonstrated theoretically its power and efficiency to resolve such a dilemma. We will see more predictions tested in more implementations, and exemplar technologies and systems emerge within the decade.

In his latest book on climate change, Bill Gates analyzes the carbon emissions by sources, and proposes a comprehensive action plan to achieve our goals to reach net zero by 2050 [110]. Gates systematically goes through how we plug in (for power), make things, grow things, get around, and keep cool and stay warm, and outlines the technologies we have and innovations we need. The treatise here provides a complementary framework based on fundamental forces and interactions that give us primary energies, and how their production and consumption are coupled to and can impact the major systems and materials cycles on Earth. If we mostly use forms of energy within the bio-geo-chemical system essential to life, we are bound to have sustainability problems such as climate change, as the laws of thermodynamics dictates. If we instead use more energy external to such systems and cycles, such as direct solar and nuclear energies, there is potential to achieve long term sustainability and go beyond. The new paradigm outlines how we can scale up civil nuclear energy quickly and predictably, and support many more deployment scenarios beyond electricity (see, e.g., [111]).

The paradigmatic predictions made here are neutral to types of reactors and fuels at this level. More specific analyses and predictions are beyond the scope of this review and treatise. We can, however, endeavor to contemplate which level of designed-in safety will be more likely selected through market competition, with the understanding that emergent phenomena and systems are intrinsically probabilistic in distributions. Level III, probabilistic safety, has become increasingly unacceptable. Level I, fundamental safety, appears to eliminate most safety concerns and thus are likely among the early entrants for the second nuclear era. Level II, radioactivity safety, is achieved with trade-off between efficiency and safety, with potential for higher system efficiency if risk perceptions and tolerances improve and accident consequences become materially and demonstrably less damaging and extensive. Level I and II designs are thus complementary, with Level I designs more likely to gain entries in early stages, facilitating increased production, deployment, and acceptance. Level II designs will gain more shares in the long run when the industry and markets are more established and mature, and risk perceptions and tolerances improve. Level III designs will need to evolve, and current plants and new builds may improve their prospects and performances by modifying certain aspects to achieve Level II safety.

It is worth highlighting again that in this new paradigm, the higher the total installed capacity target is, the lower the average cumulative unit cost will be. Decarbonizing broader sectors of economies using more nuclear energy from reactor power modules with assured nuclear safety will help the world reach more ambitious climate goals with improved economics. It will be highly valuable to compare such a pathway with others, especially the one reported by IEA, and improve them to broaden the pathway and increase the likelihood to success. It can be also viewed as a scale-up solution in comprehensive action plans such as the one proposed by Gates.

Once this new paradigm is established and expanded at sufficient scale in time to help mitigate climate change, other worthy objectives in resource and conversion efficiency, and in closing fuel cycles for improved sustainability, will come to the forefront and have the demands and resources at scale for economic development and deployment.

This is a promising global solution in need of global cooperation across several industries. The spirit and efforts of this forum and special issue inspire another East-meets-West of historical significance [112], and will extend from North to South all over the world, as humanity faces climate challenges and applies energy solutions together. Paraphrasing Eisenhower, if the dreadful trend of civil nuclear power stagnation and decline can be reversed, this greatest source of energy can be developed into a great boon, for the benefits of all humankind.

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