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Small Modular Nuclear Reactors Suitability for Data Centers

White Paper 186

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Energy Management Research Center

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Executive summary

Small Modular Reactors (SMRs) offer a promising solution to the energy challenges in data center sector. Reliable low-carbon power and generation profile matching the demand is a sustainable alternative to existing sources.

SMRs are manufactured in controlled environment with built-in scalability and high safety. While weather-decoupled power from advanced nuclear technologies could revolutionize the energy landscape, educating decision makers is critical to advancing their deployment.

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FAST TAKES:

- Data Center Power Dynamics
    - Rely on diverse grid-level power sources and require robust backup systems.
    - Must explore alternatives beyond traditional power plants due to industrial electrification.
    - Must pursue sustainability, regulatory compliance, and green energy adoption, while delivering efficient cooling, and resilient operations.
- Small Modular Reactors (SMR)
    - Offer the potential for reliable, low-carbon energy supply to data centers.
    - Deliver the potential for enhanced operational safety, improved energy resiliency compared to renewable alternatives. They may offer reduced environmental impact due to scalable design and advanced risk mitigation protocols.
    - Need continued technological advancements, an improved regulatory landscape and ongoing international cooperation to evaluate their potential.

CONSIDERATIONS:

As the demand for energy-efficient, reliable and sustainable power solutions for data centers continues to grow, SMRs continue to emerge as a promising alternative to current constraints. These advanced small-footprint reactors offer a compelling mix of lower capital costs, shorter deployment times and significant environmental benefits compared to other options. Yet, they are still unproven at scale.

To make informed decisions, here's a detailed overview of current SMR technologies. Determining if an SMR can meet the needs of your project, you'll need to consider:

1. Power needs, including prime and back-up power
2. Availability options including regulatory restrictions
    a. Stand-alone
    b. Connectivity
    c. Integration
    d. Storage
3. Safety, siting and security assessments
4. Time to deployment including regulatory approvals and construction
5. Environmental and sustainability considerations including
    a. Resource utilization
    b. Lifecycle impact from construction to decommission
6. Providers, ecosystem and partners to reduce risk:
    a. Experience in region
    b. Experience with regulatory bodies,
7. Familiarity with insurers and financial providers (including risk management)
8. Incentive structures and agency programs
9. Human capital and resources needs to install and manage
10. Stakeholder engagement
    a. Regulatory
    b. Nation/State/Locality
    c. Community

Introduction

Data centers are central to driving the electrification and digitization of the global economy. They have been the primary instruments of the increased adoption of Artificial Intelligence (AI). However, data centers and AI are two levers impacting energy demand in unprecedented ways.

News cycles have focused on their consumption of energy, yet there's also significant potential upside to the story. Energy-intensive smart algorithms have two tracks of benefits – the first is improving data center operations and energy management. The second is supporting decarbonization and improving the sustainability efforts of carbon intensive industries including manufacturing, and transportation.

To achieve the former, data centers are singularly focused on reducing their own carbon footprint. They're examining multiple paths forward – increasing utilization of renewable energy, introducing efficient cooling technologies, and most recently by adapting to meet sustainability regulations.[1] However, the struggle for consistent power availability power is rising, becoming a serious concern in recent years.

Among the challenges is sourcing local power. The Power Purchasing Agreements (PPA), or a virtual substitute (VPPA), initially developed under much different energy scenarios, are finding it difficult to fulfill their commitments at the required levels.[2] These programs, designed to drive adoption of renewables, fall short of closing the gap between demand and availability.

The sector needs alternatives. Nuclear can fill the gap.

Nuclear energy is the most abundant and second largest source of low-carbon electricity after hydropower.[3] In 2022 nuclear provided 18% of US energy (772 TWh)[4] and almost 22% of EU energy (609 TWh).[5] Analyses indicate that an effective transition of the economy to net-zero by 2050 requires adding up to 800 GW nuclear power, to cover 20% of global electricity supply.[6]

Achieving electrification with renewables alone is challenging given land and raw materials scarcity. Furthermore, the intermittent nature of wind and solar energy leaves data center operators with resiliency concerns. Battery Energy Storage Systems (BESS) onsite storage and energy management systems could mitigate this challenge but are at early stages of adoption. More details about BESS can be found in Schneider Electric White Paper 185: Understanding BESS: Battery Energy Storage Systems for Data Centers.

According to the International Energy Association (IEA), "Nuclear power plants contribute to electricity security in multiple ways by keeping power grids stable and complementing decarbonization strategies since, to a certain extent, they can adjust their output to accompany shifts in demand and supply. As the share of variable renewables like wind and solar photovoltaics (PV) rises, the need for such services will increase."[7]

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[1] Energy efficiency directive, 2023, European Commission

[2] Daniel Tipping, Welcome to the new PPA market paradigm, Apr. 2024, Wood Mackenzie

[3] Eric Hoegger, Are Nuclear-Powered Data Centers in Our Future, Jun. 2023, CyrusOne

[4] Nuclear Power in the USA,2024, World Nuclear Association

[5] Nuclear energy statistics, Jan. 2024, Eurostat

[6] What will it take for nuclear power to meet the climate challenge?, Mar. 2023, McKinsey

[7] Nuclear Power, 2023, IEA

While the truth is we need to do many things at the same time, the global capacity factor for nuclear power is two times more than renewables.[8] The advantage of nuclear reactor performance is operations unaffected by the region of deployment, unlike in the case of renewables.

The lifetime of a solar plant can be technically limited to the lifetime of steel supports, reaching 80 years. Predictive algorithms offering performance monitoring can support replacing individual sub-performing panels or inverters to extend solar plant life to the lifetime of the steel supports. Offshore wind and PV may seem to outperform nuclear energy in a debate about technology decarbonizing the power sector,[9] but this fails to consider the overall impact on the grid.

Evolving nuclear technology has attracted the attention of the data center sector as a low-emission and reliable energy source.[10,11] Many countries are either building new reactors or putting idle ones back online, despite prior safety concerns and higher costs for reliable low carbon power.[12] World nuclear energy leaders like Japan[13] and France[14] are restarting investment in nuclear power. They're developing more efficient nuclear fusion technology,[15,16] despite having a longer horizon line to benefit.

Research focuses on two areas: proven approaches to reactors and focus on process monitoring; or new applications of known materials.[17] Despite project delivery challenges in the [18] this cutting-edge business shows promise for nuclear powered data. [19]

Small modular reactors (SMRs) provide secure power, matching supply with demand and reducing downtime of data centers. Further improvement is expected with implementation of AI technologies that solve complex operational challenges[20] and mitigate regulatory struggles.[21] Nuclear technology may deliver optimal long term green energy, exceeding many times over the equipment lifetime of wind and solar.[22]

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[8] Bolson, et al., Capacity factors for electrical power generation from renewable and nonrenewable sources, Dec. 2022, PNAS

[9] Korea Opposition Re-Election Gain Hinders Nuclear Push, Apr. 2024, BloombergNEF

[10] Moss, Microsoft hires Erin Henderson to head 'nuclear development acceleration' for data centers, Jan. 2024, DCD

[11] Moss, Microsoft hires Archie Manoharan as director of nuclear technologies, joins from micro modular reactor firm, Jan. 2024, DCD

[12] Caronello, Five Key Charts to Watch in Global Commodities This Week, Feb. 2024, BloombergNEF

[13] Oda, Japan Nuclear Regulator Removes a Hurdle for Tepco Plant Restart, Dec. 2023, BloombergNEF

[14] EDF intends to restart 27 nuclear reactors before the end of 2022, Sep. 2022, Ener Data

[15] China to Set up Nuclear Fusion Company to Develop Technology, 2024, BloombergNEF

[16] Fusion energy and ITER, 2022, European Commission

[17] Could liquid neon be the answer to monitoring the safe operation of Small Modular Reactors?, Jan. 2024, Canadian Nuclear Laboratories

[18] Wade, Southern's Vogtle Nuclear Project Has Been Delayed Again, Feb. 2024, BloombergNEF

[19] Swinhoe, Blockchain firm Standard Power to procure 24 small modular reactors from NuScale for two US data center sites, Oct. 2023, DCD

[20] Kulp, The DOE mulls how AI can help shore up power grids, May 2024, TechBrew

[21] Moss, Microsoft trains generative AI to handle SMR nuclear regulatory process, Dec. 2023, DCD

[22] Erickson, "Renewables" vs Nuclear Power, Sep. 2017, Duluth Reader

Elephants in the room: safety, regulatory and technology footprint

Nuclear safety

Nuclear safety is oftentimes a debate between emotions and empirical data.

SMR may be considered an approach to address that tension: low-carbon sources supporting decarbonization while mitigating concerns. Despite any apprehension, several countries pledged to triple nuclear energy by 2050, national security risks or not.[23] Modular reactors carry with them questions about potential proliferation of nuclear weapons, especially regarding fuel cycle technologies, and nuclear terrorism. While all infrastructure is vulnerable to security concerns, nuclear bears more baggage.

Furthermore, the interstate collaboration that should mitigate nuclear energy risks is not well facilitated. Most of early stage SMR technologies in development (76%) are at risk for instability due to designs of core power control systems[24] and operations characteristics.[25] Skeptics are quick to share their uncertainties about the risk of nuclear power in various scenarios,[26] but increasingly this becomes a debate over technology development costs and time.

Safety of SMR is generally provided with reactor shut-down technologies or smart algorithms controlling operations along the entire lifecycle, from development, deployment,[27] operations and maintenance, to decommissioning.[28] New technologies used in SMR design provide guarded, protective systems offering superior passive-safety with cost efficient risk improvement.[29] Operations of SMR are expected to be supported by AI tools focused on cybersecurity, as well as resiliency and performance.

Standardized safety measures still lag technical progress, which is to be expected. So, too, does regulation (as AI and social media regulation has demonstrated). Rigorous regulatory frameworks, controlling standards bodies, and international collaboration await further developments. Widespread operator training protocols are facilitated through international cooperation. These are fundamental in building a positive image of nuclear energy. A well-regulated and supervised SMR technology offering low-risk high-efficiency energy on demand is a promising solution to meet the net-zero goals of power-hungry industries, including the data center sector.

Nuclear regulatory requirements

Regulatory requirements in the nuclear sector have evolved but remain inconsistent across regions. This makes the time and cost intensive construction of a traditional nuclear plant demanding. Especially considering the limited number of companies capable of executing such challenging projects.

Greater experience among construction professional teams is the tradeoff – without greater collaboration, standards, and expanded staff education across the entire

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[23] Squassoni, New Nuclear Energy: Assessing the National Security Risks, Apr. 2024, The George Washington University

[24] Xie, et al., Reactivity disturbance suppression method for small modular reactors based on core coolant flow control, Sep. 2022, Nature

[25] Tirone, Nuclear Power's Expansion Risks Collapse on Widening Conflicts, Apr. 2024, BloombergNEF

[26] Stapczynski, Japan Quake Shows Beefed-Up Nuclear Safety Works: Energy Daily, Jan. 2024, BloombergNEF

[27] He & Degtyarev, AI and atoms: How artificial intelligence is revolutionizing nuclear material production, Sep. 2023, Bulletin of the Atomic Scientists

[28] Mancini, et al., Nuclear decommissioning risk management adopting a comprehensive artificial intelligence framework: An applied case in an Italian site, Apr. 2023, Progress in Nuclear Energy

[29] Jack, Europe's grid is under a cyberattack deluge, industry warns, Nov. 2023, Politico

cycle, expansion is constrained. A cross-border framework of mandated guidelines and fuel management with laws addressing non-proliferation aspects must be in place before market advancements. It's an orchestrated dance where regulators, technology companies and developers must act in concert.

Some of those concerns are mitigated in SMR technology, considering how the supply chain is developed to handle nuclear grade materials and equipment. A slow evolution of the nuclear energy sector is moving regulatory aspects towards simplification of procedures.[30]

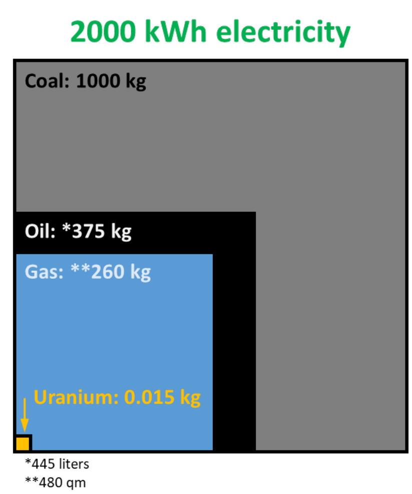
Yet, substantial investment of time and money is needed to move these operations to scale. In most cases, nuclear-grade materials and components are not widely mandated for small units so strict regulatory requirements will not obstruct development of modular technology.

Footprint of nuclear technology

Fossil fuel-derived power is a major contributor to global carbon footprint. A greener alternative, nuclear power has an optimal carbon footprint with emissions below 50 gCO2/kWh. It is a fraction when compared to gas-generated (approx. 450 gCO2/kWh) or coal-generated power (approx. 1050 gCO2/kWh).[31] Besides, uranium offers one of the best-known mass-to-energy ratios (see Figure 1).

Figure 1

Fuel comparison to generate 2000 kWh electricity.



A one GW nuclear plant generates 0.03 kg waste per MWh.[32] Intermittent resources provide green power with comparable amounts of operational waste, but the main doubt is the radioactive residues and at end-of-life in SMR technology. Operational waste from a coal plant is nearly 90 kg ash per MWh on top of carbon dioxide emitted to atmosphere. Wind power is more favorable with 0.16 kg waste (i.e., plastic composites building blades) while photovoltaics gives 1.67 kg waste (i.e., toxic heavy metals like arsenic or cadmium), both per MWh and generated during decommissioning.[33] Regardless of our energy choices, waste must be considered during all process – from design, build, maintain and decommission. Furthermore,

[30] Nuclear Power Plant Licensing Process, Jul. 2004, US Nuclear Regulatory Commission

[31] What is the role of nuclear in the energy mix and in reducing greenhouse gas emissions?, Dec. 2022, LSE

[32] Ritchie, How much waste do solar panels and wind turbines produce?, Nov. 2023, Sustainability by numbers

[33] Amin, et al., Radionuclide emissions from a coal-fired power plant, Oct. 2013, Applied Radiation and Isotopes

plant operations and physical footprint including area required will have impact on the decision.

Studies on spent nuclear fuel show that even the least sophisticated method of storing nuclear fuel waste (excluding fissile material recovery) have a comparable environmental footprint to renewable energy.[34] Spent fuel processing and SMR technologies entering the current market allow saving uranium resources and decrease timescales of potential longevity of the waste in depository.

The vast timescale of spent fuel storage must be considered. Analyses show that high concentrations of radioactive plutonium-239 and uranium-235 may be chemically unstable and induce nuclear reaction even after removal from the reactor.

Fast reactor technology is amongst the most promising; future nuclear technologies will increase efficiency from today's 5% by at least an order of magnitude.[35] Many newly developed nuclear technologies are fast reactors benefitting from reduced nuclear waste by recycling spent fuel from current reactors. The most sophisticated technology evolution used in today's 4th generation large reactors employs a far more common uranium isotope U-238. These are designed to be safer and more sustainable.[36]

Reactors in development offer various heat generation technologies with a common objective of destructing byproduct radioelements in spent fuel. However, nuclear energy in general uses 5t/MW of key minerals, mainly copper, nickel and rare earth elements.[37] This is less than photovoltaics or onshore and offshore wind plants, 7t/MW and 10-15t/MW, respectively.

Transitioning to modular reactors solves some the challenges faced by conventional nuclear power plants.

Small Modular Reactors (SMRs)

Small Modular Reactors (SMRs) promise advancement of nuclear technology, solving power struggles for energy-intensive sectors. They also raise several questions regarding capex costs, safety, waste generation. Those aspects weigh down public perception of nuclear power.

SMRs follow the same physical principles as traditional reactors: nuclear fuel heats coolant which in turn boils water to produce steam used to move electricity-generating turbines. Both are fueled with HALEU or LEU, a trade of which has recently drawn global attention.[38] Advanced Nuclear Reactors (AMRs) that are likely to be the next generation of modular nuclear technology, will be capable of using broader spectrum of nuclear fuel including material currently classified as spent fuel waste. Efforts to develop new forms of fuel resulted with the TRISO[39] technology (particles of more resistant and high-performance fuel), metallic fuel (low temperature fuel) and molten salts (liquid fuel with excellent safety characteristics). Material that can be used to fuel sodium- or gas-cooled reactors are an alternative to the common HALEU.

Modular nuclear technology spans a wide capacity range - up to 300 MW, or below 50 MW for smaller units called microreactors. This range offer an advantageous solution to energy-intensive sectors like data centers. SMR solutions are easier to

TRISO

TRi-Structural ISOotropic
uranium encapsulated core-shell particles with a multilayer structure that allows retaining byproducts of nuclear fission.

LEU

Low-Enriched Uranium
<5% enriched uranium U-235.

HALEU

High-Assay Low-Enriched Uranium
5-20% enriched uranium U-235.

[34] Taylor, at al., A Review of Environmental and Economic Implications of Closing the Nuclear Fuel Cycle – Part One: Wastes and Environmental Impacts, Feb. 2022, Energies

[35] Are there different types of nuclear reactor?, World Nuclear Association

[36] Dume, Nuclear: what is a 4th generation reactor?, Mar. 2022, Polytechnique insights

[37] The Role of Critical Minerals in Clean Energy Transitions, 2021, IEA

[38] Natter, Russia Uranium Supplier Issues Force Majeure Notice After US Ban, May 2024, BloombergNEF

[39] TRISO Particles: The Most Robust Nuclear Fuel on Earth, Jul. 2019, Blue Wave AI labs

place in production versus large nuclear plants but that's not the only upside. SMRs are built from reliable designs and manufactured in factories, so they can be deployed in short time with anticipated consistent quality.

Small nuclear reactors are neither new nor unique. They were first used to power submarines and ice-breaker vessels in 1950's, providing proven resiliency and stability.[40] In 2020 more than 20 companies in the US were developing nuclear reactors, mostly SMRs.[41]

Nuclear reactors often fall in three design families with 70% of working plants covered by pressurized water reactors (PWR). The emerging designs for SMRs use liquid metals, molten salts, or gases as coolant instead of water and consume recycled or composite fuel (see Figure 2). The degree of modularization, technology, and licensing readiness levels vary across designs.[42]

Figure 2

Most promising SMR technologies.

Molten salt reactor (MSR)

- Molten fluorides or chlorides used as coolant
- Potential to use plutonium or actinides (*consumes waste from other reactors*)
- Fuel-coolant interaction allows reduction of generation downtime from refueling
- Operates at high temperatures and at lower pressures (*efficiency and safety gains*)

Sodium-cooled fast reactor (SFR)

- Molten sodium used as coolant
- Fueled with uranium or depleted uranium (*high level waste management with additional mitigation of plutonium and other actinides*)
- Operates at high temperatures and at lower pressures (*efficiency and safety gains*)

Very high temperature reactor (VHTR)

- Gas used as coolant (*potential application in other industrial processes*)
- Generates flexible range of heat outputs for electricity generation and various industrial needs
- Retains fission products thanks to coated particle fuel and low power density

For most aspects in the decision process around new nuclear technology as power source, the determining factor is cost.

Cost overview

Wind and solar feature moderate price tags but require massive land area, a provision around energy storage for sustainable operations and offer a relatively short life span. A traditional nuclear plant requires less land than renewables and has higher capacity factor, but the CAPEX costs are tremendously high. SMRs fill the gap with small size, high-capacity factor, and acceptable relative cost.

Power plant costs, besides the OPEX burden like fuel and maintenance, is driven by the design, build, and early tooling. Even 80% of nuclear energy costs comes from plant construction of which the majority are indirect costs.[43] In comparison, only about 20% costs of natural gas energy is related to building process, 70% being the cost of fuel.[44] This paints, in stark relief, a picture of why other energy sources may have made more financial sense (and dollars).

[40] Nuclear-Powered Ships, Feb. 2023, World Nuclear Association

[41] What is High-Assay Low-Enriched Uranium (HALEU)?, Apr. 2020, Blue Wave AI Labs

[42] Small Modular Reactors: Challenges and Opportunities, 2021, Nuclear Energy Agency

[43] Economics of Nuclear Power, Sep. 2023, World Nuclear Association

[44] Enterline, Risky Reliability: Will Regulators Address the Price Risk of the Next Generation of Gas Power Plants?, Apr. 2024, Regulatory Assistance Project

SMR technology offering compact, modular infrastructure is expected to shift the cost equation, and increase the competitiveness of nuclear power. However, some costs are hard to avoid. Quality control requirements on nuclear-grade elements increases concrete costs by 23% and steel costs by 41%.[45] Those costs are often generated by additional documentation and testing.

The lack of a common, accepted regulatory framework further increases costs of nuclear energy. It extends projects with additional requirements appearing during the construction stage. And while almost all large projects are fraught with cost overruns,[46] current approaches to nuclear construction result in an average build time double what it was in the1960s.[47] With each new strategy delivered, SMR technology is likely to reduce costs by solving major drawbacks:[48]

- Improve maturity, stability, and predictability of the regulatory pathway
- Provide simplified and more experienced project management
- Secure reliable and accessible network of suppliers

Levelized Costs of Energy (LCOE)

Average net cost of electricity generation over lifetime of an asset or power plant.

Table 1 shows an overview of LCOE from sustainable sources. SMRs are forecasted to be significantly cheaper to build than large nuclear reactors but should be integrated into an Energy Storage System (EES) to increase resilience and grid independence while removing the variability of weather conditions. Modular reactors are likely to provide secure energy cheaper than concentrated solar power (CSP) photovoltaics, although the estimated cost is currently aspirational. Optimism in simplified construction and inherent safety features need to be proven before the cost becomes a true selling point. Current cost estimates for SMRs are higher than known cost of common renewables but the value of SMR to user is in secure, not intermittent power.

Modular nuclear technologies are versatile and besides supplying power, they can be used to directly produce hydrogen from nuclear fission.[49] This process is forecasted to be cheaper than powering electrolysis with renewable or gas-generated electricity.[50] This may increase ROI and open investment to additional sources of funding with incentives,[51] especially regarding forecasted hydrogen position in the market.[52]

Renewables including hydroelectric share similar emission profiles for generated power to nuclear energy.[53] Traditional nuclear plants are expensive while renewables optimize the value proposition with significantly lower Levelized Costs of Energy (LCOE).

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[45] Dawson & Sabharwall, A Review of Light Water Reactor Costs and Cost Drivers, Sep. 2017, U.S. Department of Energy, Office of Scientific and Technical Information

[46] Park, Cost Overruns and Schedule Delays of Major Projects: Why We Need Reference Class Forecasting, Feb. 2021, Columbia University

[47] Three Mile Island: The driver of US nuclear power's decline?, 2013, Bulletin of the Atomic Scientists

[48] Unlocking Reductions in the Construction Costs of Nuclear, 2020, Nuclear Energy Agency

[49] Judge, Shell and NuScale to use nuclear power to make hydrogen, Dec. 2022, DCD

[50] Bhashyam, Blue and Nuclear Hydrogen to Get a Boost from New EU Rules, Feb. 2024, BloombergNEF

[51] Natter, Biden's Hydrogen Tax Credit Rules Deal Nuclear Industry a Blow, Dec. 2023, BloombergNEF

[52] Lorentz, et al., Green hydrogen: Energizing the path to net zero, 2023, Deloitte

[53] Nuclear Power Versus Renewable Energy, Jul. 2022, Change Oracle

Table 1

Price of electricity from different sources.

Technology (median)	Capacity *[MW]*	LCOE *[$/MWh]*
Photovoltaics[54]	100	44
Photovoltaics (CSP)[54]	100	112
Wind power (offshore)[54]	600	66
Wind power (onshore)[54]	100	39
Hydro power (river)[54]	94	87
Nuclear power (LTO, 10-20 years)[54]	1000	34
Nuclear power (SMR, NuScale)[55,56]	640	58-89
Nuclear power (SMR, Rolls-Royce)[56]	470	35-50
Nuclear power (SMR, Westinghouse)[57]	640	89

Licensing SMRs

Regulatory processes for SMR technology are subjected to several decision-limited stages, making the burden much easier than for conventional nuclear plants. Geolocation and technology application may have key importance in regulatory processes especially at early stage of SMRs introduction to the energy mix. This factor will likely fade with time, as more deployed units drive consistency.

Running initial projects on current nuclear sites with existing infrastructure can shorten middle deployment phases like licensing with environmental assessment and site preparation. Standardization the nuclear fuel trade is an impediment to scaling nuclear power implementation.[58] This is oftentimes driven by IP protection of nuclear fuel developers and is likely to disappear with broader deployment of SMRs.

A shift in governmental support environment indicates coming changes for the industry. Initial incentives within the Inflation Reduction Act (IRA) in the US market excluded nuclear. Now governmental policies consider SMRs as green power, crucial in decarbonization and power security.[59] This has driven funds directed at supporting research on nuclear fuel for advanced technologies, independent of reactor type.[60]

Environmental footprint and water use

The physical footprint of nuclear technology is low, with land required to generate similar amount of power shrunken in the extreme: 360 times less than wind and 75 times less than solar.[61] The full system can exist in a football field-size area: a facility with the nuclear reactor, a separate generator system and control unit with

[54] Dalton, Generation IV/Economic Modelling Compares Costs Of SMR To Conventional PWR, Oct. 2020, NUCNET

[55] Small Nuclear Power Reactors, Feb. 2024, World Nuclear Association

[56] Schlissel, Eye-popping new cost estimates released for NuScale small modular reactor, Jan. 2023, Institute for Energy Economics and Financial Analysis

[57] Levelized Cost of Electricity Calculator, 2020, Nuclear Energy Agency

[58] Tirone, World's No. 1 Uranium Producer Wins Partial Victory at Regulator, Sep. 2023, BloombergNEF

[59] Fehrenbacher, The IRA is key to accelerating advanced small nuclear, Aug. 2023, AXIOS

[60] Mignault, Nuclear Energy in the Inflation Reduction Act, Aug. 2022, Bowles Rice

[61] Anthropogenic Causes of Bird Mortality: Climate Change, Fossil Fuels and Renewable Energy, Oct. 2014, Change Oracle

additional waste and maintenance buildings. The total area is enough to host several 77MW units; much smaller than the required area for similar generation capacity renewables.[62]

Resource scarcity becomes an important aspect in products and processes design when following the rules of a circular economy. Water use in an SMR is around 60 L/MWh which is far lower than the requirements for a large concentrated solar power (CSP) plant or traditional nuclear plant, both reporting above 3000 L/MWh.[63,64] The former operates with a cooling process that accounts for much of the water consumption, mainly through evaporation and other losses. Technology advancements will further reduce water use.[65] In fact newly developed SMRs offer different cooling designs besides water systems (NuScale) like molten salt system (Terrestrial Energy or Stellaria Energy) or sodium-cooled system (Toshiba). The last one is most likely to obtain approval from the US Nuclear Regulatory Commission.

Nuclear waste generation and management

Development of nuclear waste management is supported by research grants that drive work on efficient technologies minimizing environmental footprint of SMR. Separation technologies developed in the CURIE program run by the US DOE mitigates proliferation of nuclear material and lead to radiotoxicity reduction in spent fuel. Cutting waste that requires permanent disposal and implementation of monitoring systems supports decreased mining for critical minerals and provides sustainable nuclear feedstock for SMRs.

A burden of any size of nuclear reactor is what is left after power generation. SMRs offer a different waste generation profile to PWRs with similar spent fuel but with higher amounts and greater frequency, up to a factor of 30.[66] While this number sounds alarming in the abstract, it's not in the comparative. For any nuclear technology, operational waste is considered along waste generated during decommissioning. Operational waste for SMRs is associated mainly with reactive chemicals and coolants that are used to protect an external ecosystem from radiation. However, the overall amount of waste compares favorably with conventional renewables. It is a matter of managing waste using newly emerging secure and robust technologies. Some SMR concepts reduce spent fuel nuclear waste thanks to destruction of minor actinides, a major part of the long-term radioactivity.

Skeptics highlight weak points in the sustainability of nuclear power, found on large nuclear plants rather than on modular reactors. Comparison between common PWR reactor and those closest to market from Terra Power, X-energy and NuScale highlight source of SMR waste concerns. Back-end waste depends on burn-up rates and specific design features. The Natrium reactor (Terra Power) compared to PWR offers a 40% lower initial spent fuel activity.

However, long-term activity can be higher because of increased Plutonium content in SMRs. The 10,000-year radiotoxicity of SMR spent fuel is 47% higher for the same reason. The Xe-100 reactor (X-energy) also delivers superior performance to common PWR and to the VOYGR reactor (NuScale), with a 10,000-year radiotoxicity rating 66% lower (less plutonium in spent fuel). But the spent fuel volume for Xe-100 is significantly larger due to fuel design.

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[62] Patel, Two Big Nuclear Regulatory Milestones for Idaho NuScale SMR Project, Aug. 2023, Power

[63] Water consumption solution for efficient concentrated solar power, Jun 2019, European Commission

[64] Cooling Power Plants, Oct. 2020, World Nuclear Association

[65] Martinez-Perez et al., Comparative study of energy performance and water savings between hygroscopic and rankine cycle in a nuclear power plant. Case study of the HTR-10 reactor, Dec. 2023, Results in Engineering

[66] Shwartz, Stanford-led research finds small modular reactors will exacerbate challenges of highly radioactive nuclear waste, May 2022, Stanford News

The ONWARDS (Optimizing Nuclear Waste and Advance Reactor Disposal Systems) project granted to a consortium of several companies addresses key aspects of nuclear industry evolution.[67] This concentration of time and talent on solutions across providers and the ecosystem offers promise. The goals are to provide:

- high precision measurement
- recycling of spent fuel and other materials subjected to radiation
- AI-enabled treatment of functional SMR materials
- safe nuclear energy infrastructure along a complete value chain

This is the approach undertaken by Finland and Sweden, countries at the final stage of building world's first final repository for spent nuclear fuel.[68] Low-enriched uranium oxide will be securely stored in crystalline bedrock in casted graphite and copper containers. The facility offers long term functionality accounting for extreme events like earthquakes or coming ice ages.

A sustainable approach to technology deployment starts considering the entire lifecycle, including decommissioning. In this perspective, SMR building construction materials can be classified as either A, B or C in Low-Level Waste (LLW) category. This includes building materials activated by neutrons or contaminated by radioactive elements. Decommissioning in such case depends on used technologies and footprint estimation carries large error. The most dangerous, reactor components classified as Greater-Than-Class-C (GTCC) LLW, require care in disposal and management. The examples show some variations. The VOYGR reactor shows LLW at 90% of the conventional PWR. However, GTCC for the Xe-100 reactor is large due to graphite blocks protecting other structures from activation. The same is forecasted for the Natrium reactor with neutron reflectors that need to be disposed as GTCC.

Fears of nuclear energy oftentimes go beyond spent fuel waste and radioactive material disposal. Operational risk mitigation for nuclear technologies is crucial for wider acceptance of this technology.

Safety concerns and technology acceptance

Gaining society's acceptance for SMRs may be a long process. From today's support level of 42% in EU[69] and 57% in the US[70] it may require more efforts to transform power grid towards a substantial share of fission-generated energy. Especially in the current situation when conventional nuclear reactor projects have suffered from safety issues[71], delivery delays[72] and cost overruns.[73]

Nuclear safety is high on a list of these technology disadvantages but scalability in fact makes SMRs more reliable and safer. Elements of factory-made units undergo strict quality control while operational safety is achieved thanks to reactor's self-regulation basing on natural laws of physics.[74] Multilevel failure avoidance systems for modular technology presents a model for safeguarding SMRs:[75]

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[67] Optimizing Nuclear Waste and Advanced Reactor Disposal Systems, 2022, Advanced Research Projects Agency

[68] Finland to open the world's first final repository for spent nuclear fuel, Aug. 2022, Vattenfall

[69] Nuclear Power in the European Union, Oct. 2023, RANE

[70] Leppert & Kennedy, Majority of Americans support more nuclear power in the country, Aug. 2024, Pew Research Center

[71] A Brief History of Nuclear Accidents Worldwide, Oct. 2013, Union of Concerned Scientists

[72] Alsharif & Karatas, A Framework for Identifying Causal Factors of Delay in Nuclear Power Plant Projects, May 2016, Procedia Engineering

[73] Beaupuy, EDF's UK Hinkley Nuclear Costs Balloon as Plant Delayed Anew, Jan. 2024, BloombergNEF

[74] CNL talks nuclear energy at Arctic Development Expo, Jun. 2021, Canadian Nuclear Laboratory

[75] Nuclear Island, Alfa Laval

- Main safety systems initiated without operator's decision that drive risk mitigation with no need for complete reactor shutdown[76]
- Passive safety systems with limited number of moving elements to enable safety protocols without need for backup power (i.e., rapid heat removal in emergency situations or during refueling)
- Reactor shell designed and built to sustain extreme weather conditions
- AI-supported security structure allows detecting malfunctions at early stage
- Hydrogen generated during standard operation is safely removed and incinerated to minimize risk of fire or explosion
- Closed-loop cooling offers safer and more effective solutions with less impact on the environment; steam generator blow-down provides required water quality along cycles

Most safety concerns are based on a subjective impression that the general nuclear technology is unsafe. The first SMRs are starting to get approvals from the Nuclear Regulatory Commission (NRC).[77] We have yet to see actual data-driven criteria that positions SMR relative to other existing industrial processes, it's too early to know.

The inability to generate sufficient renewable energy to electrify the economy drives the consideration and adoption of alternative sources of power. This transition will be supported by the most mature technology capable of providing significant contribution to the mix. Versatility in SMRs allows several years of operation without refueling and offers the possibility to operate independently or connected to the grid. Performance is optimal when SMRs co-exist with renewable technologies, where digitized energy management systems and practices support effective power distribution and resilience of the ecosystem. Operation-critical sectors of digitalized economy like data centers are expected to use SMR technology.

SMRs for data center power

Alternative sources of energy deployed locally provide reliable and resilient power – they're fundamental to a healthy digital economy. Most alternatives have limited potential to improve holistic access to power, they aren't sufficient at scale.[78] Eco-diesel or hydrogen-powered generators offer support in securing power for the sector or running specific solutions like byproduct hydrogen from manufacturing plants.[79] Despite storage capacity growth,[80] nuclear technology is an optimal investment for data centers resilient power offering broadly controlled power.

In response to growing environmental regulations the IT industry is facing increasing mandates for sustainability reporting, with existing policies already directly targeting data center sector.[81,82] Data centers with dedicated small modular nuclear reactors are planned across the US[83] and Europe.[84] The first nuclear-powered data

[76] Experimental Breeder Reactor-II, Argonne National Laboratory

[77] Judge, Modular nuclear player NuScale gets US regulatory approval, Jan. 2023, DCD

[78] Vincent, Microsoft Knows Future of Data Center Power Will Be 'Everything Everywhere All at Once', Jan. 2024, Data Center Frontier

[79] Judge, Honda and Mitsubishi to test data center powered by waste hydrogen, using recycled auto fuel cells, Jan. 2024, DCD

[80] Sekine, Energy Storage: 10 Things to Watch in 2024, Jan. 2024, BloombergNEF

[81] Energy efficiency directive, 2023, European Commission

[82] Data Center Certifications and Compliances, Colocation America

[83] Chernicoff, Nuclear-Powered Data Centers: Modular Reactors on the Horizon, Mar. 2023, Data Center Frontier

[84] Robinson, Swedish datacenter operator wants to go nuclear, Mar. 2023, The Register

center is already operating in Pennsylvania, powered by 2.5 GW conventional nuclear plant.[85] Another of many similar planned facilities will be located in Connecticut.[86] Deployment of data centers near existing nuclear power plants facilitates the regulatory process but also has limitations, driven by aging infrastructure.

There is good alignment between energy generation profiles from SMR technology and electrical loads of data centers. Data centers most likely will be the key beneficiates of more accessible nuclear energy. Bret Kugelmass, CEO of Last Energy indicates "data centers are one target niche."

Hyperscale data centers in particular struggle with undisturbed access to green and resilient energy. Nuclear technology can be an optimal solution for energy-intensive units.[87] A data center consuming up to 50 times the energy per floor space of a commercial office building will benefit from baseload carbon-free energy that is weather decoupled and offers a noticeable generation buffer.[88]

The scarcity of reliable power outside the current Tier 1 data center campuses will continue to attract modular technology. SMRs seems to be the optimal solution for larger data centers, especially in these power-constrained regions while microreactors may be more suitable as an alternative to energy storage or a better solution to power smaller data centers.

In fact, nuclear energy is the most effective source of energy now available, with negligible emissions and land use, considering capacity factor (see Figure 3).[89]

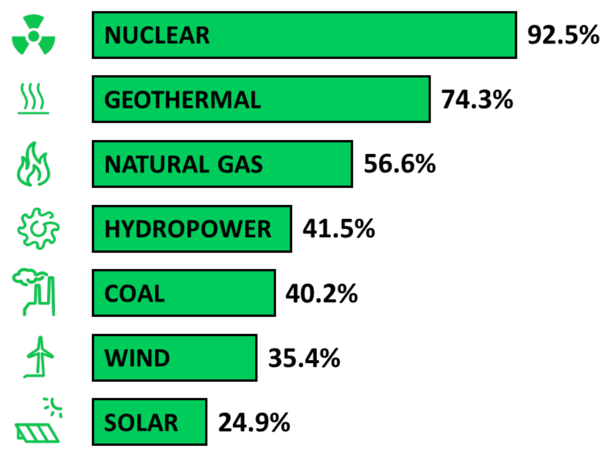

Figure 3

2020 capacity factors by energy source.[89]

The data center industry can also partner up with other branches of the economy to share nuclear energy between IT and a power-hungry manufacturing sector. Region-specific characteristics will impact types of SMR deployment.[90]

Onsite localization providing proximity to customer can mitigate challenges of energy transmission, like the USA. Localization model in Europe will most likely depend on the power range of the SMR, the power generation capacity in the country and the type of investment. Smaller sites and land-use optimization requirements cause reduction of modular reactors' resiliency and increase dependency on larger

[85] First nuclear-powered data center at Susquehanna completed, Jan. 2023, World Nuclear News

[86] Rogers, Nuclear-Powered Data Center Planned in Connecticut, Feb. 2023, GlobeSt

[87] Lawrence et al., Five Data Center Predictions for 2024, Jan. 2024, Uptime Institute

[88] Edwards, Nuclear-Powered Data Centers: Practical or a Pipe Dream?, Apr. 2023, Information Week

[89] Nuclear Power is the Most Reliable Energy Source and It's Not Even Close, Mar. 2021, Energy.gov

[90] Stevanka & Chvala, Deployment of small modular reactors in the European Union, Mar. 2024, NST Open Research

ecosystem. This may drive deployment of units that supply more than one customer but require connection to utility-scale plants.

Progressing digitization of the economy will support faster and more efficient implementation of nuclear power to in the energy mix.[91] Digital tools like AI can support development of technology and improve sustainable operations,[92] i.e., by enabling previously inaccessible resources or running plant simulations in digital twins. Licensing, now easier for SMR than for traditional large reactors, can be further accelerated by machine learning.[93,94] AI can deliver its promise only when data centers can access enough energy to run the algorithms.[95] Surging demand can cause an industry-wide energy crisis could be ended with adaptation of nuclear technology.

There may be mismatch between modular nuclear technology and data center changing demand profile, as most SMRs are built for steady state generation. This has implications on both the reactor and the data center, especially when demand variability can't be mitigated. We need to examine how SMRs would participate across a data centers complete usage profile to determine the best path to optimize performance.

Future of SMR in data center industry

Transmission bottlenecks and climate policies mandating retirement of fossil-fuel power generation are causing disruption in data centers. The sector's energy shortage is not going to be mediated by increasing renewables in the short term. Their share in energy mix - because of supply chain challenges and insufficient development of crucial infrastructure – is just not available yet. Data centers operators focusing on renewable microgrids must now choose between a lower cost and shorter lifetime of Tier 2 PV or a higher investment for long-lasting Tier 1 PV. Expansion of minerals mining required to build and deploy sufficient solar capacity could have negative effect on efficiency of photovoltaics, especially Tier 1.[96,97]

We've currently seen an overestimation of expected wind power supply[98,99] suggests lower than expected performance. Meanwhile, storage infrastructure is evolving with improvement of price-to-capacity ratios.[100] Smart tools managing distributed grids are enabling efficient adoption of renewables across industries.

However, long approval times for new transmission lines and problems with distribution networks are driving data center developers towards on-site generation solutions. This is a chance where SMR technology could play a pivotal role as an on-site power supply. The company Last Energy has already secured several 20 MWe (60 MWth) reactors in Europe,[101] while the company Stellaria Energy received LOI to deliver 550 MWe by 2036. The technology is not constrained by access to water

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[91] Accelerating a Carbon-Free Future, Dec. 2023, Microsoft

[92] Vlasov & Barbarino, Seven Ways AI Will Change Nuclear Science and Technology, Sep. 2022, IAEA

[93] Artificial Intelligence for Accelerating Nuclear Applications, Science and Technology, 2022, IAEA

[94] Moss, Microsoft trains generative AI to handle SMR nuclear regulatory process, Dec. 2023, DCD

[95] Glitt, AI's Power Problem and How To Fix It, Jul. 2023, Data Center Knowledge

[96] Mineral requirements for clean energy transitions, 2020, IEA

[97] Material and Resource Requirements for the Energy Transition, Jul. 2023, Energy Transitions Commission

[98] UK energy minister condemns wind farms for overstating output, Feb. 2024, Energy Voice

[99] Lee & Fields, An overview of wind-energy-production prediction bias, losses, and uncertainties, Mar. 2021, European Academy of Wind Energy

[100] CATL tops global EV battery market for the seven consecutive year, Feb. 2024, CATL

[101] Patel, Last Energy Secures PPAs for 34 SMR Nuclear Power Plants in Poland and the UK, Mar. 2023, Power

resource other than municipal water. There are 21 other advanced technologies that are similar and can make an impact on the market.[102]

Cost-related delays observed for conventional reactors are less likely to repeat for SMRs given their smaller scale and reductions in required project budget. Building energy infrastructure on-site will be a big factor in reducing costs of SMR technology. AI-driven testing will accelerate research and use of digital tools – such as digital twins to model and pretest a facility – will likely lead to efficient management of project financing and permitting, finally allowing to deploy first-of-a-kind (FOAK) units in selected ecosystems.[91] They will also lead to longer term optimizations in operations. Some of the required nuclear capacity with SMR technology may be a solution for shortage of skilled labor force in the sector. Modular reactors require significantly less staff and efficiency factor of conventional plant can be improved by 30%.[103]

SMRs offers reliable and scalable, safe source of baseload carbon free energy for data centers. Technology can be deployed either onsite or offsite with connection to the main grid. The latter can decrease resilience of the utility grid and may regionally introduce uncertainty for data center developer and operator. However, effective integration of SMRs in microgrids based on renewables provide sustainable power with capacity to effectively manage changing demand. Safe modular architecture includes elements manufactured under strict quality control.

Reactors have minimal operational risk due to self-shutdown designs and are powered by recycled spent fuel. Refueling once in a decade and maintenance will provide undisrupted continuous power delivery more than 95% time. Questioned competitiveness with renewables focuses on lower waste generation and reduced environmental carbon footprint. Technology offering improved mass-to-energy ratios achieved thanks to novel uranium fuel and reactor designs requires regulatory standardization and homogeneity. Access to skilled personnel along the supply chain will increase as SMRs become more popular.

Some of the nuclear energy is likely to be offered within over a decade long PPAs, contracts where customers purchase power from a system installed, owned, and operated by a developer. This model enables SMR developers to deliver competitive returns to their investors.

Conclusion

While nuclear fuel is the most abundant source of energy able to generate firm and low-carbon baseload electricity, legacy designs extensively use water and have a spotty reliability and safety record. SMR technology has matured, and their safety and reliability claims have data center operators intrigued. While there is much excitement for the technology, it must be proven before regulators allow for mass deployments. The industry is in process of establishing an optimized deployment model allowing for effective adoption of modular technology in data center industry. SMR technology is competitive to photovoltaic and wind in waste production. Where modular reactors can work best is in concert with renewable resources as a complementary generation technology for green power.

Additionally, and it goes without saying every new technology requires a thorough vetting. In this case, an SMR evaluation would also include a security and risk assessment, as dictated by the data center operator and its partners to address any local and national concerns. These are separate and apart from their safety, resilience and sustainability. Such an audit would be included in normal planning and outside the scope of this technology overview.

[102] Small Modular Reactor Dashboard, 2023, Nuclear Energy Agency

[103] Staffing requirements for future small and medium reactors (SMRs) based on operating experience and projections, Jan. 2001, IAEA

The Data center industry will need to consider higher upfront costs for nuclear power to a generation profile matching their demand. It's the most realistic path to meeting sustainability commitments. Safe and resilient reactors deployed onsite or as grid infrastructure may be a remedy to power shortages if regulatory and manufacturing regimes become standardized across geographies.

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