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NEXUS-DC: Nuclear Energy eXpedition for US Data Centers

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Content Note and Outline

Content Note:

The content of this presentation is taken from the INL Data center workshop, lecture notes, publish articles and INL's internal reports. This presentation focused on the general overview of nuclear-powered data center in the U.S.!

Presentation Outline

- **Part-I: Objective, Motivation, Overview of Nuclear-Powered Data Center in the U.S.**
- **Part-II: Site selection and Regulatory Requirements**
- **Part-III: Community Engagements, Deployment and Techno-economic Consideration, and Summary**

One Page Overview: Nuclear-Powered Data Centers

Key takeaways:

- ⚡ High demand for small to large nuclear reactors offering N+1/N+2 options to ensure 99.99% reliability.
- ❄️ Prioritize reliable power and cooling solutions before integrating other options like hydrogen co-generation.
- 🌐 Strategic site selection: water resources, grid access, land, and optical fiber connectivity are essential.
- 🤝 Community engagement and partnerships with DOE and DOD for support and regulatory compliance are vital.
- ⏳ Urgency for regulatory streamlining to achieve deployment within 6-7 years (max 10 years).

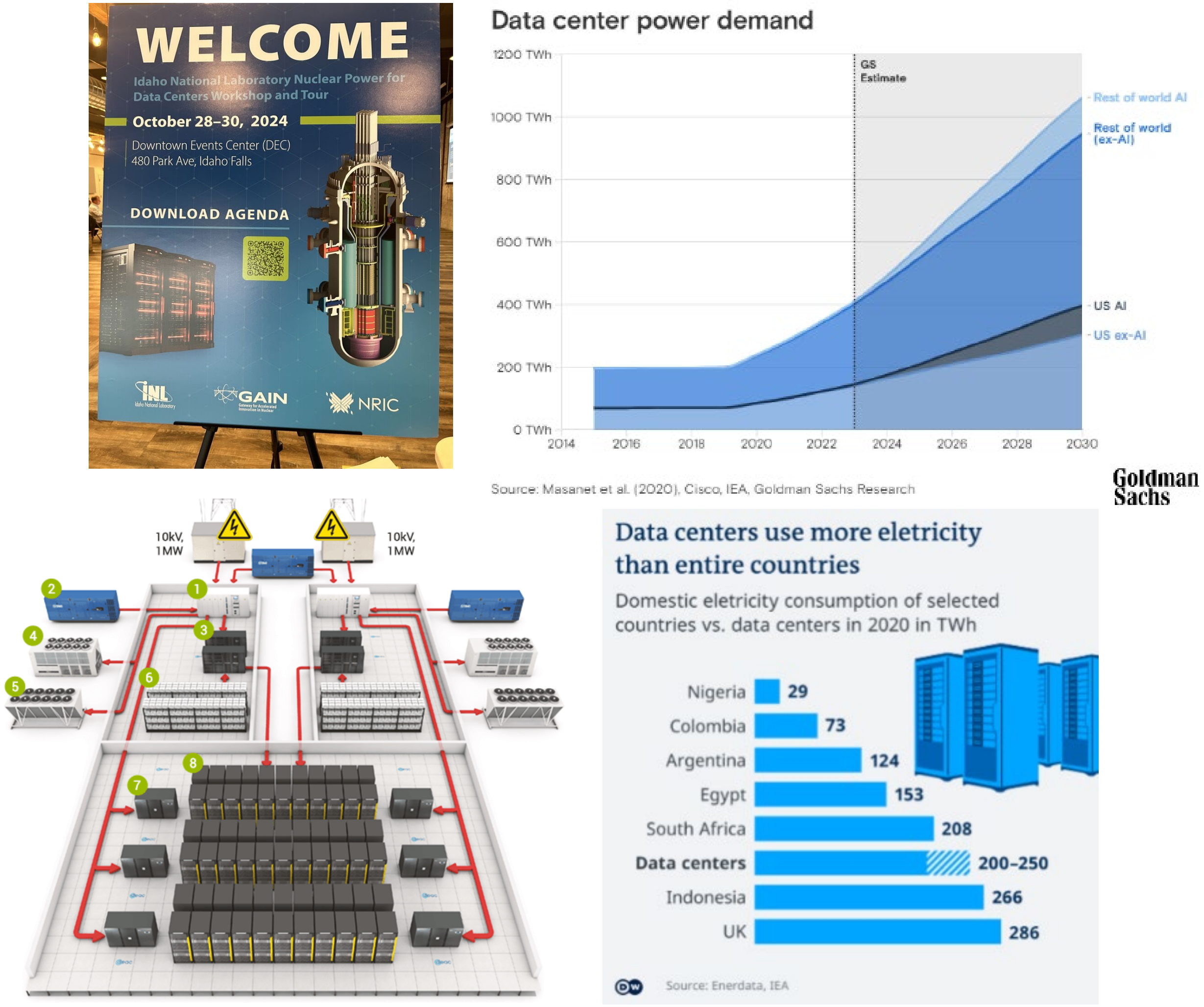


Figure: Data center: (a) INL workshop, (b) power demand worldwide, (c) facility overview, and (d) power consumption.

Source: https://energycentral.com/c/ec/us-data-center-energy-train-wreck
https://blog.publiccomps.com/a-primer-on-data-centers/

Objective and Motivation

Objective: Accelerated deployment of nuclear-powered data centers to meet the escalating energy demands of data centers in the USA

Motivation: This study aims to provide actionable insights for stakeholders to accelerate the deployment of nuclear-powered data centers, thereby enhancing energy reliability, sustainability, and national security in the USA.

Therefore, a general techno-economical analysis understanding would be supportive for these target challenges:

- **Goal: Strengthen the Techno economic analysis of nuclear-powered data centers**
- **Goal: Enable U.S. Leadership in Global Nuclear Energy Markets with NEXUS-DC**

Here, NEXUS-DC is for "Nuclear Energy eXpedition for US Data Centers,"

- a pursuit to identify the road-blocks with realistic accelerated deployment actions to play
- focus on reactor demand, site selection, community engagement, and regulatory frameworks.

Part-I:

Overview of Data Center: Industry Growth and Status

- **Data center industry are energy hungry: need clean, reliable, scalable, and economical energy!**
- **New data centers prefer sites with access to land and water, as well as grid and optical fiber connectivity!**

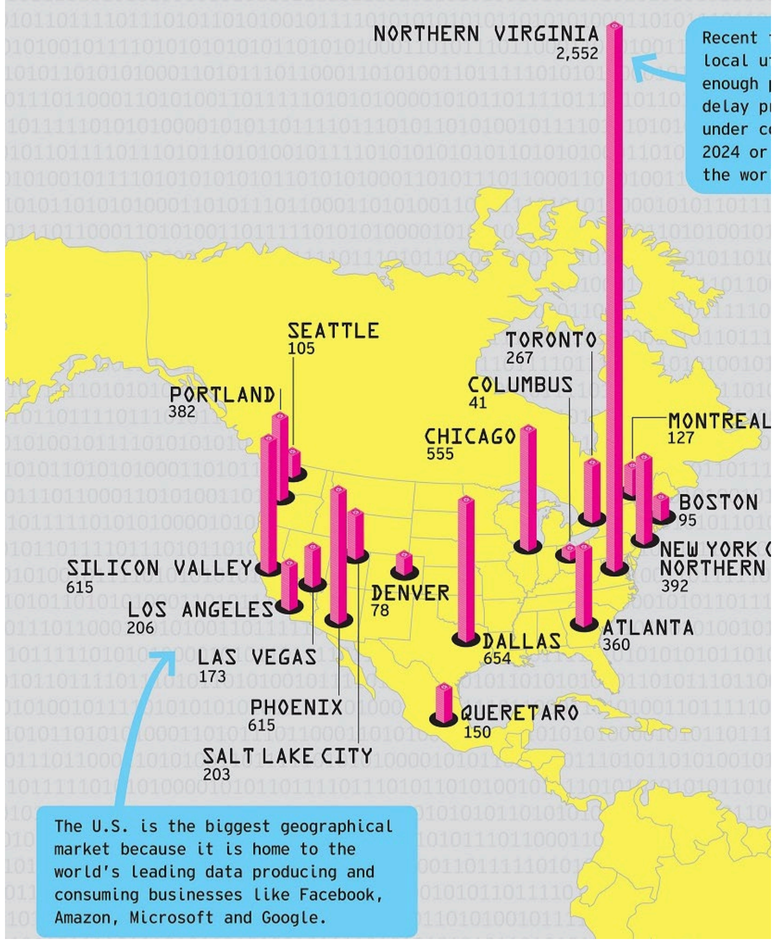
Worldwide Data Centers

Current
~8,000 Data Centers globally
~33% in the U.S.

~460 TWh demand globally (52 GWe gen
~200 TWh in the US (22 GWe generation)

By 2026
~800-1000 TWh global demand
~260 TWh U.S. demand

By 2030
U.S. Data Centers will need
30-35 GWe of additional capacity



Data centers consume a significant amount of electricity
- Significant growth is led by hyperscale data centers
- The goal is to increase the use of carbon free energy
- Renewable energy is an option, but reliability is a challenge
- Challenge for utilities to meet the timely demand

Nuclear energy provides carbon-free, dispatchable and reliable which Data Center is looking for!

Taken from [1], For more information: https://brightlio.com/data-center-stats/ and https://www.visualcapitalist.com/cp/top-data-center-markets/ [2]

Overview of Data Center: Capacity and Types

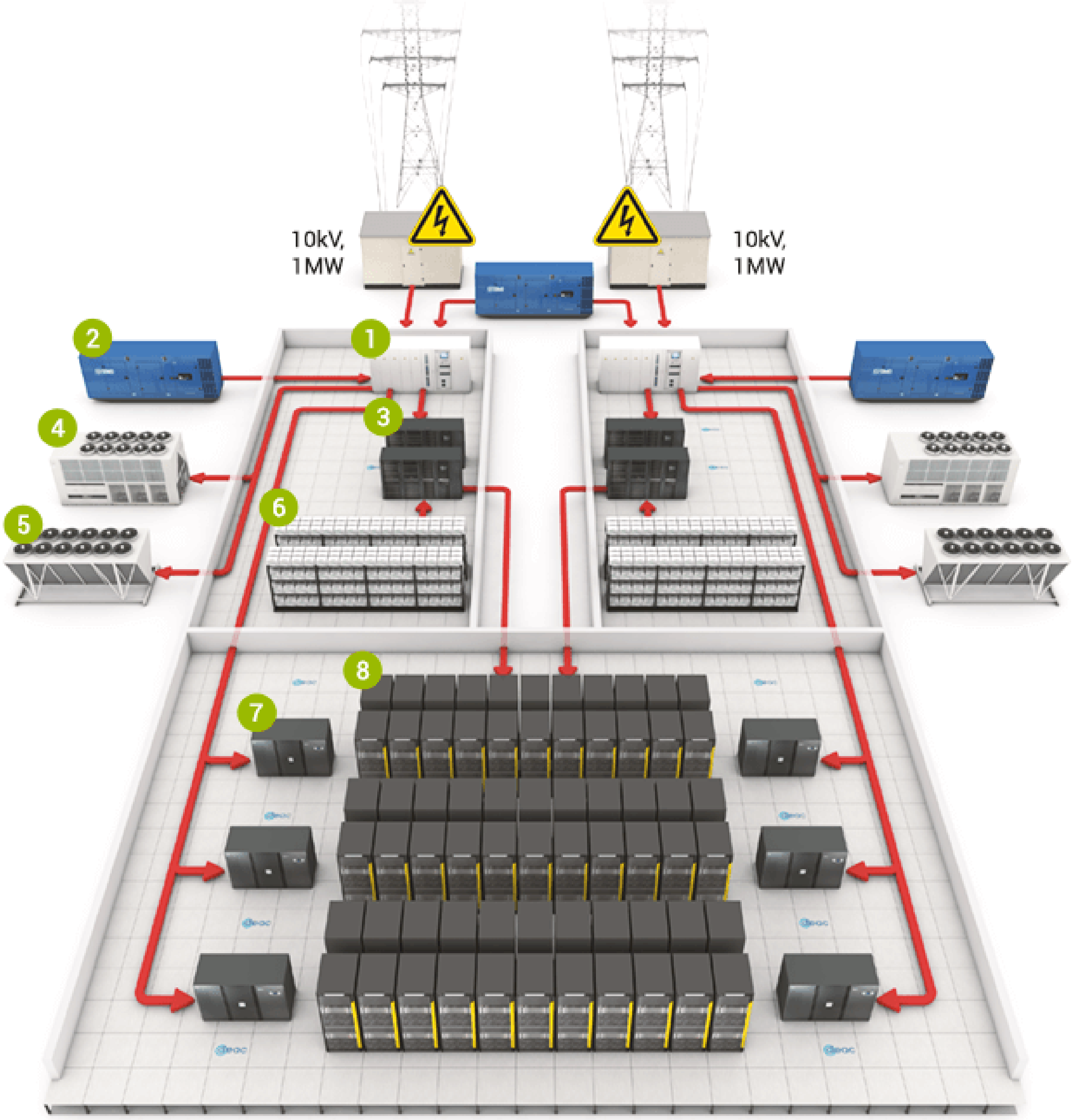
- **Small Data Centers:**
  - Facilities under 5,000 square feet of computer floor space
  - Comprise more than half of all servers in data centers
  - Represent the largest share of data center load.
- **Colocation Facilities:**
  - Multi-tenant data centers
  - The owner leases space, power, and cooling to multiple customers
  - Customers have varying IT hardware and needs.
- **Enterprise Data Centers:**
  - Owned and operated by a single company
  - Critical to the firm's operational integrity
  - Often sizable, though not as large as hyperscale data centers
- **High-Performance Computing (HPC):**
  - High server utilization rates and high-power requirements
  - Typically low availability requirements
  - Used by universities, research centers, and increasingly private businesses
- **Hyperscale Data Centers:**
  - Owned by large tech firms, cloud providers, and telecommunications organizations
  - Massive in size and energy/water requirements
  - High requirements for continuous, uninterrupted operation.

Source: https://betterbuildingssolutioncenter.energy.gov/data-center-toolkit [3]

Overview of Data Center: Visual Representation

- Items in traditional data center:

1) Main power distribution with Automatic Transfer Switch (ATS)
2) Diesel Generator
3) Uninterruptible Power Supply (UPS)
4) Network Power chiller
5) Dry cooler
6) UPS batteries
7) Network Power climate control
8) Servers, storage, and networking equipment
9) Electric grid connected power transformers

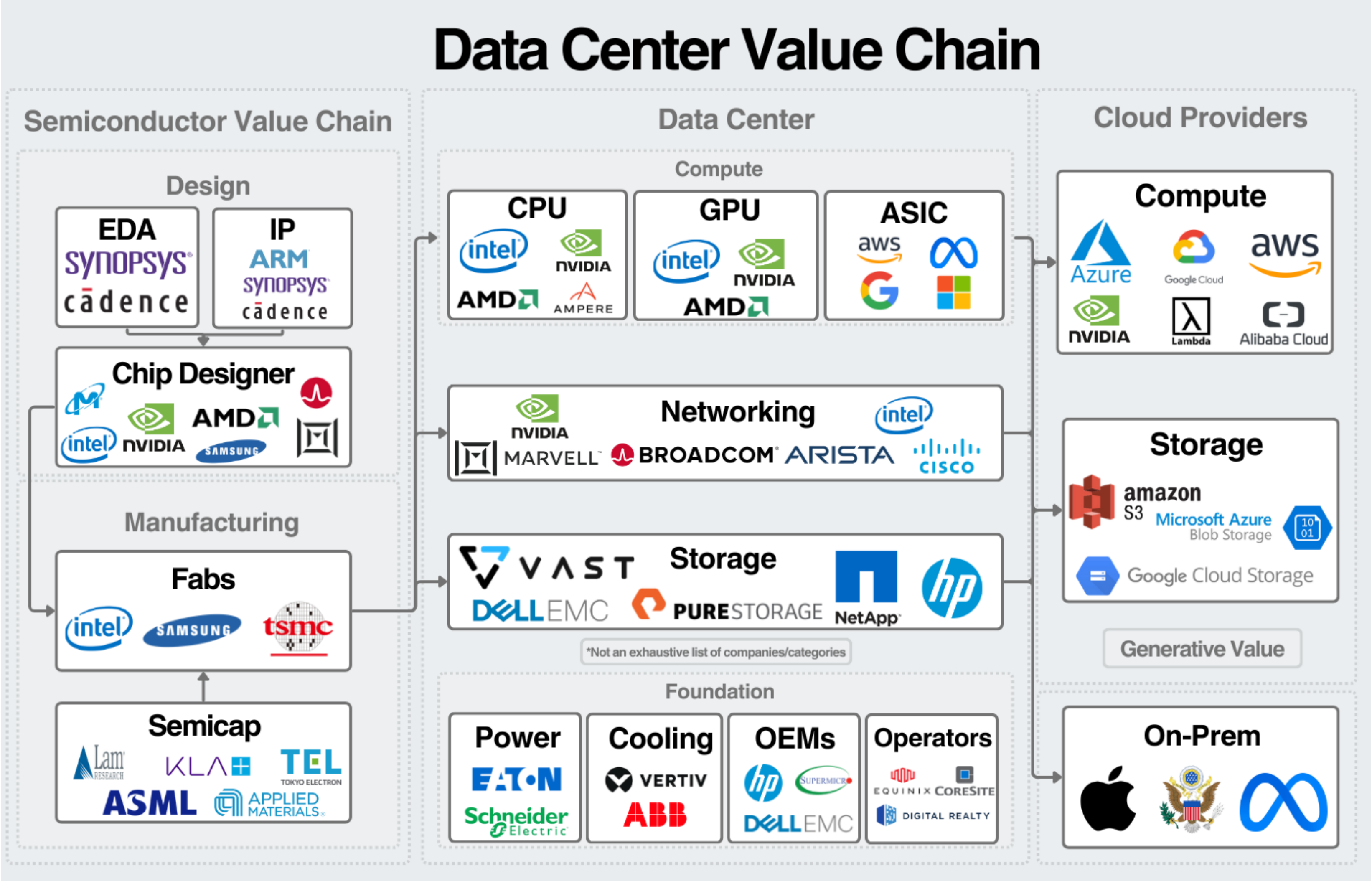


Source: https://blog.publiccomps.com/a-primer-on-data-centers/ [4]

Overview of Data Center: Value Chain

- **Products/services related to data center:**
  - Semiconductor: design and manufacturing
  - Data center cloud providers: compute, networking, storage, power, cooling, and operating software

All the major tech industries (e.g., Microsoft, Amazon, Google, Intel, Nvidia, AMD, HP and DELL) product and/or services are somehow connected to data center value chain.

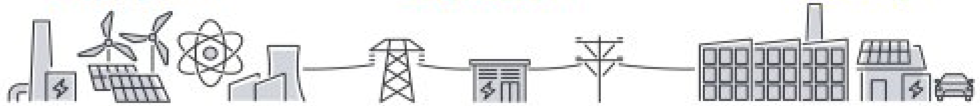


Source: https://blog.publiccomps.com/a-primer-on-data-centers/ [4]

Overview of Data Center Industry (cont'd)

- **The U.S. rising total energy demand potentially growing ~15-20% in the next decade.**
- **Data center electricity demand can present challenges in an evolving power system, targeted actions can help the U.S. maintain a reliable, affordable, secure, and resilient power system!**
- **DOE Resources Available to Support Data Center Electricity Needs:** https://www.energy.gov/sites/default/files/2024-08/DOE%20Data%20Center%20Electricity%20Demand%20Resources.pdf [5]

Source: https://www.energy.gov/policy/articles/clean-energy-resources-meet-data-center-electricity-demand [6]

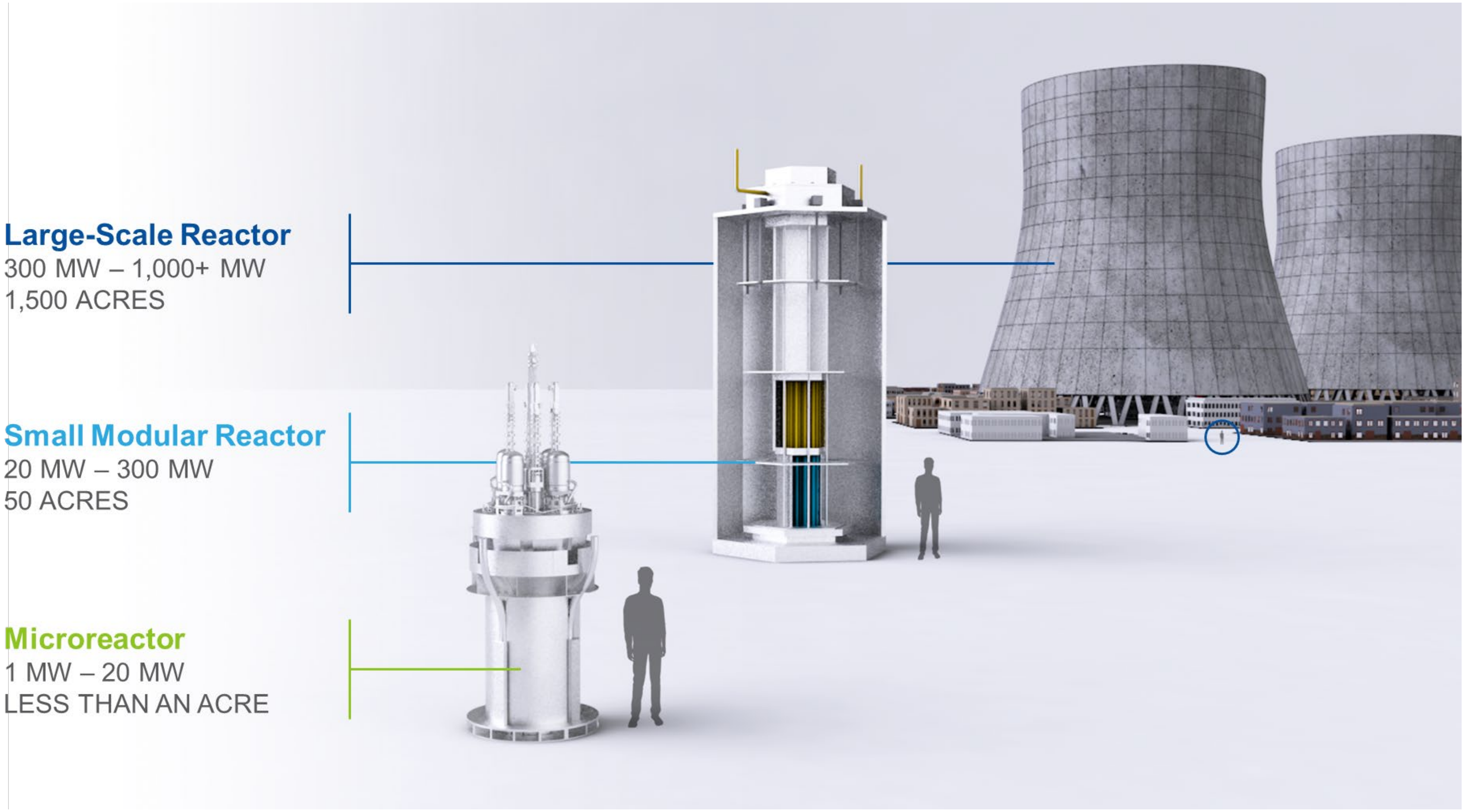


Grid Scale Clean Energy Deployment	Grid Infrastructure Enhancement and Expansion	Energy Efficiency and Demand Side Flexibility	Maximizing Data Center Efficiency and Operational Flexibility
Expand existing supply *(including repurposing existing infrastructure)* • *Solar* • *Onshore wind* • *Storage (batteries)* • *Hydropower* • *Conventional geothermal (hydrothermal)* • *Nuclear (including uprates and relicensing)* • *Offshore wind* • …	**Enhance existing transmission and distribution** • *Advanced reconductoring* • *Grid-enhancing technologies* • *Distribution automation* • *Point-to-point HVDC* • *Advanced flexible transformers* • …	**Improve energy efficiency** • *Building efficiency* • *Geothermal heating and cooling* • …	**Improve data center efficiency** • *Hardware efficiency* • *AI algorithm efficiency* • *Building automation* • *Building efficiency* • *Geothermal heating and cooling* • …
Scale emerging solutions • *Advanced nuclear* • *Next-gen geothermal* • *Long duration energy storage (LDES)* • *Carbon capture storage (CCS) on power plants* • *Clean hydrogen* • *Concentrated solar power* • …	**Expand transmission and distribution** • *Advanced conductors* • *Interregional and regional high voltage DC / AC transmission* • *Distribution system* • …	**Manage and flex demand** • *Virtual power plants* • *Distributed energy resources* • *Microgrids* • *Fuel cells* • …	**Enhance operational flexibility and efficiency** • *Flexible operational processes* • *On-site power generation and facility design optimization* • …

Advanced key enablers:
- Proactive planning, evolving regulatory decision-making and processes
- Grid market frameworks that fully value energy solutions, modernizing interconnection
- Permitting enhancements, innovative tariff structures, new financing structures
- Supply chain and workforce development

Overview of Reactor Systems: based on reactor sizes

Mostly three sizes: (a) Large-scale, (b) Small modular reactors (SMRs), and (c) Micro-sized [7].



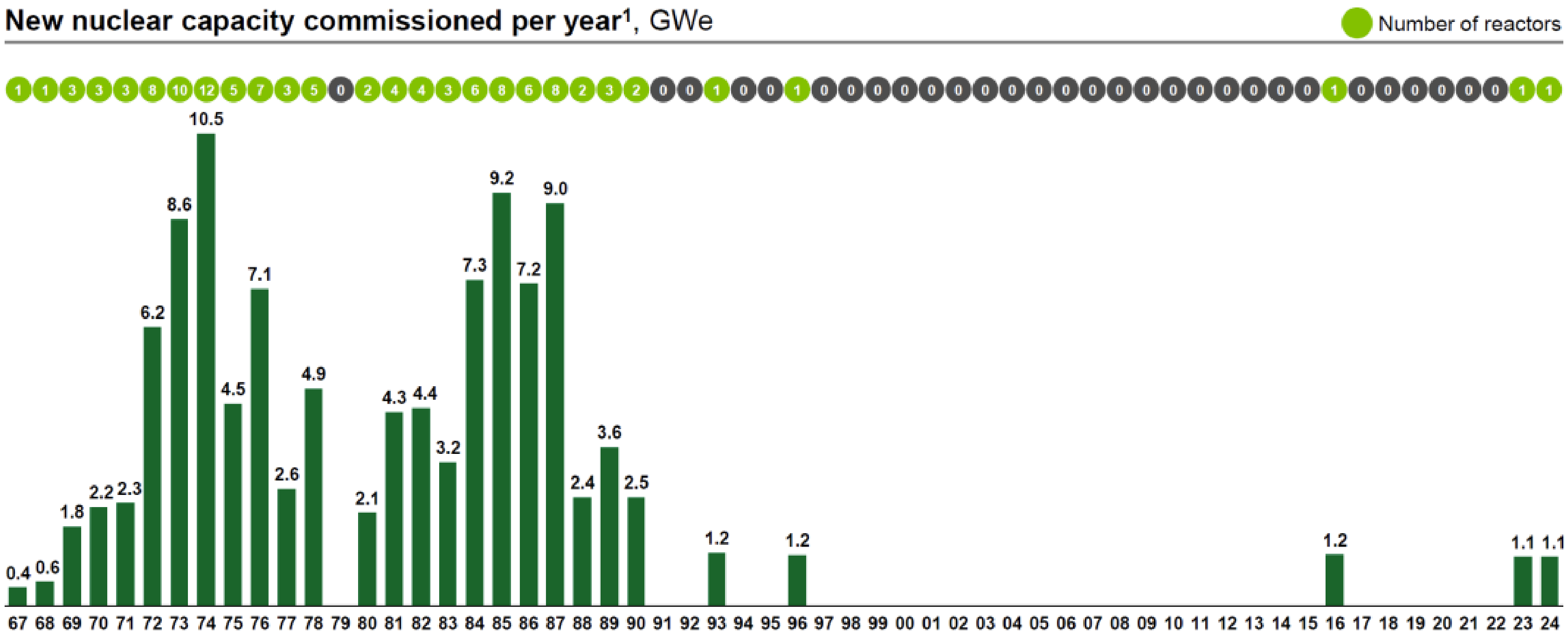
Despite the recent surge in interest, the basic SMR concept is not a novel one. Initial plant designs in the 1950s—including the very first commercial reactors—were, in many ways, SMRs with power output ranges of 10–100 MWe [8].

SMRs Development phases: more than 80 SMRs are under design, development, demonstration, deployment, and beyond (4D+) phases worldwide.

USA Nuclear Context: large-reactors

- USA will need 200 GWe of new nuclear by 2050; tripling current 100 GWe capacity (>7 GWe/year!)
- Has been done before (12 units in 1974), but it remains a huge challenge with supply chain decay.
- Comparison with China: added 34 GWe in last 10 years.

Most of the US fleet was built 1970-1980s; in 1974, 12 reactors came online



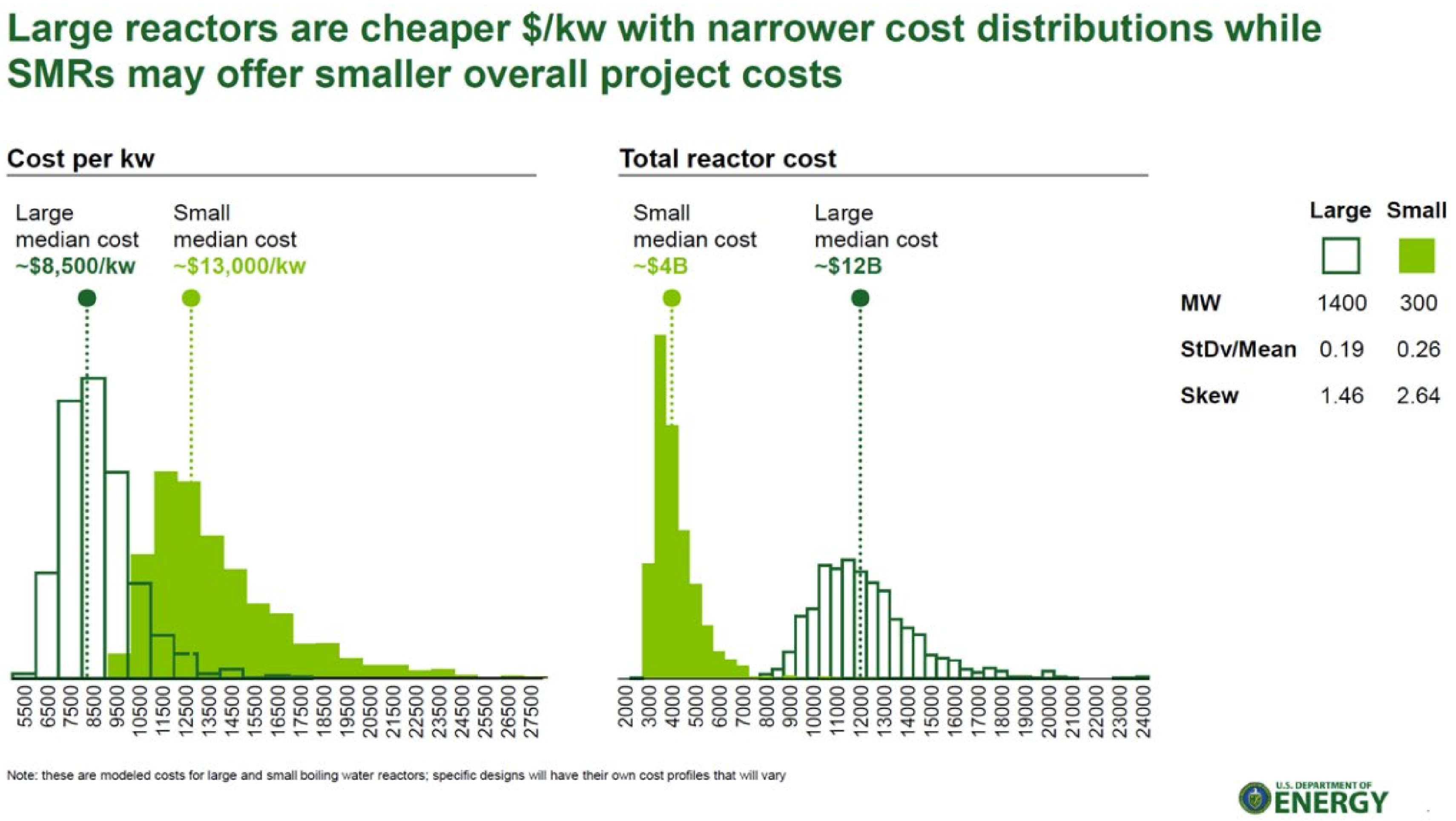
1. Excludes test and prototype reactors; Note: Watts Bar 1 & 2 construction originally began in 1973 and halted in 1985; construction resumed on Unit 1 in 1992 and Unit 2 in 2007

Source: Advanced Nuclear - Pathways to Commercial Liftoff [9]

Existing nuclear fleet produce extremely cheap (**will be approximately $32/MWh**) electricity if lifetime extensions taken into account− **88 out of 92 US reactors were granted 60-year lifetime extensions**

Taken from [1].

USA Nuclear Context: large reactors vs SMRs (cont'd)



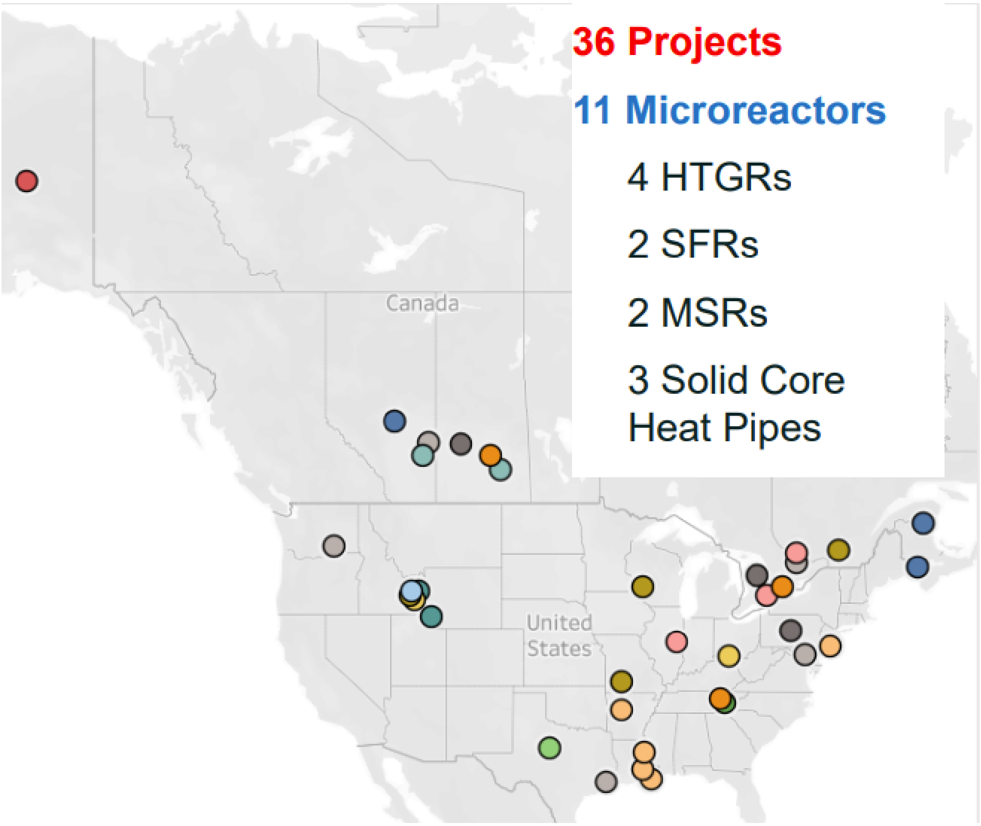
Source: Advanced Nuclear - Pathways to Commercial Liftoff [9]

SMRs are preferable over large reactors for data center considering the factory fabrication, small, modular configuration and multi-unit capacity addition!

Taken from [1].

Part-I:

North America Nuclear Context: SMR Projects (cont'd)



Developer
- ARC Clean Technology
- BWXT
- GE-Hitachi
- Holtec
- Kairos Power
- Nuclear Energy eXperimental Testing Research Alliance (NEXTRA)
- NuScale Power
- Oklo
- TerraPower
- Terrestrial Energy
- To Be Determined (TBD)
- Ultra Safe Nuclear Corporation (USNC)
- Westinghouse
- X-energy

25 SMRs
- 12 Light Water Reactor (LWR)
- 5 High Temperature Gas Reactor (HTGR)
- 4 Sodium Fast Reactor (SFR)
- 2 Molten Salt Reactor (MSR)
- 2 Fluoride Salt-Cooled High-Temperature Reactor (FHR)

Taken from [1].

18 deployment dates prior to 2030!

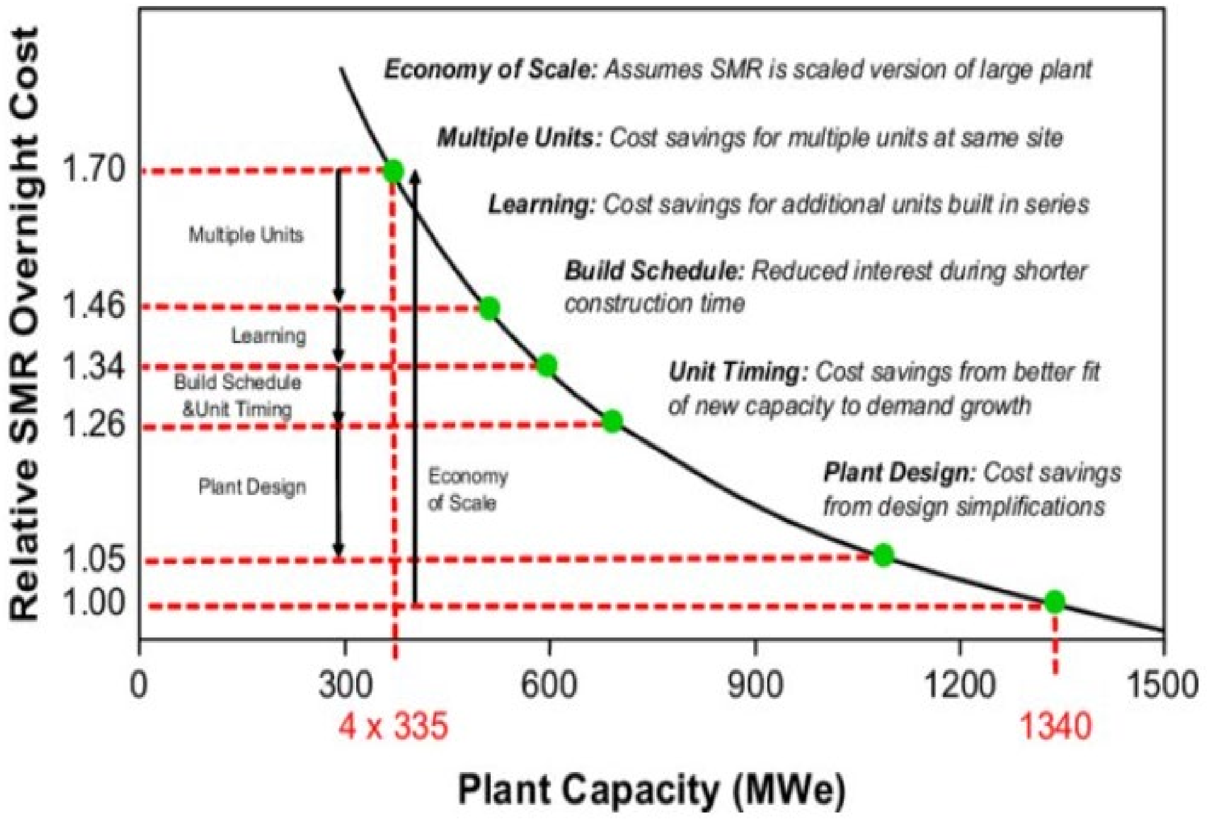
Source: https://public.tableau.com/views/NIAMap-NorthAmerica-June8/Sheet1 [10]

SMRs and Advanced Reactor: Technology Development

- **Stages Reactor Technology Development [7][11]**
  - Near-Term vs. Long-Term Development
    - Near-Term Technology Development Can be achieved by adopting/buying existing technology
  - As per IAEA's buying cases (Section 5.1)
    - Owner/Operating Organization or Licensee Roadmap

Thus, cases for buying, developing, and inventing require detailed techno-economic studies!

SMR and microreactor designs which are ready for demonstration or deployment could be suitable for consideration.



Economic scaling factor for SMRs and a single large reactor plant [12].

SMRs and Advanced Reactor: Technology by Coolant

GAS: Gas is used to transfer heat from the core. Helium is favored because it is inert and does not react with other materials or deteriorate components.

Micro Modular Reactor (3.5-15 MWe)
- Fuel: TRISO 🟢
- Company: Ultra Safe Nuclear Corp.

Fast Modular Reactor (44 MWe) 🟣
- Fuel: Uranium oxide 🟢
- Company: General Atomics

Xe-100 (80 MWe per module)
- Fuel: TRISO 🟢
- Company: X-energy

Energy Multiplier Module (265 MWe) 🟣
- Fuel: Uranium carbide 🟢
- Company: General Atomics

Kaleidos (1.2 MWe)
- Fuel: TRISO 🟢
- Company: Radiant

WATER: Highly purified water carries heat from the reactor core.

VOYGR (77 MWe per module)
- Fuel: Uranium oxide
- Company: NuScale Power

SMR-300 (300 MWe)
- Fuel: Uranium oxide
- Company: Holtec International

BWRX-300 (300 MWe)
- Fuel: Uranium oxide
- Company: GE-Hitachi

AP300 (300 MWe)
- Fuel: Uranium oxide
- Company: Westinghouse

MOLTEN SALT: Melted (or molten) salt transfers the heat, which has a high boiling point, so the reactors can run at higher temperatures and lower pressures. Fuel can be in the salt or in solid form.

Fluoride Salt-Cooled High-Temperature Reactor (140 MWe)
- Fuel: TRISO (solid fuel) 🟢
- Company: Kairos Power

Integral Molten Salt Reactor (195 MWe)
- Fuel: Uranium molten fluoride
- Company: Terrestrial Energy

Molten Chloride Fast Reactor (310 MWe) 🟣
- Fuel: Molten salt 🟢
- Company: TerraPower

LIQUID METAL: Liquid metal, often sodium or lead, transfers the heat in these reactors. Liquid metals do not slow down neutrons and are typically used for fast neutron reactors.

Aurora (15 MWe) 🟣
- Fuel: Uranium metal alloy 🟢
- Company: Oklo

ARC-100 (100 MWe) 🟣
- Fuel: Uranium metal alloy 🟢
- Company: ARC Clean Technology

Natrium (345 MWe) 🟣
- Fuel: Uranium metal alloy 🟢
- Company: TerraPower

Aalo-1 Microreactor (10 MWe)
- Fuel: Uranium Zironium Hydride
- Company: Aalo Atomics

HEAT PIPES: Heat pipes made from steel alloys transfer heat away from the reactor core with no moving parts.

eVinci (5 MWe)
- Fuel: TRISO 🟢
- Company: Westinghouse

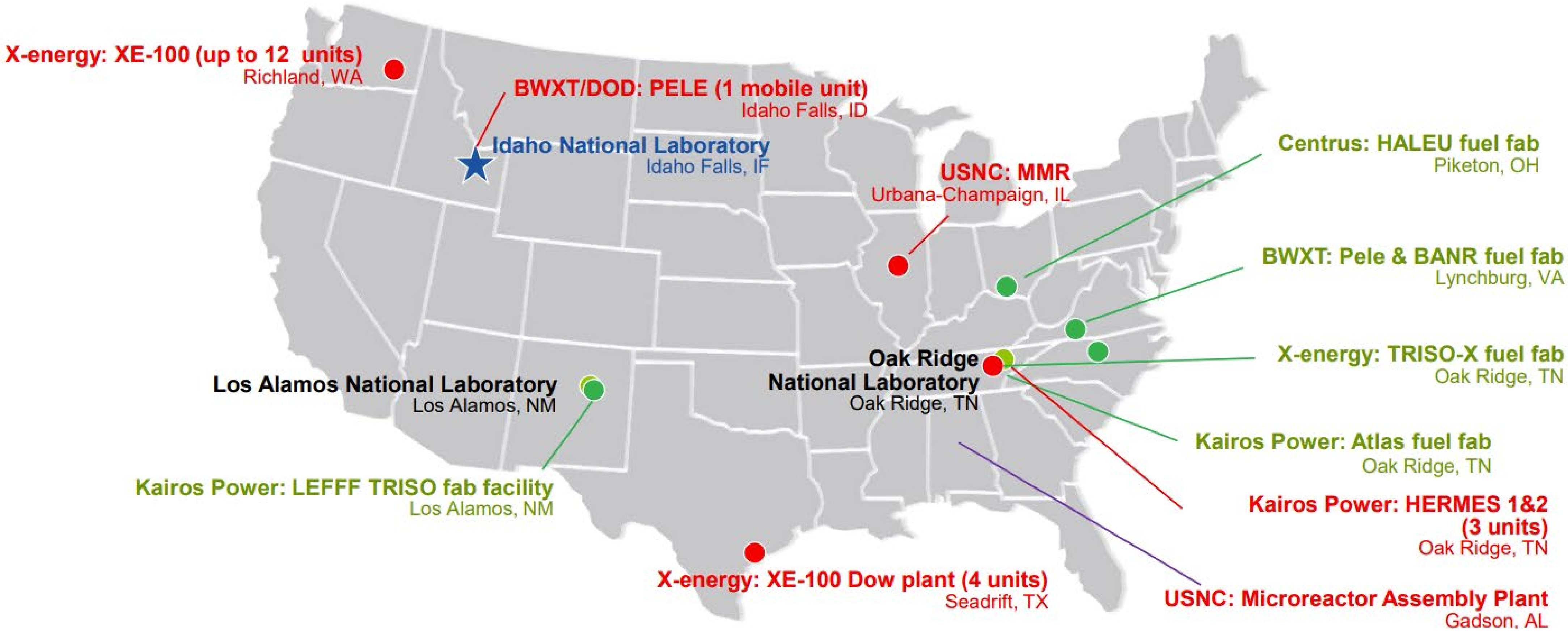
Taken from [1].

Includes only companies that are engaged in formal licensing or pre-licensing activities with the Nuclear Regulatory Commission for power-producing reactors.

🟢 HALEU (High-assay low-enriched uranium is 5-20% U-235)

🟣 Fast neutron reactor

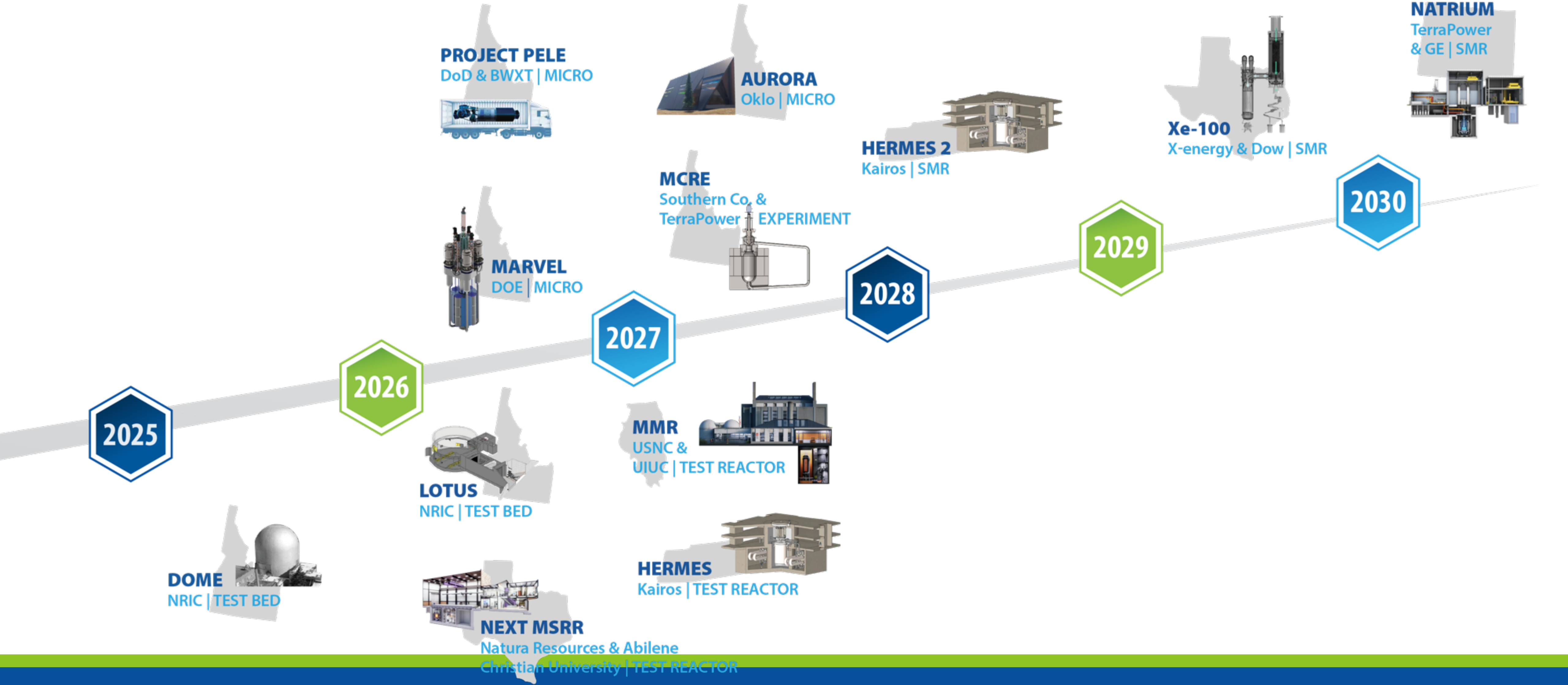
SMRs and Advanced Reactor: Planned Reactor and Fuel Fabrication Facilities



Taken from [1].

Part-I:

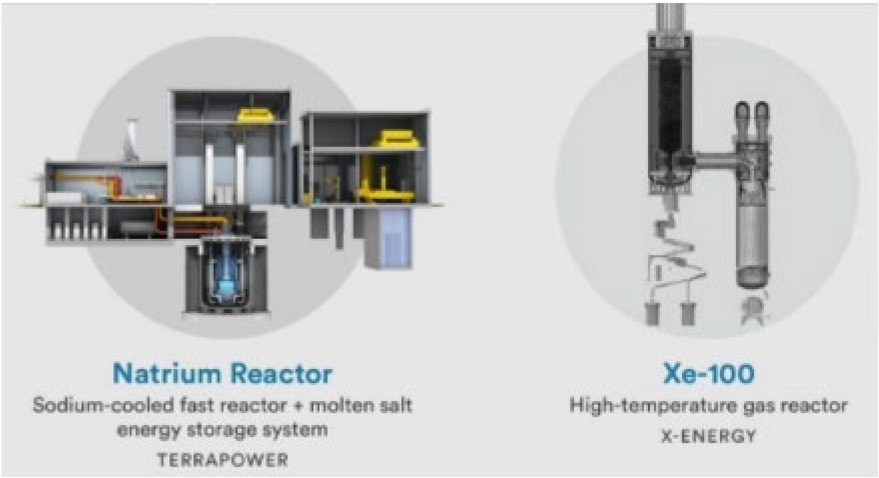
SMRs and Advanced Reactor: Demonstration Status in the U.S.



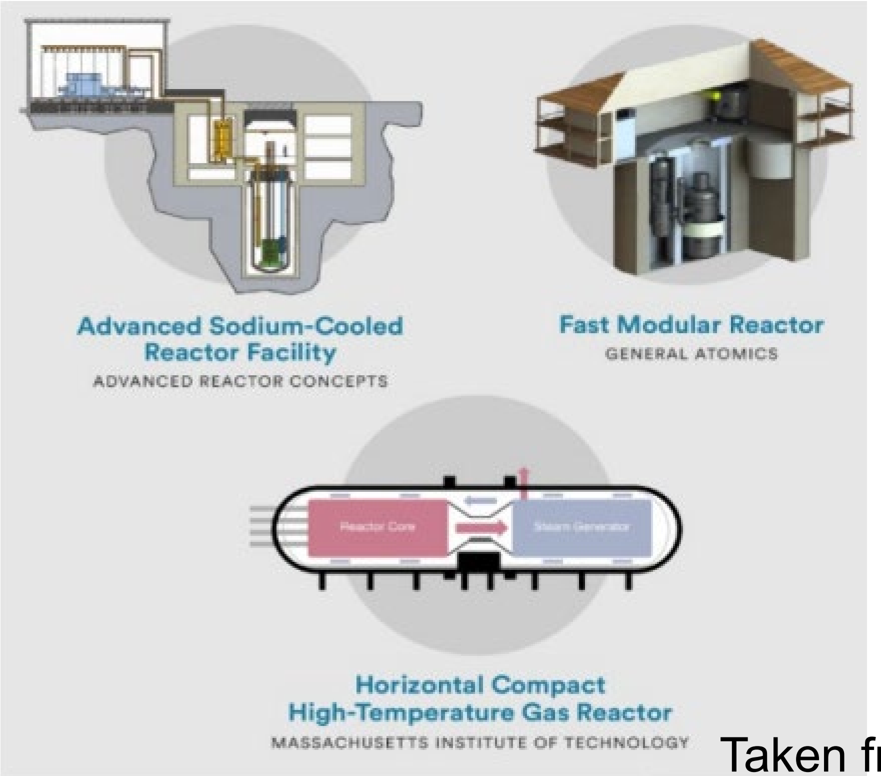
SMRs and Advanced Reactor: Demonstration Projects at INL

- **Bridge the gap between development and commercialization**
- **Learn by doing reduces risks associated with first commercial build**
- **Builds confidence with regulators, develops supply chain**
- **INL scope range:** Modeling & Simulation, Irradiation & post irradiation experiment (PIE), Fuel design & fabrication
- Digital Engineering and project management tools

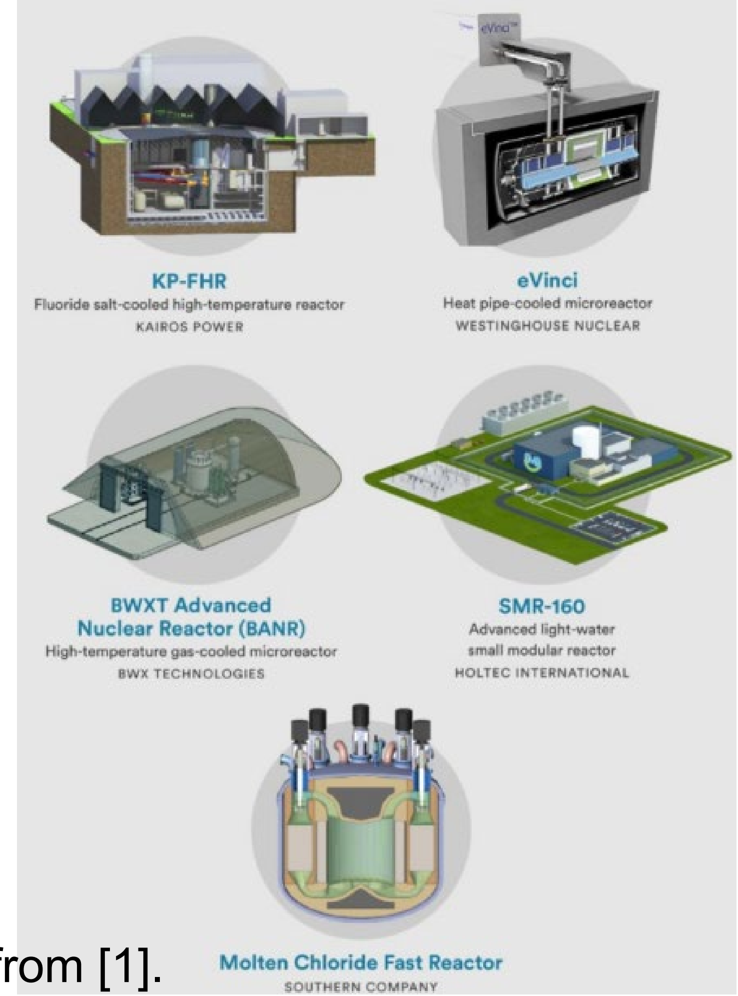
Demonstration



Concept Development



Risk Reduction



Taken from [1].

NEXUS-DC: Nuclear Energy eXpedition for US Data Centers

- **Rising Energy Demand:**
  - Significant U.S. energy demand increase due to data centers, industrialization, and electrification.
  - Data centers lead growth, driven by generative AI.
  - Potential rise from 4% to 9% of U.S. electricity use by 2030
  - Nuclear energy producing 46% of the U.S.'s carbon-free energy
  - Rising demand risking higher household electricity rates and grid reliability
  - Tech companies are asked to source their own energy by the community

- **Nuclear Energy as a Potential Options**
  - Various reactor types and capacities—large to small—offer flexibility in deployment
  - Co-location with existing plants, restarting shutdown plants, and building new reactors are key strategies for tech companies.
  - These reactors can be sited close to data centers, providing tailored power solutions
  - Bipartisan support, exemplified by the ADVANCE Act and other legislative measures
  - New business models and regulatory frameworks are emerging to support tech-nuclear projects.
  - First-of-a-kind projects face logistical challenges but pave the way for future advancements.

NEXUS-DC: Energy Supply Options

- **Nuclear reactors are ideally positioned for data center use**
  - Design standardization and modular construction, high capacity factors (93%+)
  - Multiple modular units lead to less downtime and enable islanded off-grid use
  - Can be located near or next to data centers, minimizing the need for transmission lines
  - Nuclear energy density leads to small footprints/land which is **x360 for wind and x75 for solar**

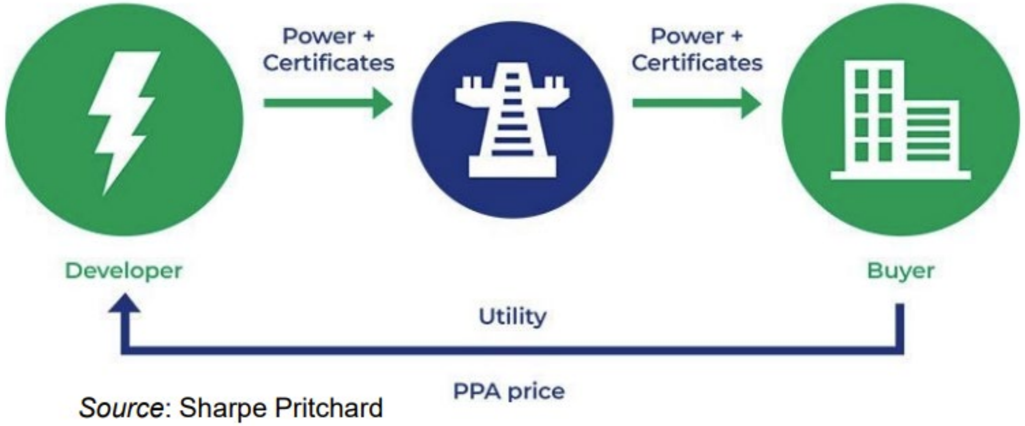
- **Renewed interest in large GWe reactors**
  - **Re-start closed reactors, power uprate, and life extension** (total capacity for 60-95 GWe)
  - **Utilizing the existing reactor site and grid connection for new and SMR addition**

- **Recent initiatives**
  - Constellation has signed a 20-year power purchase agreement with Microsoft that will see Three Mile Island unit 1 restarted, five years after it was shut down
  - Amazon has announced it has taken a stake in advanced nuclear reactor developer X-energy, with the goal of deploying up to 5 GW of its SMRs in the USA by 2039
  - Google and Kairos Power Partner to Deploy 500 MW of Clean Electricity Generation

NEXUS-DC: Energy Supply Options (Cont'd)

- **Nuclear reactors with Power Purchase Agreement (PPA)**
  - A PPA is a contractual agreement between a power producer and a purchaser
    - commonly used for clean energy projects like wind, solar, and hydroelectric, and nuclear
    - For energy providers, PPAs provide financial stability by ensuring a steady revenue stream
    - For purchasers, PPAs offer predictable and lower-cost electricity compared to market rate

- **Natural gas now and nuclear later?**
- **Coal plant site transition to nuclear option?**
  - **Could be a short-term solution but need transition strategy and resource allocation**
  - Realistic if reactor deployment time >10 years



Source: Sharpe Pritchard

- **Nuclear baseload with oil/gas/renewable peaking?**
  - **For optimized plant capacity and alternative energy selection**
  - Grid integration with base load, microgrid for peaking load?

Taken from [1].

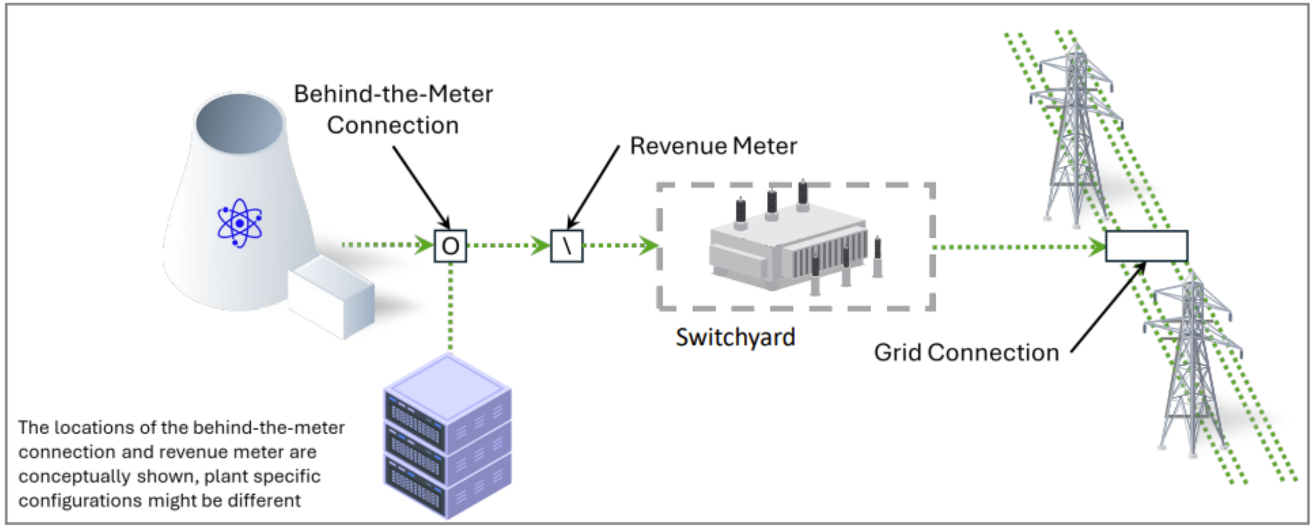
NEXUS-DC: Energy Supply Options (Cont'd)

- **One Large Reactor or few SMRs or several/many micro-reactors?**
  - One Large Reactor (1000MW+):
    - Benefits: Economies of scale, potentially lower cost per megawatt, and robust energy output
    - Challenges: Long development and regulatory approval timelines, high upfront capital cost
    - Options: Restarting shut-down plant, power-uprate, and added capacity to existing plant site
  - Fewer Smaller Reactors (300MW each)
    - Benefits: Faster deployment, multi-unit demand-based capacity addition and scale-up
    - Challenges: Higher cost for FOAK, costs reduce for multiple units are deployed
    - Options: **Best option,** flexible for site selection, **no readily available licensed reactor**
  - Several Micro-Sized Reactors (<50MW each):
    - Benefits: suitable for smaller or medium size data center, highly modular and scalable, and lower initial capital investment per unit, could be base load and peaking load
    - Challenges: Higher initial cost per megawatt, need for a greater number of installations for larger size data center, and potential regulatory challenges with new technologies
    - Options: Suitable option with SMRs, high comparative cost against gas and oil, **no readily available licensed reactor.**

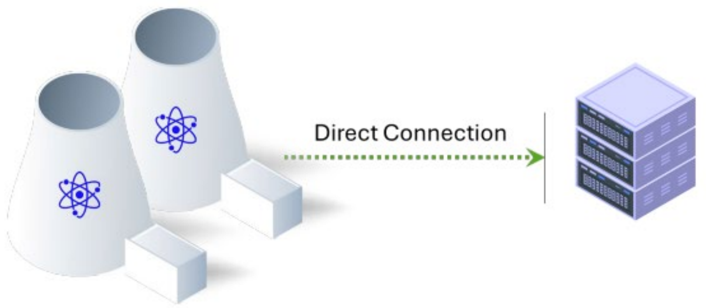
NEXUS-DC: Energy Supply Options (Cont'd)

Grid connectivity, microgrid, and island options?

- Behind the meter option
  - Benefits: no transmission cost, no microgrid needed
  - Challenges: impact on plant and regulation
  - Options: **support accelerated deployment if grid connectivity available,** suitable for exiting plant site, and SMRs



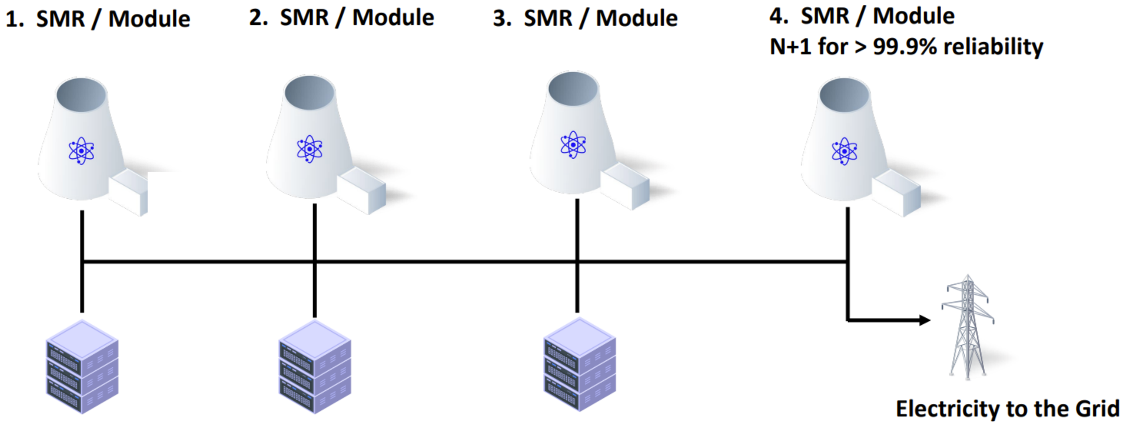
- Direct connection
  - Benefits: no grid connectivity required
  - Challenges: impact on plant and regulation, need backup capability
  - Options: suitable for exiting plant site, with **SMRs with microgrid**



Taken from [1].

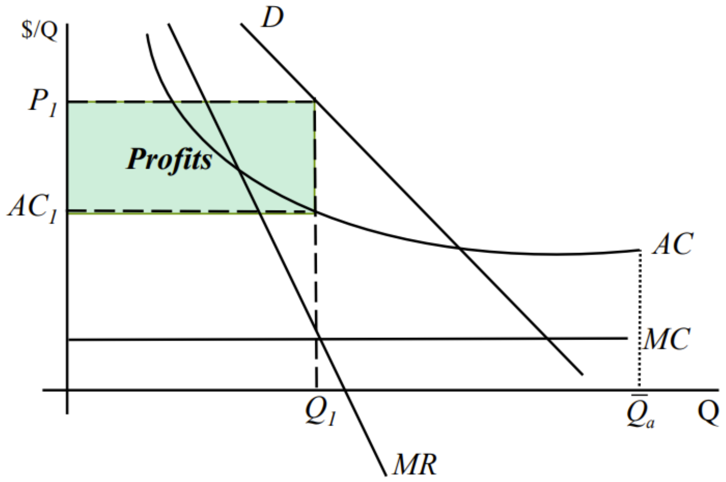
NEXUS-DC: Energy Supply Options (Cont'd)

- **Accelerated deployment and for 99.99% reliability**
  - modular construction with N+1 reactors
  - microgrid and grid connectivity

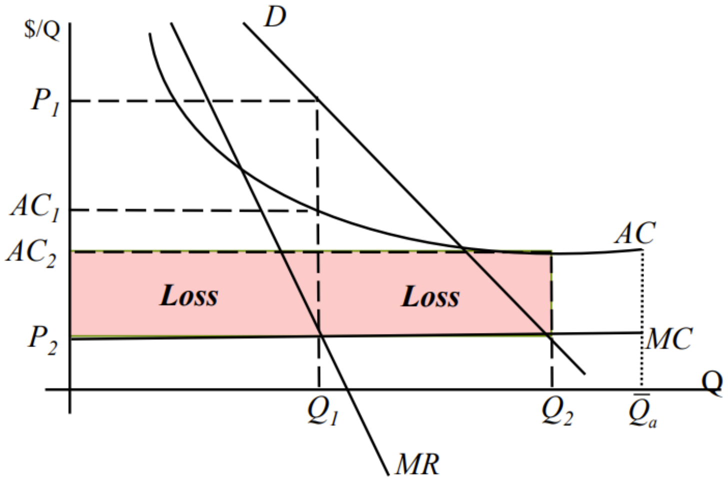


- **Economic analysis and optimization**

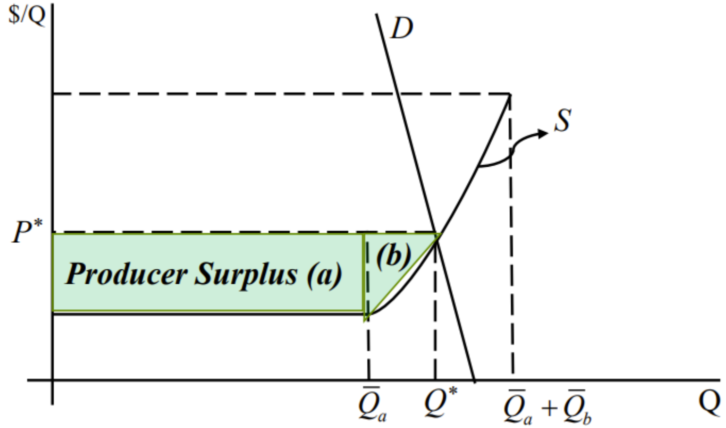
Stylized Generator Cost Structure



Stylized Generator Cost Structure



Stylized Market Model



Taken from [1].

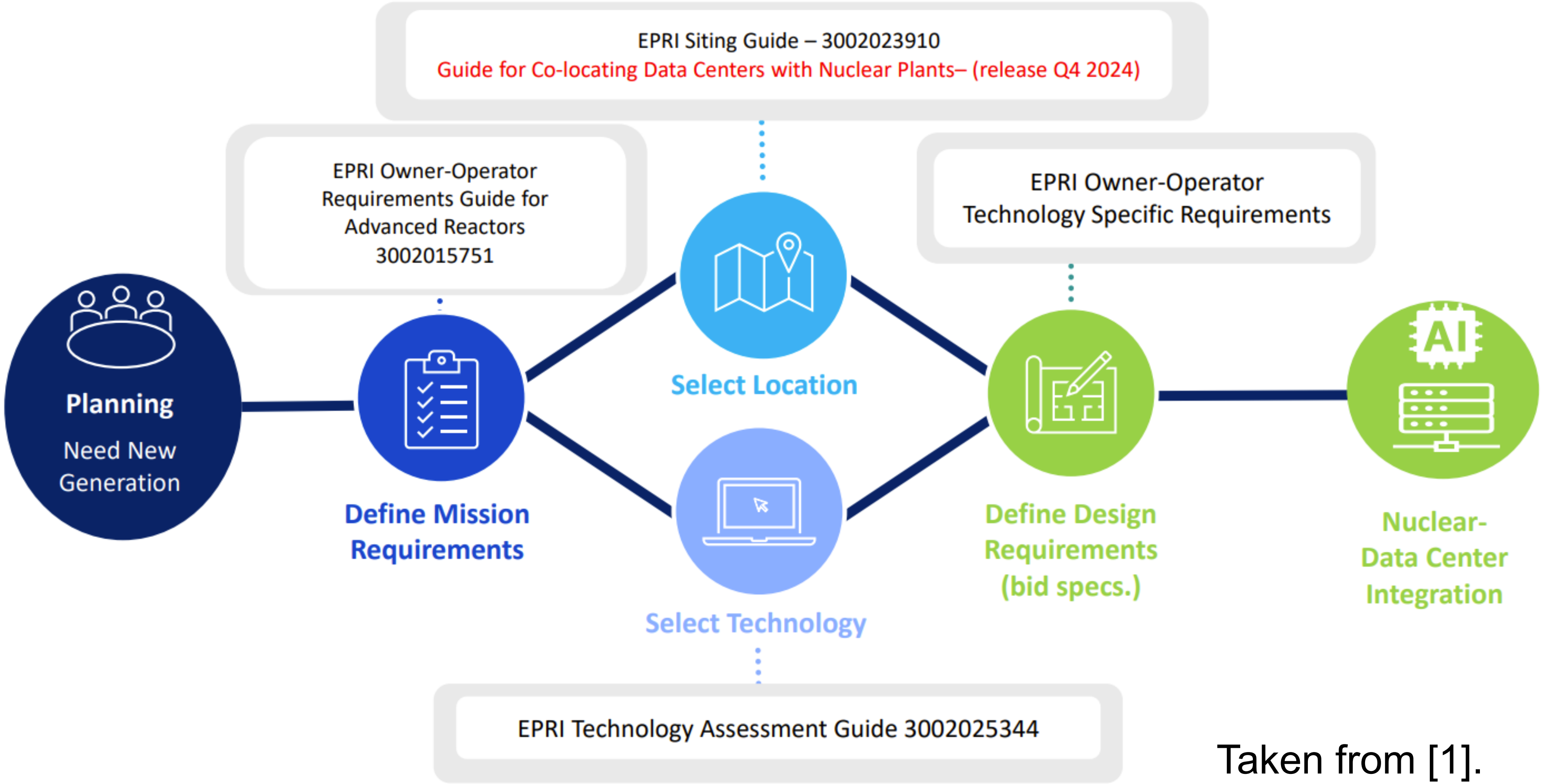
Here, P: Price, Q: Cost, D: Demand curve, S: Supply curve, AC: Average cost, MC: Marginal cost, and MR: Marginal revenue

NEXUS-DC: Site Selection

Site selection is the primary steps for reactor deployment and regulatory approval!

EPRI site selection guidance could be leveraged for

- accelerated nuclear power data center deployment!
- easier understanding about the options, requirements and potential road-blocks!

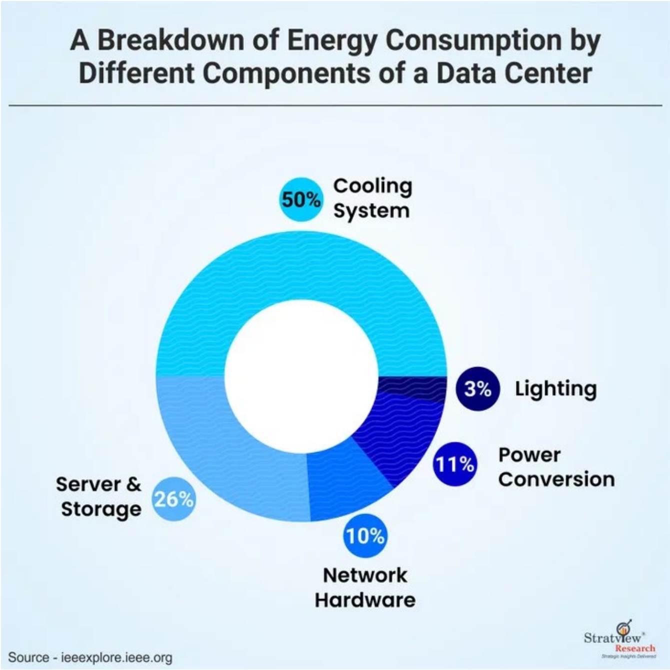


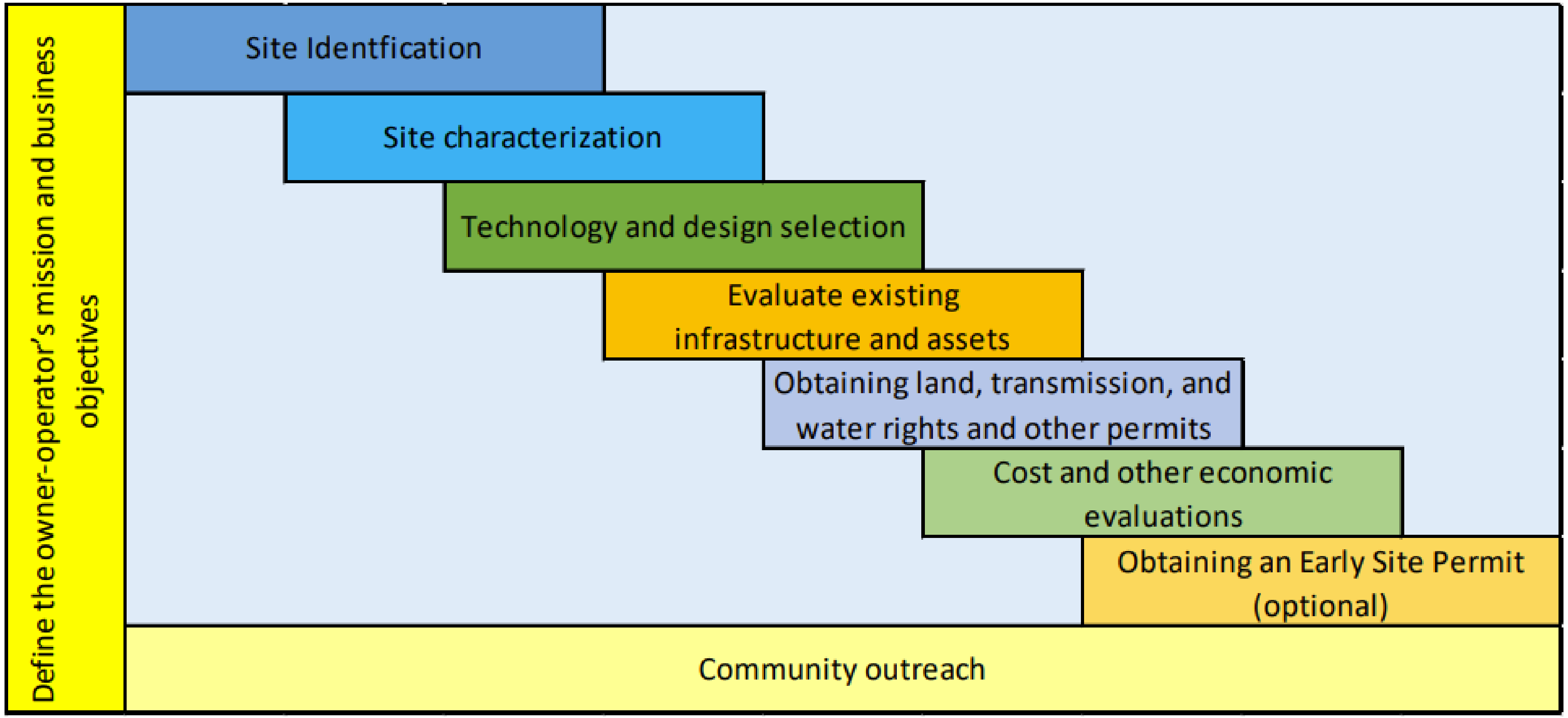
Taken from [1].

NEXUS-DC: Site Selection (cont'd)

New data centers prefer sites with access to land and water, as well as grid and optical fiber connectivity!

Site Selection Guidance





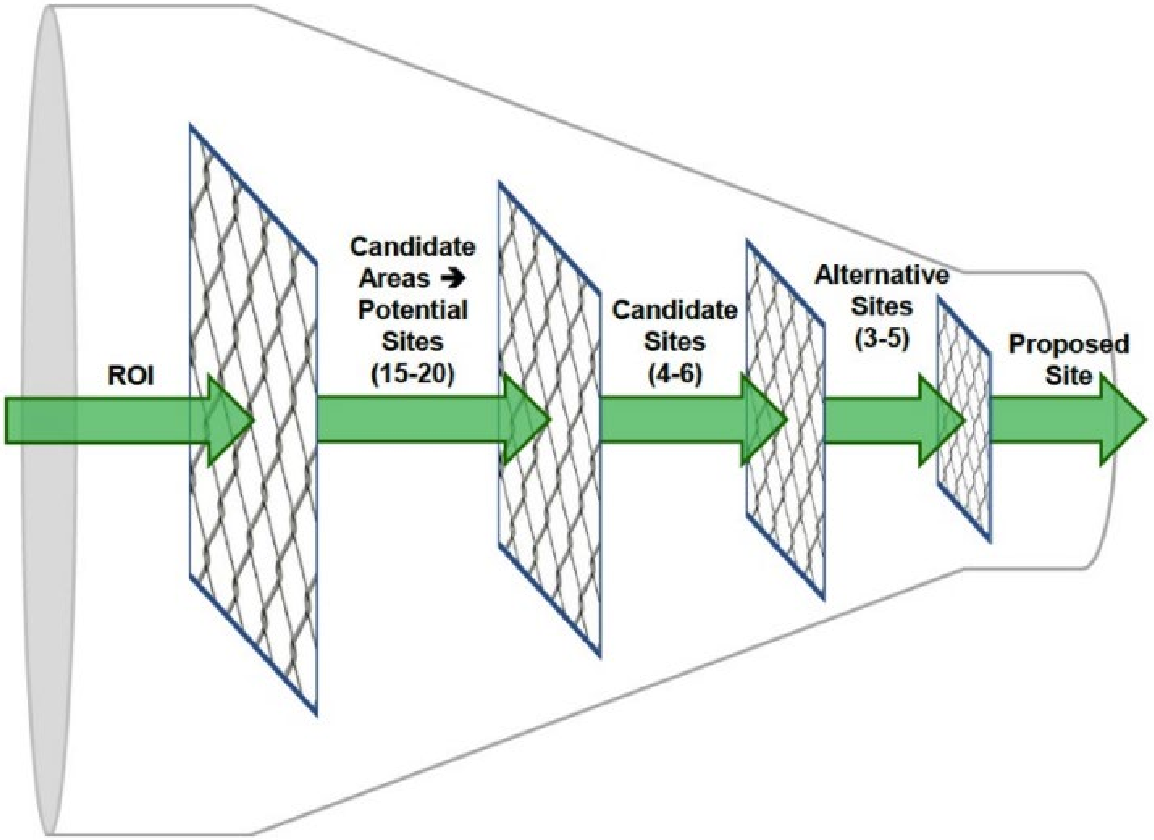
Taken from [1].

Source: https://www.linkedin.com/pulse/data-center-power-fueling-digital-revolution-ehylf/ [13]

NEXUS-DC: Site Selection (cont'd)

EPRI reactor site guiding process:

- **Identify Region of Interest (ROI)**
  - Based on business objectives
- **Screen Candidate Areas**
  - Add exclusionary criteria to assess feasibility
- **Identify Potential Sites**
  - Narrow down to discrete sites rather than areas
- **Screen Candidate Sites**
  - Quantitatively assess site characteristics
- **Identify Potential Sites and**
- **Alternatives**
  - Investigate sites for reasonable confidence



EPRI, 2022: Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities (Siting Guide): https://www.epri.com/research/programs/065093/results/3002023910 [14]

Taken from [1].

NEXUS-DC: Relevant Regulations and Guides

- **NRC Applicable Regulations**
  - 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,”
  - 10 CFR Part 52, “Licenses, Certification, and Approvals for Nuclear Power Plants,”
  - 10 CFR Part 20, “Standards for Protection Against Radiation,”
  - 10 CFR Part 51, “Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions,”
  - 10 CFR Part 100, “Reactor Site Criteria,” which establishes the requirements for proposed nuclear reactor sites

- **Other Regulations and Guides**
  - 10 CFR Part 51, “Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions,”
  - 10 CFR Part 100, “Reactor Site Criteria,” which establishes the requirements for proposed nuclear reactor sites
  - National Environmental Policy Act (NEPA)

Taken from [1].

NEXUS-DC: Relevant Regulations and Guides (cont'd)

Differences between Part 52 and Part 50

NEI

Part 52	Part 50
License before you build	Build before you license
COL (FSAR)	CP – OL (PSAR – FSAR)
Issues resolved up-front before construction investment	Lack of up-front issue resolution puts capital at risk
DC, SDA and ESP options can minimize COL application review time and cost	Potentially fastest path to deployment
Clear choice for Nth of kind	Potentially better for FOAK
"Push market"	"Pull market"
Requires greater design completion prior to construction	Allows construction with less design completion
Regulatory infrastructure in place & understood	Regulatory infrastructure needs update
Change control during construction	Unfettered changes during construction
ITAAC prior to operation	OL prior to operation

https://www.nrc.gov/about-nrc/generic-schedules.html

Part 53 Goals:

- Risk-Informed
- Performance Based
- Technology Inclusive
- Safety is Assured without unnecessary Regulatory Burden
- Efficient and Timely Licensing Approvals
- Greater Flexibility

Taken from [1].

Courtesy NEI

ADVANCE Act requires the NRC to take actions in the areas of licensing of new reactors and fuels, while maintaining the NRC's core mission to protect public health and safety.

Source: https://www.epw.senate.gov/public/index.cfm/2024/7/signed-bipartisan-advance-act-to-boost-nuclear-energy-now-law [15]

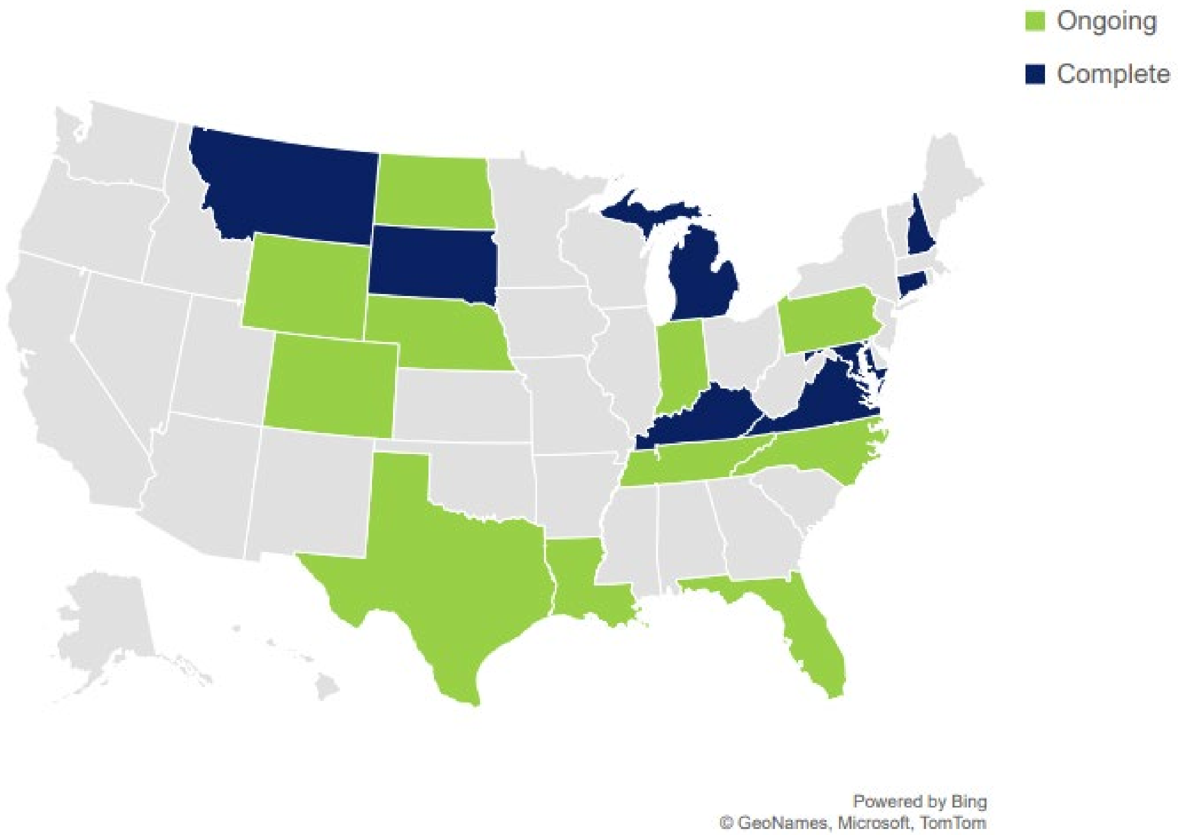
NEXUS-DC: Public Perception and Acceptance

New data centers prefer sites with access to land and water, as well as grid and optical fiber connectivity!

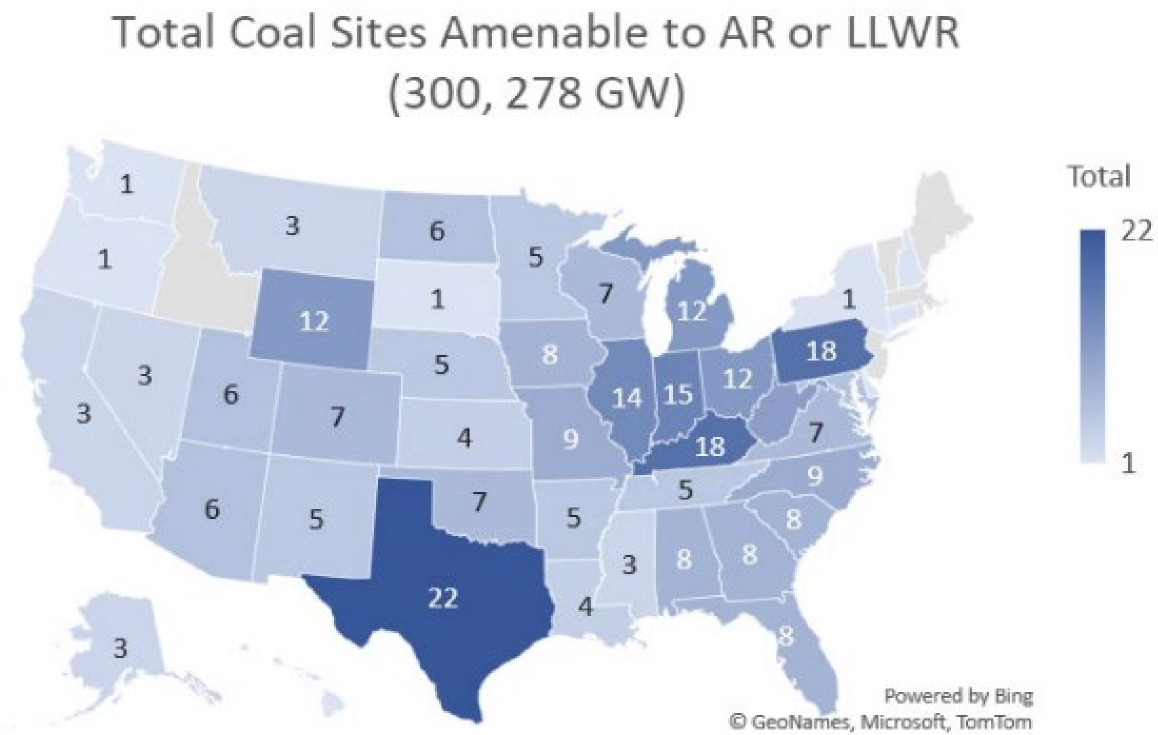
- Communities are often looking for jobs, data centers don't bring many, but nuclear plants do
- The development of a nuclear plant can significantly affect the local community
- Having an engaged and supportive community is an asset to new nuclear development
- Local stakeholders will have varied opinions on the subject
- Consider federal, state, local programs, and supporting disadvantaged communities
- Community outreach is mandatory in some countries (e.g., Canada)
- The following EPRI reports contain more information on outreach and public acceptance

NEXUS-DC: Public Perception and Acceptance (cont'd)

State Nuclear Energy Feasibility Studies



Coal to Nuclear Options/Potentials

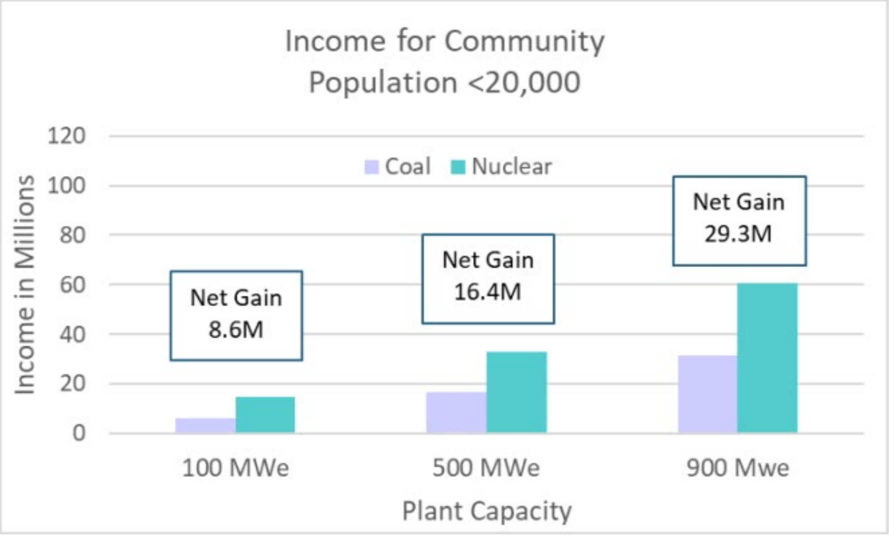


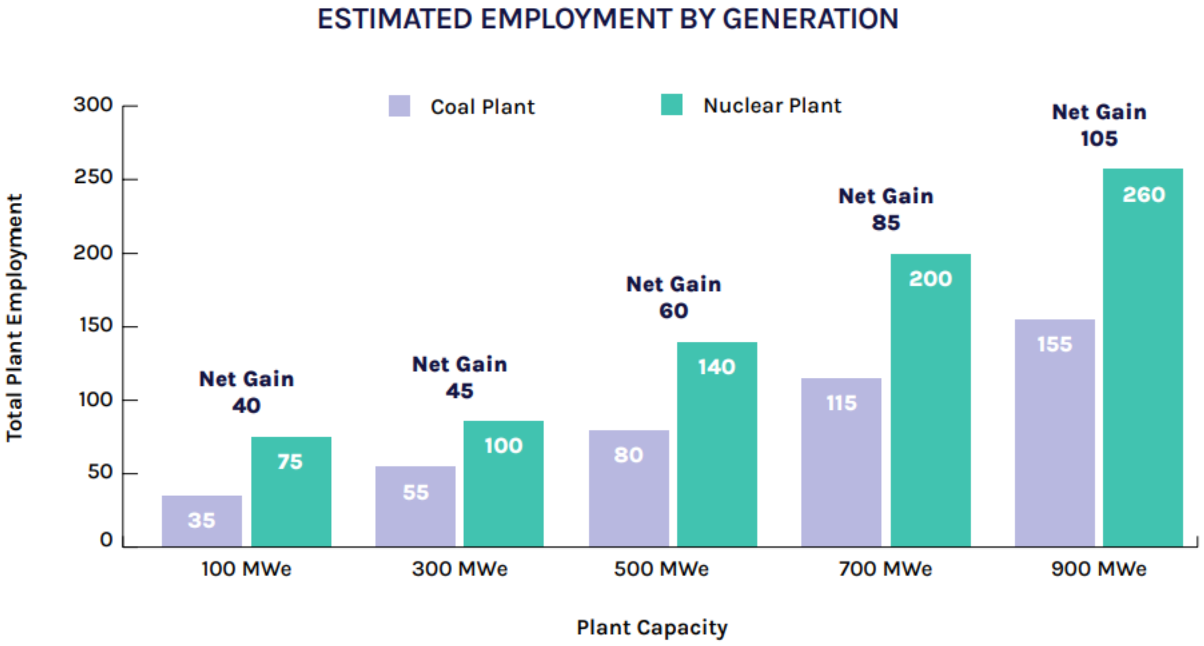
Source: https://fuelcycleoptions.inl.gov/SiteAssets/SitePages/Home/C2N2022Report.pdf [16]

NEXUS-DC: Public Perception and Acceptance (cont’d)

- **Nuclear has a multiplier of ~1.5**
  - For every $100 of electricity produced, $50 of economic activity occurs in suppliers and support industries!
- **Nuclear can bring lasting jobs to a plant for 40-80 years**
  - There are both direct jobs created as well as indirect and induced jobs
  - Many other renewable technologies only bring construction jobs

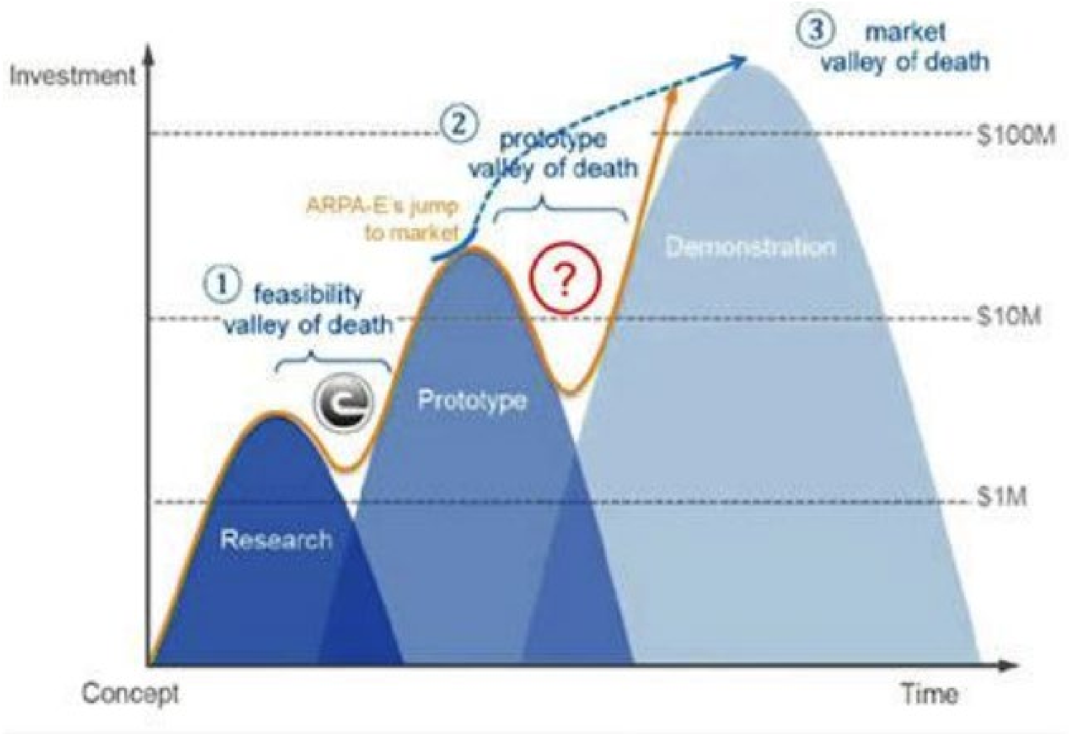
Contribution to local economy and job markets!





Source: DOE April 2024: COAL-TO-NUCLEAR TRANSITIONS: AN INFORMATION GUIDE https://www.energy.gov/sites/default/files/2024-05/Coal-to-Nuclear%20Transitions%20An%20Information%20Guide.pdf [17]

NEXUS-DC: Reactor Deployment Consideration



Bridging the Valley of Death: Transitioning from Public to Private Sector Financing

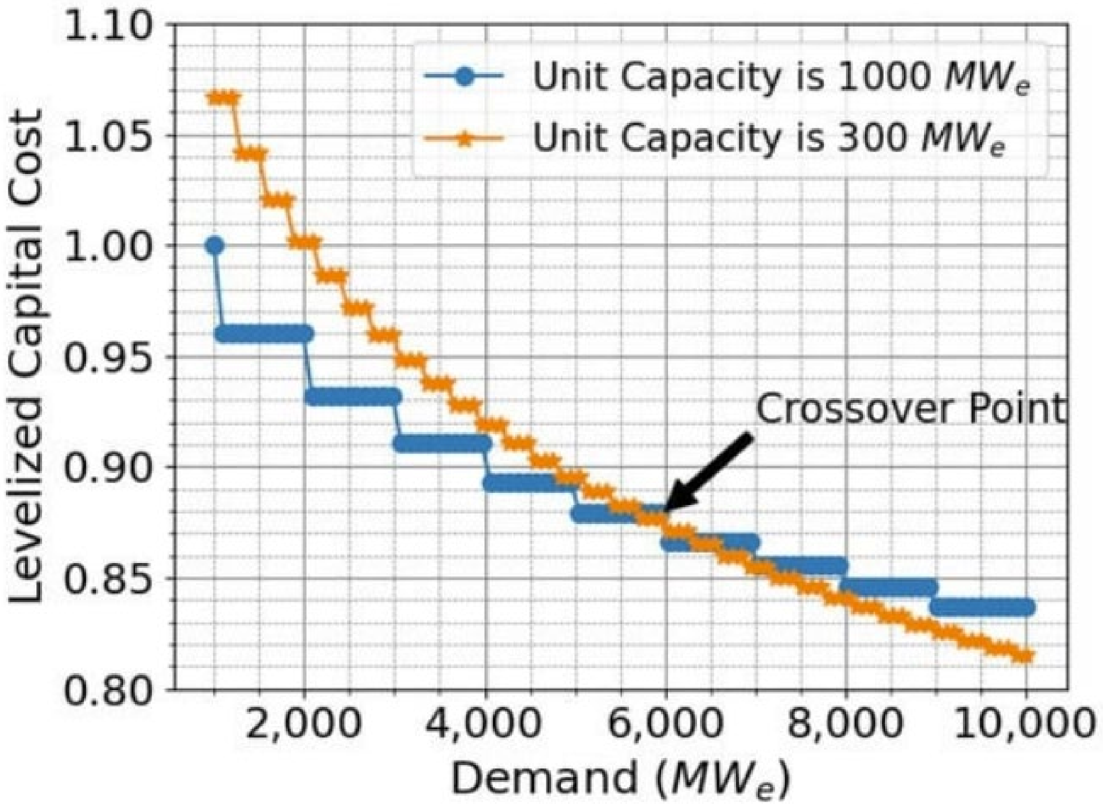
Source: https://www.nrel.gov/docs/gen/fy03/34036.pdf [18]

- **Market/Economics:**
  - business cases for First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK), and co-generation (e.g., hydrogen)
  - Spent fuel management cost and associated challenges
- **Supply chain:** fuel and nuclear grade structural materials
  - Example: reactor vessel, graphite, helium, salts, pumps, instrumentation and control (I&C)
  - Loss of supply chain from 1980s-1990s nuclear construction hiatus, needed more efforts to rebuild
  - Vendor partnerships to avoid delays and increased costs
- **Fuel:** availability (e.g., HALEU), fuel qualification including fabrication, irradiation, post-irradiation experiment (PIE)
- **Licensing:** NRC, international or DOE authorization
- **Siting:** Permits, transmission lines, transportation
- **Workforce**: qualified personals, reactor operators, welders, engineers, support staff, etc.

Taken from [1].

NEXUS-DC: Economic of Scale

- **Economic of scale penalty**—ratio of FOAK capital cost ($/kW)—could overcome
  - with multiple unit installation over time
  - with accumulated experience
- **Economic gain with cogeneration**
  - Multipurpose heat and electric applications
  - Hydrogen production for optimizing capacity
    - Constellation: Nine-Mile Point Plant, H2 production began March 2023
    - Energy Harbor: Davis-Besse Plant and Xcel Energy: Prairie Island Plant begin H2 production in 2024.
  - **Accelerated deployment could consider reactor installation first and other energy optimization unit integration later!**



The economies-of-scale penalty crossover point for the levelized capital cost of SMR (i.e., 300MWe) vs. large reactor (i.e., 1000 MWe).

Source: https://www.mdpi.com/1996-1073/17/20/5073 [19]

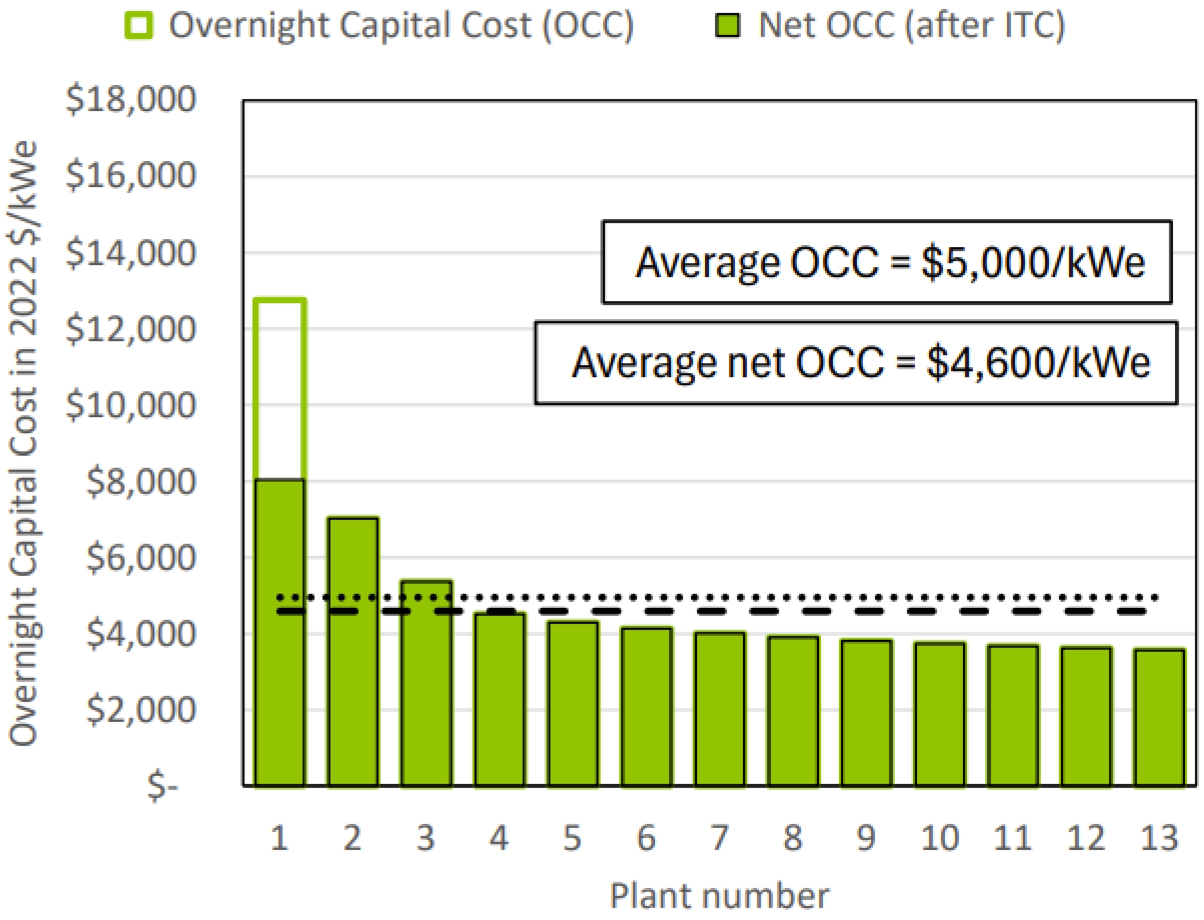
NEXUS-DC: Reactor system cost estimation

	Equations and Variables	Remarks
Estimation of various cost elements		
Overnight capital cost (OCC): cost of a plant if it were built right away, with current prices	OCC for SMRs from large reactors: $$\frac{\mathbf{Cost}(P_1)}{P_1} = \frac{\mathbf{Cost}(P_0)}{P_0}\left(\frac{P_1}{P_0}\right)^{\eta-1} \text{ and } \mathbf{Cost}(P_1) = \mathbf{Cost}(P_0)\left(\frac{P_1}{P_0}\right)^{\eta}$$ where, P_0 and P_1 are the large reactor and SMR rated power in MWe, respectively. η represents the scaling factor, which is reported to range from $0.4 - 0.7$ dependent on the specific SMR project (NEA and OECD 2011) [20].	OCC provide options for comparative cost estimation among various reactor technologies.
Co-siting factor	$$\text{Co - siting Factor} = \frac{1+(n-1)(1-F_{IND})}{n}$$ Typical values for the proportion of direct cost, F_{IND} and proportion of indivisible costs, F_{DIR} of 0.34 and 0.66 , respectively (Carelli et al. 2010) [20].	It should be noted that as n (units) increases, the Multiple Units Factor approaches $F_{DIR} = 1 - F_{IND}$, and the indivisible costs.
Learning factors	$$\text{Learning Factor} = \sum_{n=1}^{f} \frac{C_{eq}+C_{lab}+C_{mat}}{f} * c_n$$ Where, C_{eq}, C_{lab}, and C_{mat} refer to the equipment, labor, and material costs	Other learning rates are equipment and labor learning rates.
Cost estimation from FOAK to NOAK	General learning rate form, in which Y, $$Y = AX^{-b} \text{ and } b = -\log(1-R)/\log(2)$$ where, X is cost to produce the cumulative rated power, A is the FOAK cost and b is the learning rate exponent, and R is the learning rate.	A learning of 3–4.5% occurs for each doubling of rated power up until 8 GWe (Generation IV EMWG 2006; Rothwell 2007) [20].

Source: https://inldigitallibrary.inl.gov/sites/sti/sti/6293982.pdf [20]

NEXUS-DC: Cost Reduction from FOAK to NOAK

– **Comparative Construction Costs**
  - NOAK overnight capital cost (OCC) <$4,000/kWe (from DOE Liftoff Report goal) is achievable,
    – but making the average costs low is challenging, mainly due to large FOAK costs
  - Significant reduction in costs in the first 3-4 plants are achieved
    – when cost and schedule overruns are assumed to be mitigated (>50% reduction from plant 1 to 3).
  - Optimistic scenario with including tax credit (ITC) for first 4 plants projects average OCC <$4,000/kWe, which is very competitive.
  - Cost Reduction Tool: Quantifies "learning" and the capital cost evolution from plant #1 to plant #N when a large orderbook of N plants is placed.

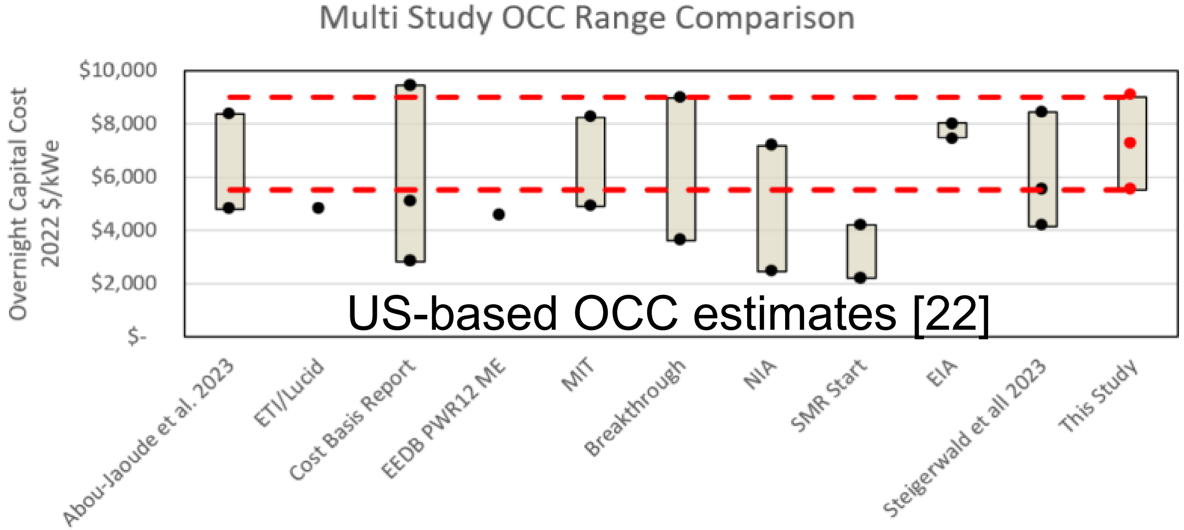


Overnight capital cost (OCC) comparison for FOAK to NOAK reactor installation

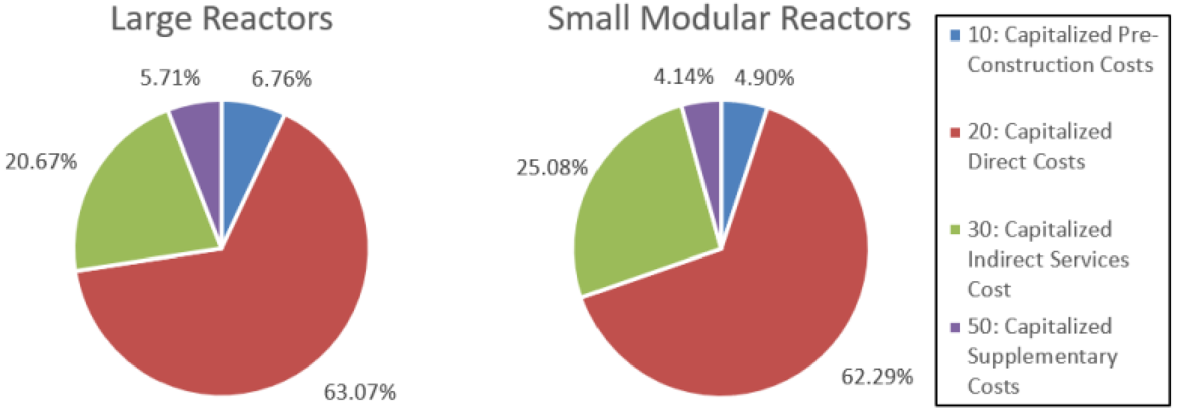
Source: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_66425.pdf [21]

NEXUS-DC: Reactor system cost estimation

- **Several cost elements are considered** [22]
  - Overnight capital cost (OCC), indirect cost (IC) and direct capital costs, levelized cost of energy (LCOE) to estimate reactor cost [23].
  - First-of-a-kind (FOAK) and Nth-of-a-kind (NOAK) estimates, and “between a first and Nth of a kind,” or BOAK are supportive.
  - OCC ranges mostly \$5000/kWe to \$9,000/kWe
  - Cost comparison of SMRs and large reactors are similar with highest variation (approx. 5%) for capitalized indirect service cost
  - Comparing to other energy sources, nuclear reactor cost estimation includes
    - Fuel fabrication, loading, and reloading cost
    - Used fuel, waste management, and plant decommissioning cost.



US-based OCC estimates [22]



SMRs and large reactors cost comparison [22]

Source: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_107010.pdf [22]

Data Center: Cooling and Thermal Management

Power Usage Effectiveness (PUE) is defined to assess the energy efficiency of data center over the year.

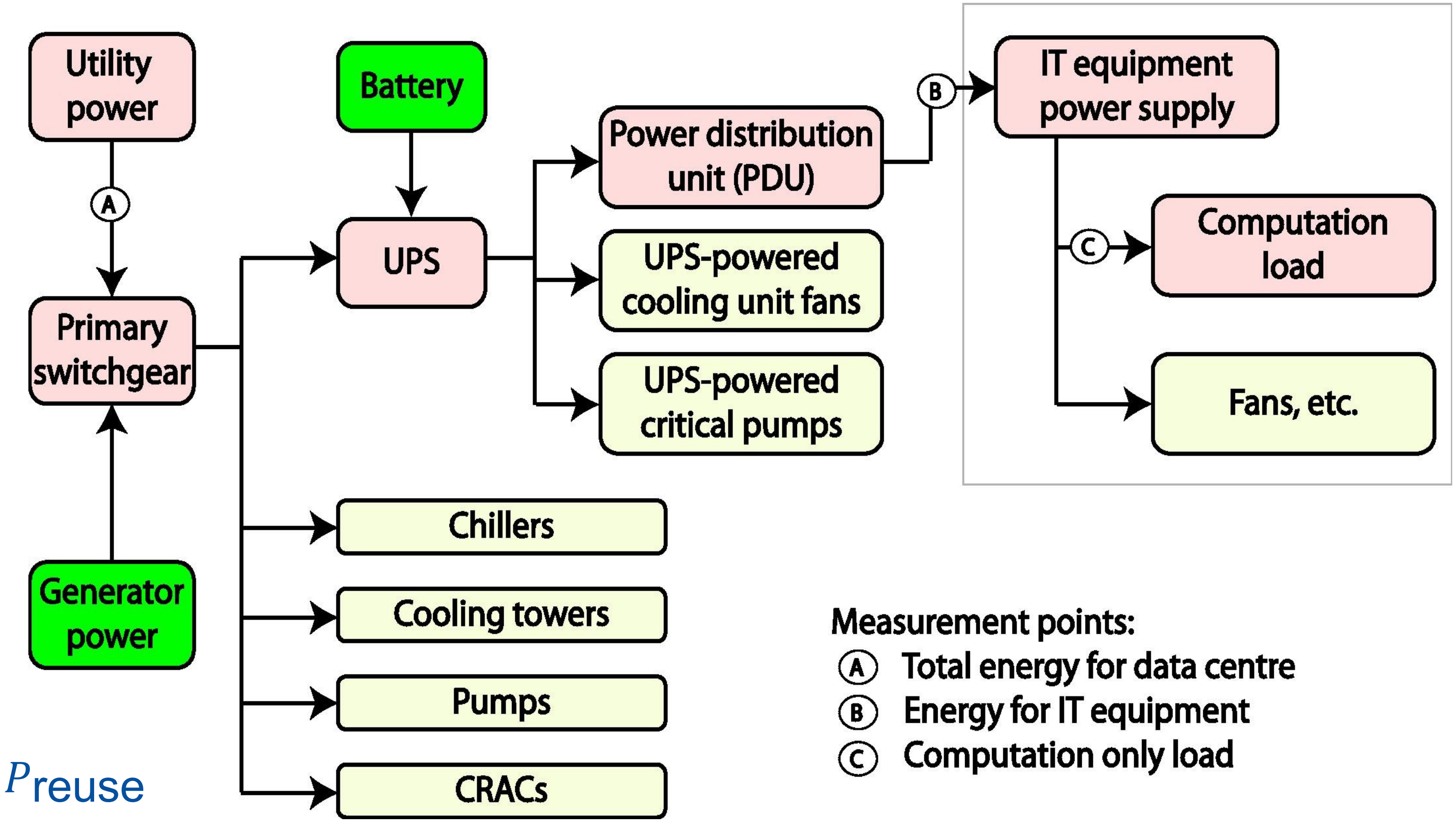
$$PUE = \frac{P_{DC}}{P_{IT}}$$

Where P_{DC} is the power of the data center, P_{IT} is the input power of the IT equipment

$$PUE = \frac{P_{cooling} + P_{power} + P_{lighting} + P_{IT}}{P_{IT}}$$

Energy Reuse Effectiveness,

$$ERE = \frac{P_{cooling} + P_{power} + P_{lighting} + P_{IT} - P_{reuse}}{P_{IT}}$$



Power flow in a typical DC and the places to measure the energy consumption

Source: https://www.sciencedirect.com/science/article/pii/S0306261917310541 [24]

Part-III:

Data Center: Cooling and Thermal Management (cont'd)

Green Energy Coefficient (GEC):

$$\text{GEC} = \frac{\textbf{Green energy [kWh] used in DC site}}{\textbf{Total energy consumption of datacenter [kWh]}}$$

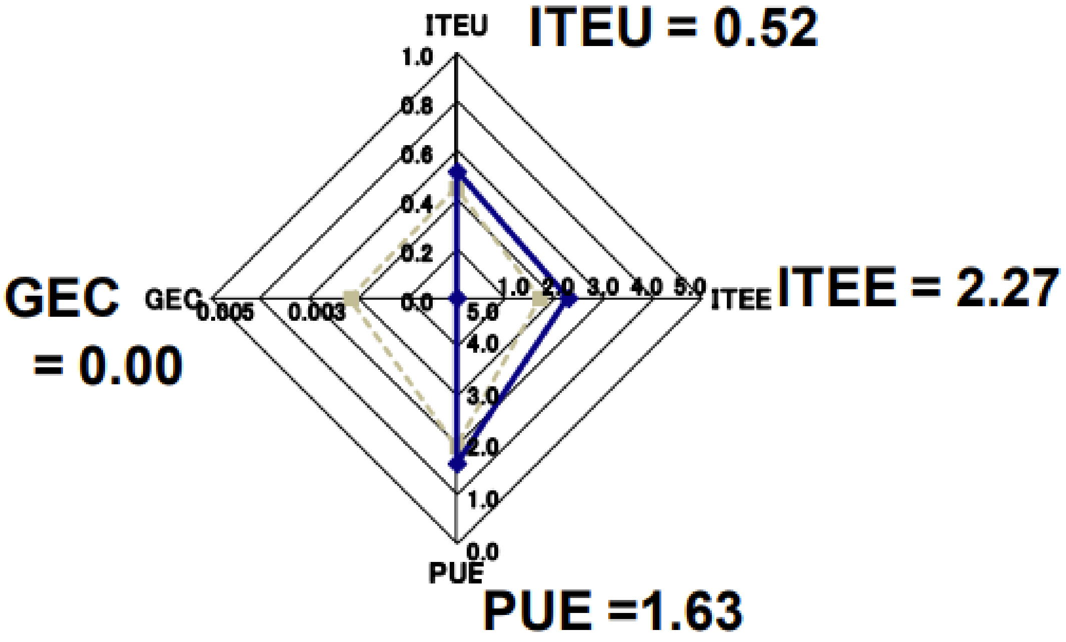
IT Equipment Utilization (ITEU):

$$\text{ITEU} = \frac{\textbf{Total energy consumption of IT equipment (actual) [kWh]}}{\textbf{Total rated energy consumption of IT equipment (rated) [kWh]}}$$

IT Equipment Energy Efficiency (ITEE):

$$\text{ITEE} = \frac{\textbf{Total rated capacity of IT equipment [Work]}}{\textbf{Total rated power of IT equipment [W]}}$$

Energy Efficiency = ITEU × ITEE × (1/PUE) × (1/ (1 - GEC))

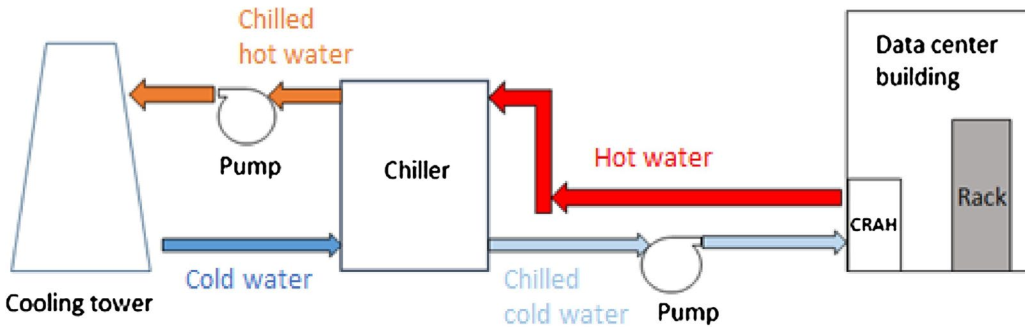


Spider web chart of Holistic Framework for Datacenter C [25]

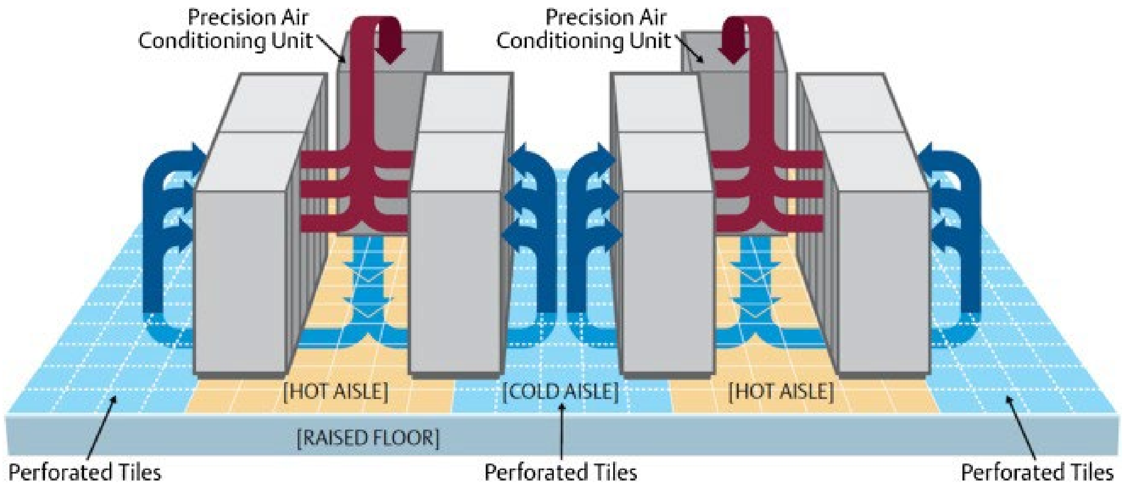
Measurement points of IT equipment are important!!

Source: https://home.jeita.or.jp/greenit-pc/topics/release/pdf/dppe_e_20120824.pdf [25]

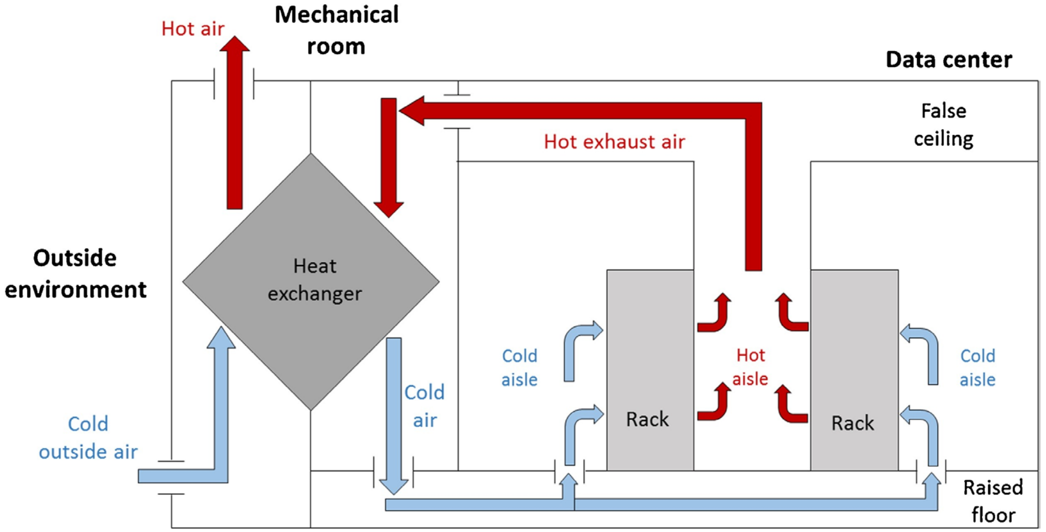
Data Center: Cooling Options



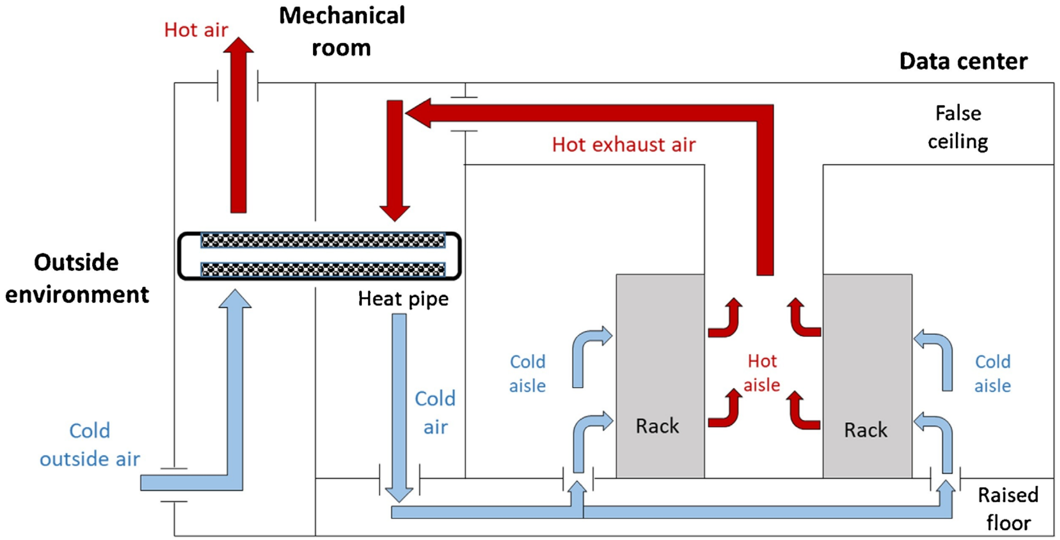
Water cooling with economizer



Active cooling with air conditioning



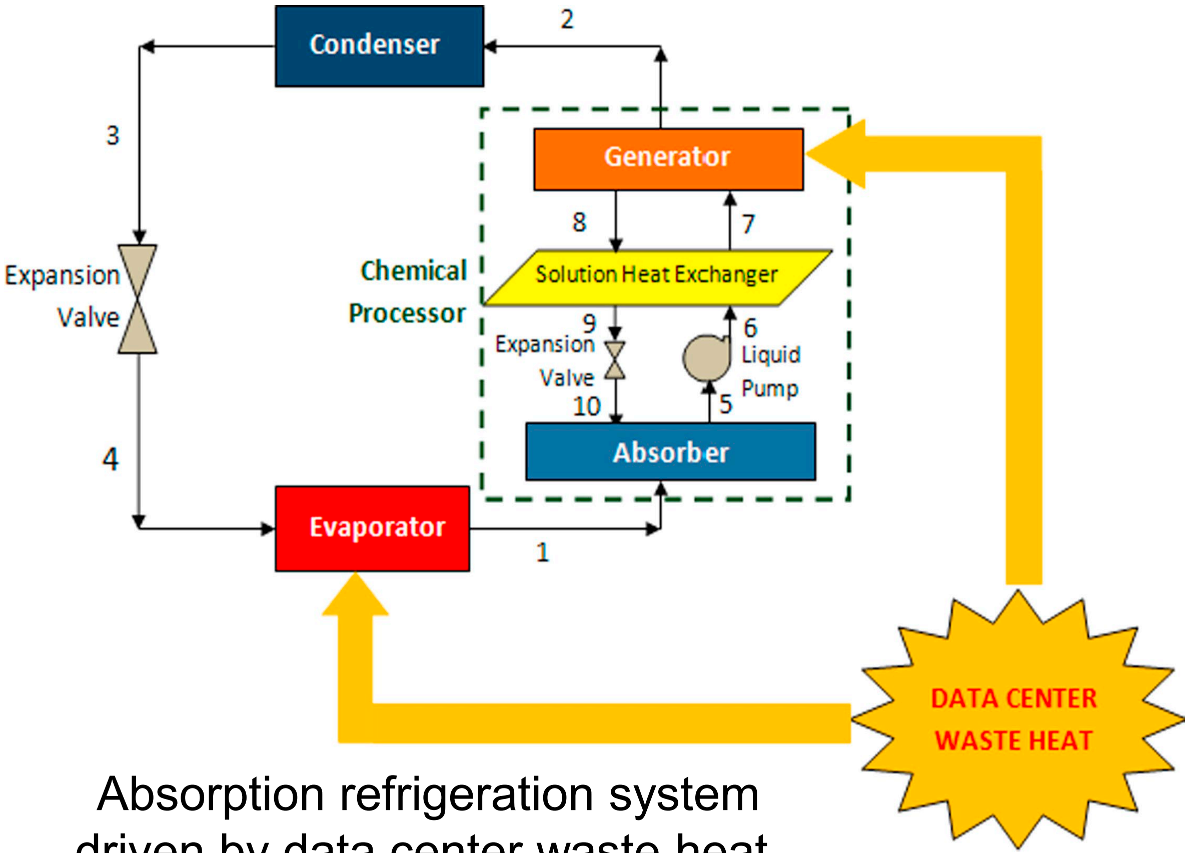
Air-to-air heat exchanger for cooling data centers



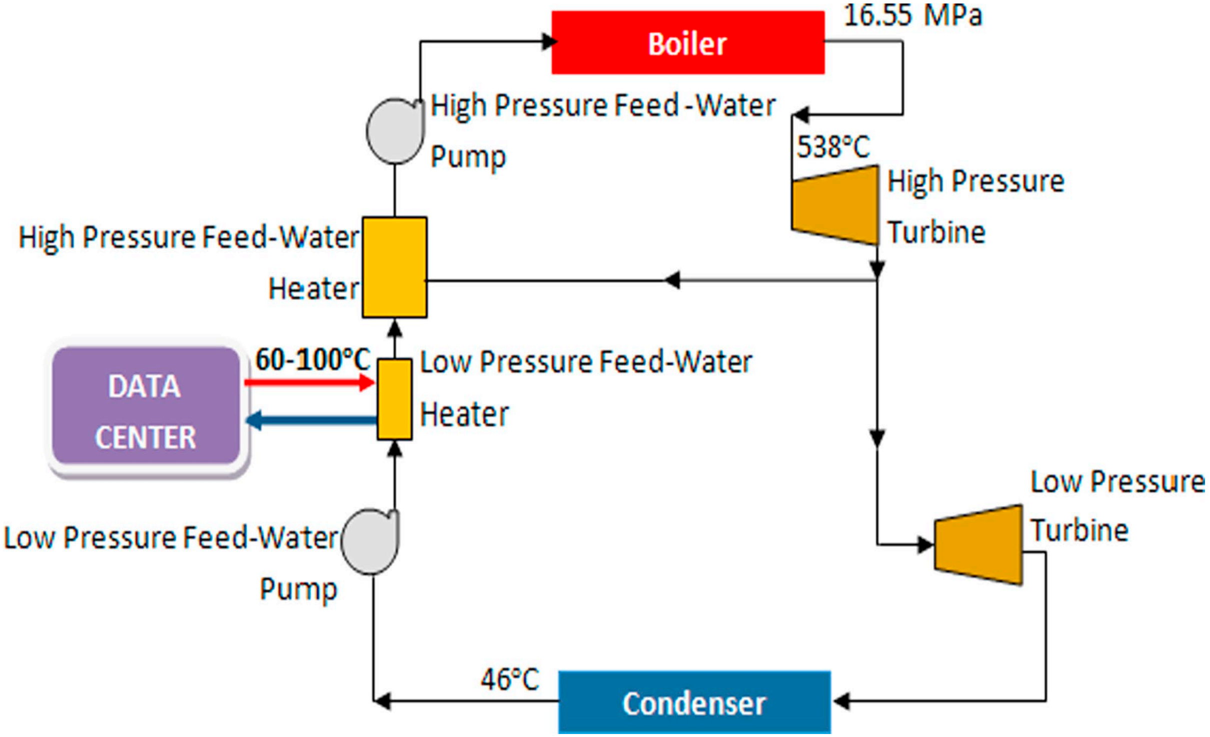
Indirect free cooling unit with a heat pipe

Source: https://doi.org/10.1016/j.suscom.2018.05.002 [26]

Data Center: Waste Heat Utilization



Absorption refrigeration system driven by data center waste heat



Waste heat utilized in a coal power plant Rankine cycle

Source: https://doi.org/10.1016/j.rser.2013.12.007 [27]

Part-III:

Data Center: Digital Engineering, AI, and Cyber

- **Artificial Intelligence (AI) R&D:**
  - Accelerating Deployment & Licensing
  - Testing, Operations & Maintenance
  - Integrated Energy Grid & Security
  - Disaster & Risk Resilience
  - Applied Energy projects:
    - INL Lead multi lab: Alexandria
    - Nuclear Research Data System
    - High Performance Computers
  - Tools: MOOSE, RAVEN, DeepLynx, SEARCH
- **Cyber security**
  - Secure from cyber attacks reactor system interconnects
  - Mitigate potential data center outages and longer-term reactor maintenance issues, creating a significant operational disruption.

Data for AI Training	Next-generation AI Platforms & Computing	Safe & Trustworthy AI Models & Systems	AI Applications
Development of methods, platforms, protocols, and other tools required for efficient, safe, and effective aggregation, generation, curation, and distribution of AI training datasets.	Development and construction of next-generation computing platforms and digital infrastructure.	Training, testing, deep understanding and validation of frontier foundation models, enhanced AI model security, privacy enhancing technologies, and other AI tools and systems.	Use AI foundation models and other AI technologies to develop a multitude of tuned and adapted downstream models to solve pressing scientific and national security challenges.

Frontiers in Artificial Intelligence for Science, Security and Technology (FASST)

Small Modular Reactor Community
Load-Smart, Protocol-Secure

Power Load Dynamics: Deep dive into data center load management, rapid fluctuation handling, and energy optimization techniques.

Direct Energy Feed Operations: Knowledge of data center power interconnects, microgrid management, and seamless energy conversion.

Power Engineering Security Protocols: Understanding security measures for power engineering systems, covering protocols like **IEC 61850**, **DNP3**, and **IEC 62351** for secure communication.

Resilient Design Principles: Integrating security-by-design concepts into SMR operations that align with data center requirements for reliability and security.

Data Center Community
Threat-Ready, Safety-Centric

Design Basis Threat (DBT): Understanding the threat model for nuclear facilities, addressing physical and cyber threats.

Response Force Coordination: Insights into security response teams, emergency procedures, and tactical collaboration.

Physical Protection Systems (PPS): Familiarization with defensive layers, access controls, intrusion detection, and response measures.

Cybersecurity Integration: How IT and OT systems are protected within nuclear facilities, covering protocol hardening and anomaly detection.

Nuclear Safety Culture: Principles of nuclear safety, including radiation protection, emergency procedures, and incident reporting.

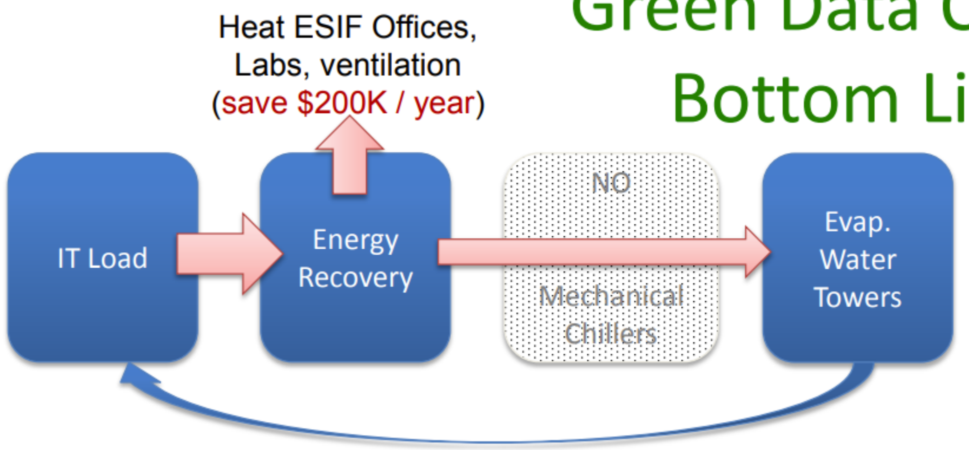
IL/CON-24-81706

Taken from [1].

Case Study: Sustainable Data Center NREL

- **Critical topics**
  - Compute, Space, Power, Cooling
  - Office/lab space heating with waste heat
    - water usage, liquid cooling and energy efficiency, carbon footprint
    - time of day utility pricing, load shifting and demand response
    - cooling arrangements, space requirement, DC safe temperature limit
    - cost (i.e., OpEx ~ IT CapEx)
  - Colling type: liquid vs. air
    - liquids are ~1000x more efficient than a
    - liquids require ~10x less energy
    - warm water cooling preferred to avoid expensive chillers and condensation concerns, and better waste heat re-use.

Green Data Center Bottom Line



Cost less to build
Cost less to operate

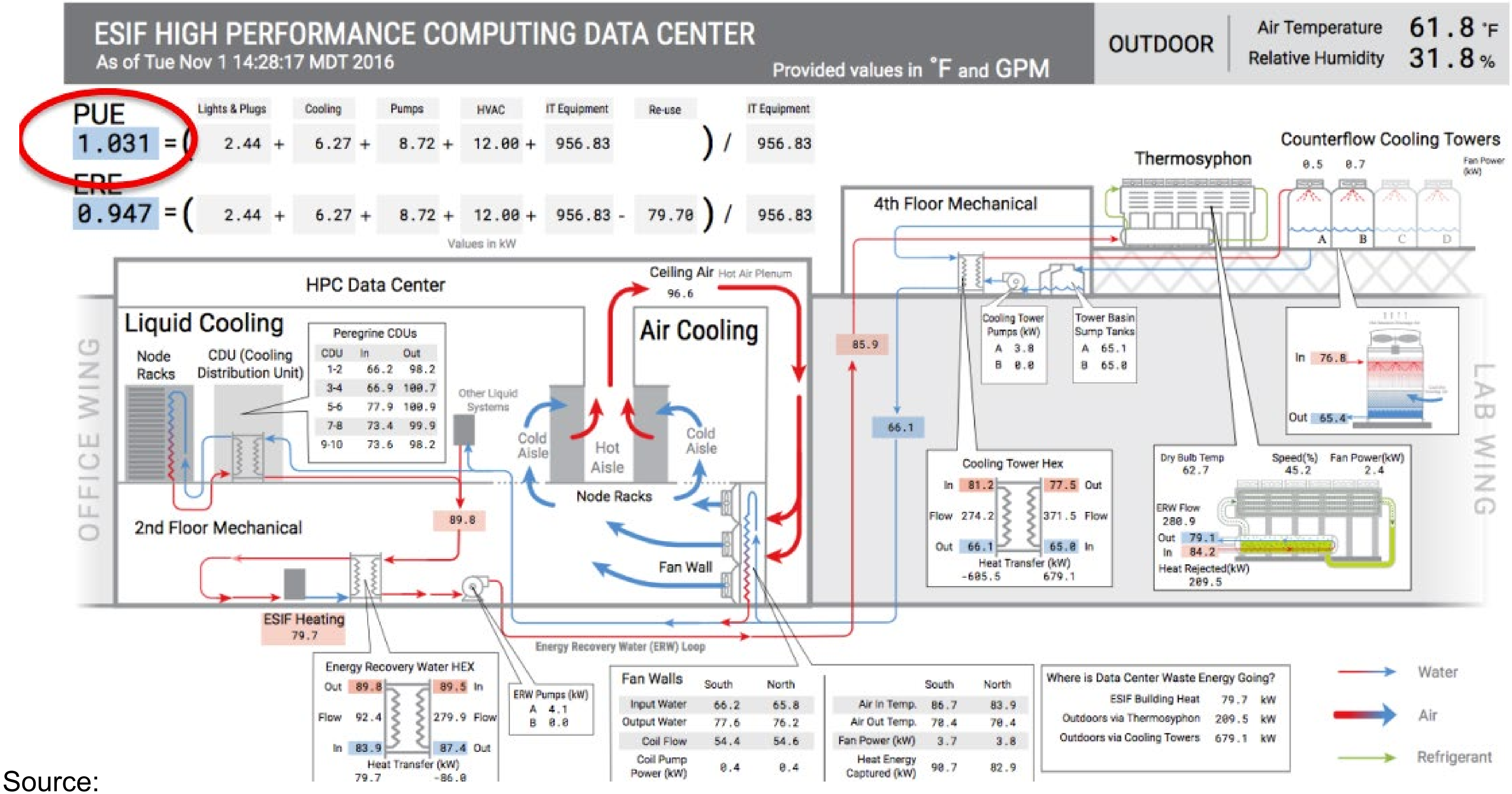
Comparison of ESIF PUE 1.06 vs efficient 1.3 data center.

CapEx	**Savings**		**OpEx** (10MW IT Load)		**Utilities**
No Chillers	No Chillers		PUE of 1.3	$13M	$10.6M
Initial Build: 600 tons		$.9M	PUE of 1.06		$2.4M
10 Yr. growth: 2400 tons		$3.6M	Annual Savings		**$24M**
10-year Savings:		**$4.5M**	**10-year Savings**		*(excludes heat recovery benefit)*
($1.5K / ton)			*($1M / MW year)*		

NREL Data Center thermal management

Source: https://betterbuildingssolutioncenter.energy.gov/sites/default/files/Sustainable_Data_Centers.pdf [28]

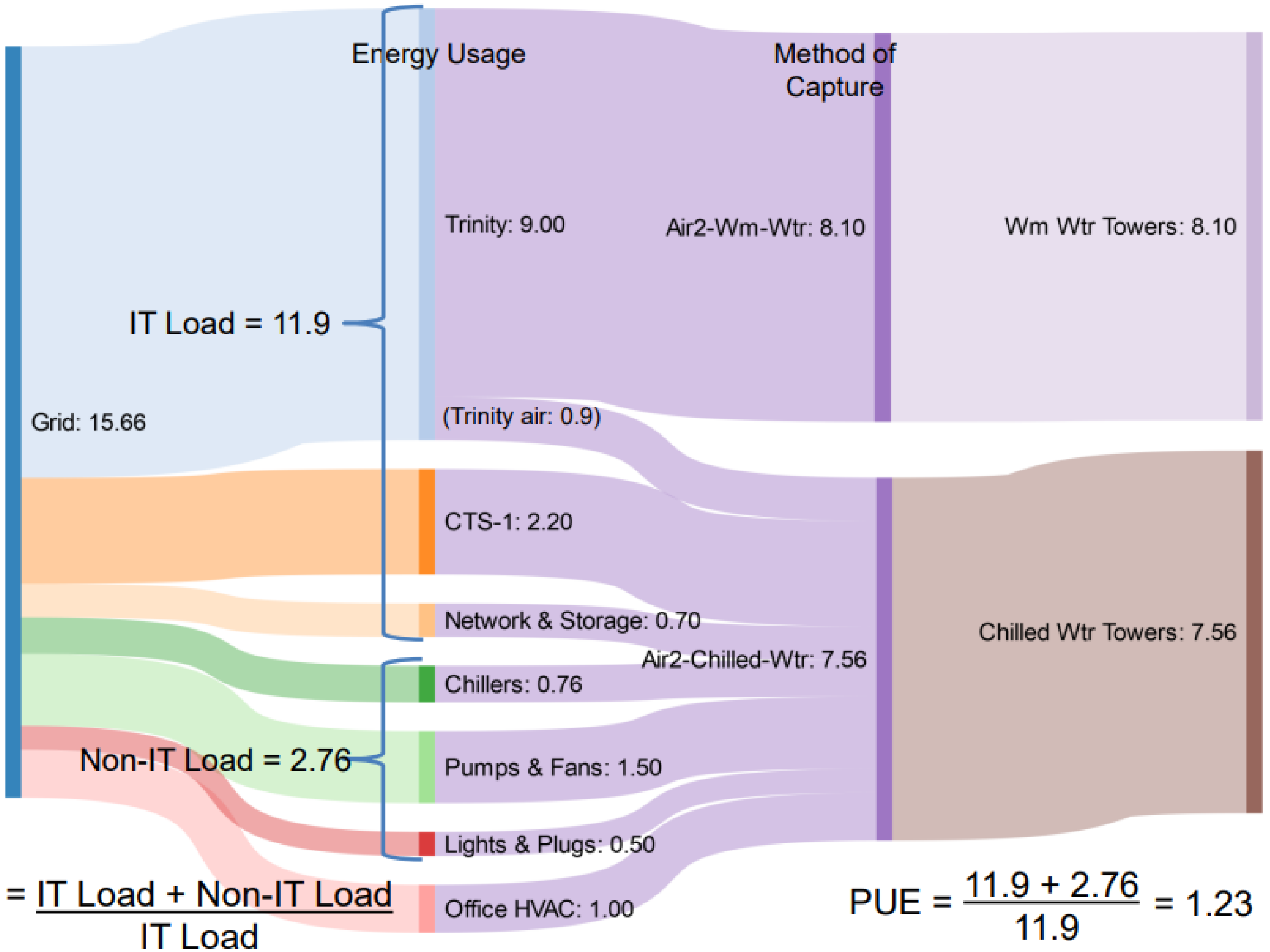
Case Study: Sustainable Data Center NREL (cont'd)



Source:
https://betterbuildingssolutioncenter.energy.gov/sites/default/files/Sustainable_Data_Centers.pdf [28]

Case Study: Data Center LANL

- **Additional Resources** [28]:
  - Center of Expertise for Energy Efficiency (datacenters.lbl.gov)
    - Energy Assessment Process Manual
    - Master List of Energy Efficiency Actions
    - Data Center Profiling (DC Pro) Tools
    - Data Center Energy Practitioner (DCEP Training)
    - Center of Expertise Training Opportunities
  - Building Your Business Case Fact Sheet
  - Better Buildings Solution Center
  - FEMP Data Center Program
  - ISO 50001 Ready Navigator
  - Energy Efficiency HPC Working Group



$$PUE = \frac{\text{IT Load} + \text{Non-IT Load}}{\text{IT Load}}$$

$$PUE = \frac{11.9 + 2.76}{11.9} = 1.23$$

Source: https://betterbuildingssolutioncenter.energy.gov/sites/default/files/slides/Everyone%20has%20a%20Data%20Center%20-%20Slide%20Deck.pdf [29]

Case Study: Energy Efficiency Data Center Business

- **Energy Savings Potential:**
  - Potential for energy and monetary savings
  - Distinct drivers, stakeholders, and barriers
- **Identifying Drivers:**
  - Factors: cost reduction, sustainability
- **Engaging Stakeholders:**
  - Strategies to win with clear benefits and ROI
- **Overcoming Barriers:**
  - Addressing challenges with solutions and best practices.

Source: https://datacenters.lbl.gov/sites/default/files/2022-06/Building%20the%20business%20case%20for%20energy%20efficiency%20in%20data%20centers.pdf [30]

Case Study: Energy Efficiency Data Center Business (cont'd)

Drivers to Energy Efficiency:

- **Reduce Operating Costs**
- **Free Up Data Center Capacity:**
  - Increases available space, power, and cooling capacity
- **Comply with Codes and Standards:**
  - for new and existing data centers
- **Upgrade Aging Infrastructure:**
  - Replace near-end-of-life equipment with newer, more energy-efficient options
- **Leverage Utility and Other Incentives:**
  - for efficient infrastructure improvements.

Barriers to Energy Efficiency:

- **Misaligned Interests:**
  - Align stakeholder interests with energy efficiency goals
- **No Dedicated Energy Efficiency Role:**
  - Projects may fall through if no one is tasked for energy efficiency improvements
  - Balancing energy efficiency with other responsibilities can be challenging
- **Lack of Awareness:**
  - Stakeholders may not be fully aware of energy reduction opportunities
  - Resource constraints can limit the ability to identify and implement cost-saving measures.

Summary

Provided a general overview of Nuclear-Powered Data Center options and discussed about site selection, regulatory requirements, community engagement and technoeconomic considerations.

Some of the critical factors are:

- **Significant U.S. energy demand increase** due to data center power requirements
  - High demand for reliable, scalable emery supply from nuclear reactors
  - Importance of N+1/N+2 redundancy configurations, ensures 99.99% uptime

- **Strategic Site Selection:** water resources, grid access, land availability, optical fiber connectivity
- **Community Engagement:** gaining public and government support, and engagement
- **Regulatory Streamlining:** overcoming lengthy and costly approval processes for expedite deployment
- **Anticipate future cooling system transitions:** Air → Chilled Water → Warm Water → phase-changing-materials ???

- **Call to Action**
  - Addressing challenges, leveraging opportunities, and advancing deployment
  - Enhancing energy reliability, sustainability, and national security.

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[1] National Reactor Innovation Center (NRIC). 2024. "2024 INL Nuclear Power For Data Centers Workshop and Tour," 28–30 October 2024, NRIC, Idaho National Laboratory, Idaho Falls, ID, USA. Available at: https://nric.inl.gov/event/2024-nuclear-power-for-data-center-workshop/ (accessed 13 November 2024).

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