A Guide to Meeting Energy Demand for Data Centers with Distributed Energy and Future Small Modular Reactors

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Introduction

The exponential growth of data center energy demand, particularly driven by advancements in Artificial Intelligence (AI), has emerged as one of the most pressing challenges for energy infrastructure globally. Between 2023 and 2030, global data center power consumption is projected to increase by 160%, pushing data centers to account for up to 8% of total U.S. electricity demand[1], [2]. This rise is primarily driven by the increasing adoption of AI servers, which consume significantly more power than traditional systems. For instance, a single AI server of a major manufacturer of AI Graphic Processing Units (GPU) can consume up to 10.2 kW at peak load, representing a 15-fold increase in computational speed but with higher power requirements per server[3], [4].

However, existing grid infrastructure is increasingly constrained, particularly in regions with concentrated data center activity, such as Northern Virginia's "Data Center Alley"[4]. Transmission bottlenecks, aging infrastructure, and long timelines for grid upgrades present significant challenges for meeting this explosive demand. Microgrids, powered by Distributed Energy Resources (DERs), offer a promising solution by reducing dependency on centralized grids, integrating generation from multiple fuels and storage, and providing load flexibility. Further, a microgrid solution improves power quality, reliability and energy security.

While Small Modular Reactors (SMRs) are not yet commercially available, a two-stage, multi-year approach can provide an effective pathway from available DER to SMR. First, current energy needs are met through existing Distributed Energy Resources (DERs)—such as renewable generation, battery systems, and Combined Heat and Power (CHP). Second, as SMRs become viable, they can be seamlessly integrated to provide scalable, low-carbon baseload power. This approach addresses immediate challenges while future-proofing data centers for sustained growth.

In this paper, we demonstrate the benefits of this multi-year approach through real-world data center examples in Santa Clara, California and Ashburn, Virginia. The same real data center profile is used in each example to compare the benefit of DERs and SMRs in very different regions. Using innovative Mixed Integer Linearized Programming (MILP) techniques through Xendee's advanced Microgrid modeling platform, we optimize energy investments, reduce OPEX costs by 60-80%, and still significantly reduce CO_2 emissions in each case.

Therefore, the innovative application of multi-year optimization not only aligns with decarbonization goals but also ensures financial viability by reducing LCOE and enhancing investment efficiency, ultimately avoiding stranded grid infrastructure investments as demand grows. This approach represents a paradigm shift in microgrid planning, offering a flexible, scalable blueprint for sustainable and resilient data center energy infrastructure tailored to both high-cost and low-cost regions.

The Data Center Power Surge: AI and Beyond

In the United States alone the power demand of data centers is expected to triple by 2030, rising from 3% to 11–12% of total electricity consumption[4], [5]. Hyperscale data centers, capable of rapid scaling to meet the growing computational needs of AI and cloud services, are at the forefront of this surge. These facilities can require upwards of 1 GW of power, equivalent to the output of a nuclear power plant[3]. Although improvements in GPUs and AI server efficiencies have been notable - such as a recent 47% improvement in performance per Watt achieved by one leading hardware provider - the sheer scale of AI workloads continues to drive net increases in energy consumption[6]. At the same time, historical efficiency gains observed between 2015 and 2019, averaging 15% annually, have begun to decelerate to 1-2% per year, underscoring the urgency for alternative energy solutions[1], [6].

3X

Increase in Power Demand by 2030

Accounting for ~12% of Total Consumption

Grid Challenges and Energy Sustainability

The rise of data centers has placed immense stress on regional power grids, particularly in areas of concentrated activity, such as Northern Virginia's "Data Center Alley"[4], [7]. Utilities and regulators face complex trade-offs: rapid energy infrastructure development to meet immediate demand risks delaying decarbonization goals, while renewable generation projects require longer timelines to scale effectively[8]. For example, Duke Energy forecasts a significant increase in gas capacity to meet an additional 2 GW of demand by 2030[9]. As indicated by data from the U.S. Energy Information Administration (EIA), the peak hourly U.S. electricity demand stayed constant for the last decade[10]. Thus, investments in transmission lines have also stalled. Data shows that the added new high voltage transmission lines dropped by 62% in the late 2010s compared to the early 2010s[11]. Thus, the U.S. electric grid is not prepared for significant load growth as expected due to AI.

The Role of Microgrids: A Resilient, Sustainable Solution

Microgrids offer a transformative solution to address the energy and sustainability challenges posed by the data center boom and this paper demonstrates that Microgrids and DER lead to lower costs compared to utility power, especially considering the issues with limited grid infrastructure expansion.

A Microgrid connects loads and distributed energy systems (e.g., PV, battery systems, wind turbines, but also thermal resources such as Combined Heat and Power running on hydrogen, among others) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A Microgrid can operate in either grid-connected or in island mode, including entirely off-grid applications.

By integrating generation, energy storage, and flexible loads, Microgrids can:

- Ensure energy reliability and resilience for critical operations.
- Facilitate the integration of low-carbon energy sources, aligning with corporate decarbonization goals.
- Optimize cost-efficiency and grid independence through advanced energy management systems.

Different Approaches to Powering Data Centers with Microgrids

A **single-step approach**, where utilities upgrade their distributions system and power plants to meet rising loads, has been used multiple times. However, this method often fails to account for sustained demand growth or future energy technologies like SMRs. Also, the rising power demand requires expensive upgrades to the cables and transformers which cannot be done quickly. New transmission projects take about 7 to 10 years to develop, approve, and construct, according to estimates from the California Independent System Operator (CAISO)[12]. As a result, costly grid expansions risk becoming stranded investments when more advanced, low-carbon DER solutions come online that would reduce the need for grid upgrades to the full extent.

In contrast, a **multi-year approach** using DERs and Microgrids offers a more strategic and cost-effective solution by leveraging Xendee's Adaptive Multi-Year Algorithm. This innovative method begins by prioritizing near-term optimization, accounting for projected changes such as increasing utility rates, technology degradation, and shifting energy demands. The process involves an iterative annual analysis where each year's design and operational decisions are optimized based on updated inputs and the results from previous years. This ensures that investments align with current conditions and anticipated future needs.

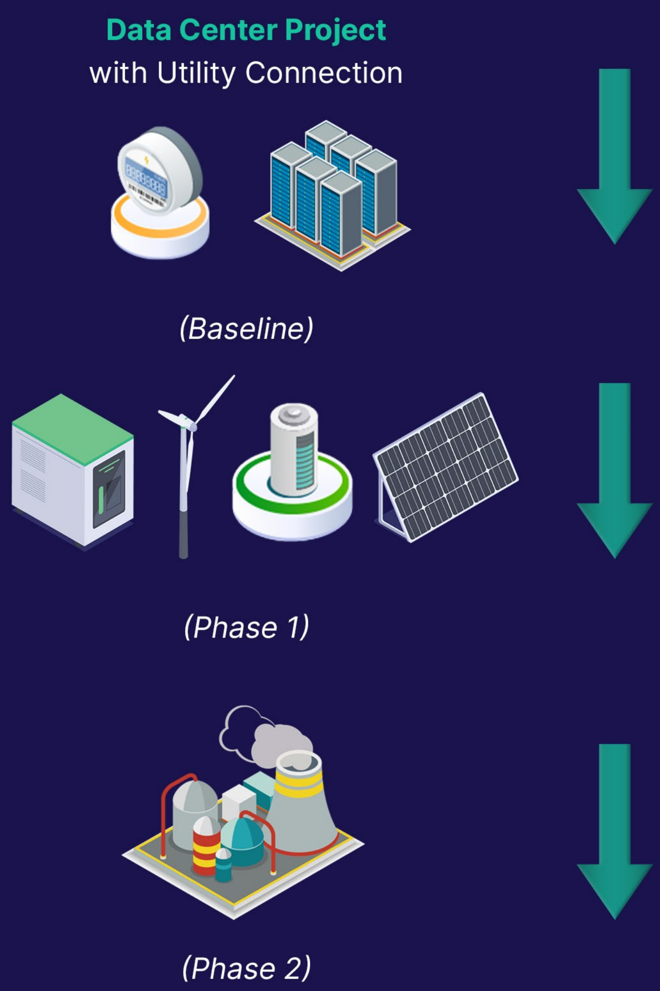
The algorithm evaluates whether investments should be made immediately or delayed until conditions are more favorable. For instance, a project might avoid renewable installations in the initial years due to high costs but integrate solar PV and storage as installation prices drop and tariffs increase. By the end of the analysis period, cumulative capacity accounts for system degradation and future requirements, ensuring no oversizing while maintaining operational efficiency. Additionally, detailed year-by-year cash flow tables are generated, providing advanced financial projections to guide planners and instill investor confidence.

Two Phases of Energy Infrastructure Deployment

This multi-year method addresses energy needs in two phases:

Phase 1. Renewables, CHP, and Energy Storage
In the short term, Microgrids can harness renewable energy sources—such as solar and wind—combined with battery storage and CHP to meet immediate demands. This reduces costs, minimizes emissions, and provides flexibility as energy needs evolve.

Phase 2. Small Modular Reactors
For the medium and long term, SMRs will deliver reliable, low-carbon baseload power, addressing the substantial load growth of data centers. SMRs mitigate the risks of rising natural gas and electricity costs while ensuring scalability and energy security.



However, with such a multi-year approach it is important to design the DERs in an effective way to avoid sunk costs later on. In other words, the DERs installed now, need to augment the SMRs of the future to create a very cost-effective solution for data centers.

By phasing investments in this manner, Microgrids achieve near-term reliability and sustainability while preparing for long-term growth with advanced energy solutions. We will demonstrate this approach by using Xendee's data center and multi-year modeling capabilities.

Xendee is a software platform for designing optimized Microgrid and EV infrastructure, and operating them efficiently in real-time. This allows users to create reliable, bankable DER systems that reduce engineering costs, energy prices, and CO2 emissions while also improving energy security and resilience to power outages

Comparative Analysis of Scenarios: Utility-Only, Utility with SMR only vs. Adopting a Multi-Year Approach with DERs, SMRs, and utility.

To illustrate the benefits of an effective multi-year strategy, this analysis compares three distinct approaches to addressing the rising energy demands of data centers:

1. **Utility-Only Case:** In this scenario, no investments in DERs are made during the project. Energy demands are met solely through existing utility infrastructure for the next 20 years.

2. **Utility with SMR only Case:** In this scenario, no significant investments in DERs are made prior to the availability of SMRs. Energy demands are met solely through existing utility infrastructure until 2035*, when SMRs are deployed to provide power. This approach assumes reliance on grid electricity until SMRs are available, which exposes the system to increasing utility costs (also due to system upgrades) and potential carbon penalties as electricity prices rise.

3. **Multi-Year Approach:** This scenario strategically deploys CHP systems and other DERs, such as battery storage, starting in 2025 to meet immediate energy demands. By 2035, SMRs are introduced to supplement and enhance the existing DER infrastructure. This phased approach leverages DER technologies to minimize operational costs, reduce exposure to rising utility rates, and align with decarbonization goals. Please note that this approach also allows for other renewables such as photovoltaics (PV), or wind, but in the case analyzed, PV or wind was not economically attractive, and thus, not selected by the algorithm.

Study Scope and Assumptions

This study focuses on data centers in two locations: one in **Santa Clara, California**, a region characterized by relatively high electricity costs, and one in the Data Center Alley in **Ashburn, Virginia**, a region characterized by lower electricity costs. The Santa Clara location is under PG&E territory and rate E-20-TOU for extra-large customers with a minimum load of 1,000 kW was used[14]. The Ashburn location is under Dominion territory, and the rate GS-3 for large general service with a minimum load of 500 kW was used[15].

A real electric load for a data center from the University of Illinois Urbana-Champaign campus is used as the basis for this study and shown in Figure 1. The same profile is used in California as well as the Virginia location. The assumption is that the cooling load matches the electric load, as the cooling requirement is proportional to the power consumed by the GPUs. The facility's total annual electric demand is around 89,305 MWh, with peak, average, and minimum loads of 13,436 kW, 10,194 kW, and 578 kW, respectively.

**SMRs might be available earlier and some assume 2030. The exact date of the commercial introduction of SMRs does not change the results significantly. However, the sunk costs due to possible grid upgrades are even worse for a shorter period. A shorter period before SMRs come online requires even greater care during planning in the multi-year approach which underscores the need for sophisticated modeling. However, in 2021, the IAEA estimated that SMRs will become commercially available between 2025 and 2035. The IAEA also estimated the earliest introduction of SMRs to not be before 2030 [13].*

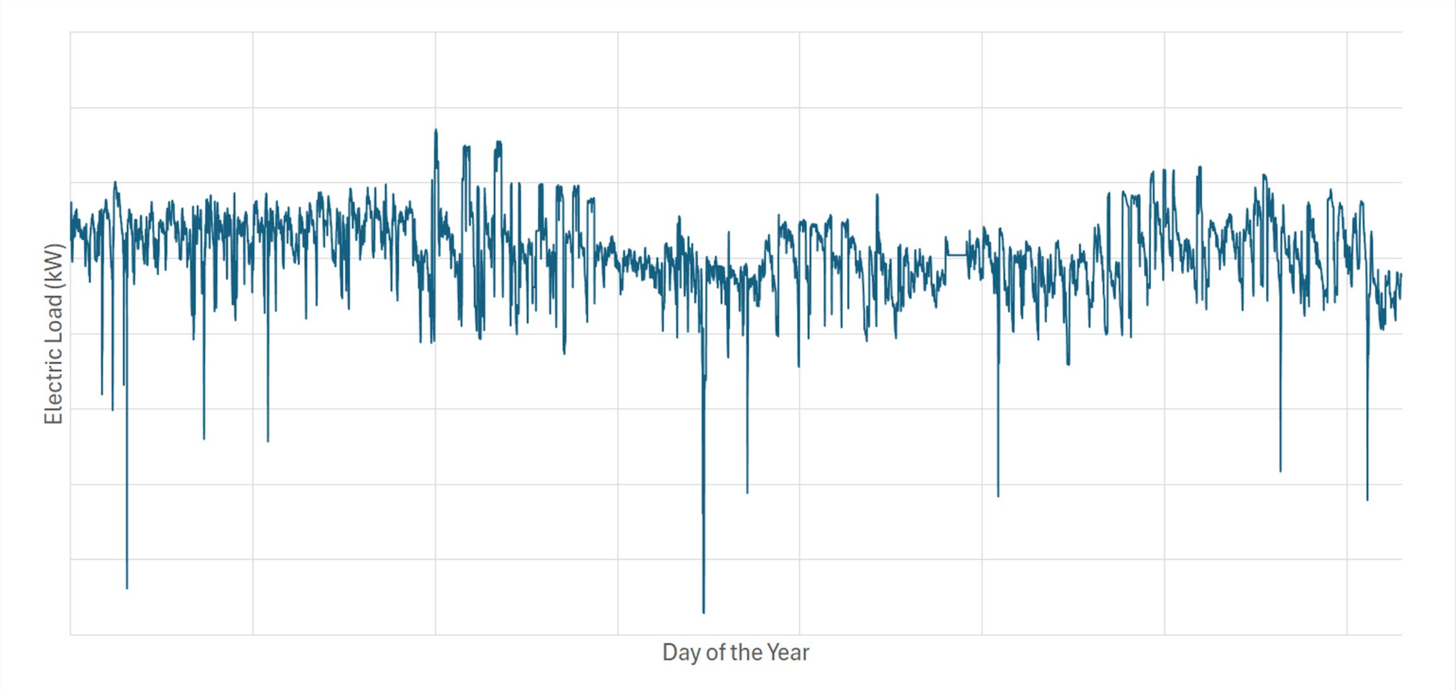


Figure 1. Graphical representation of the electric load for the data center considered in this study for a typical year. For privacy reasons the scales are removed.

The following assumptions are made to model future energy dynamics:

• **Utility Electricity Rates:** A projected annual increase of 10% in utility electricity costs due to rising natural gas prices, grid expansion needs, grid modernization and decarbonization pressures.

• **Natural Gas Costs:** An annual increase of 5% in natural gas prices, reflecting market trends and regulatory factors.

• **Timeline for DER Deployment:** In the Multi-Year Approach CHP and other DER technologies are introduced in 2025 while still relying on the utility, finding the optimal capacity and electricity-produced from DERs and the utility. This ensures that electricity provided by DERs, together with electricity from the utility, leads to the lowest overall cost. The decision on DER capacities and how much to purchase from the utility is made by the multi-year modeling approach in an automated fashion. SMRs are integrated in 2035 to address long-term energy needs.

A critical factor in this comparison is the expected rise in electricity prices over the next decade. Reliance on utility power leads to significant increase in operational expenses, particularly as grid electricity prices climb by 10% annually in some regions[16], [17]. This prolonged dependence on the grid exposes data centers to substantial cost burdens.

The multi-year approach mitigates these risks by strategically deploying CHP and renewables to reduce reliance on utility electricity. These technologies provide predictable operating costs, act as a hedge against price volatility, and offer immediate economic benefits. By 2035, SMRs complement the existing DER portfolio, delivering additional capacity to meet growing energy demands. This phased strategy not only ensures cost-effective, on-site generation but also demonstrates how proactive investment in DERs creates significant economic and environmental advantages compared to delaying action until SMRs are available.

Results and Analysis

Santa Clara, CA

The analysis for Santa Clara, CA, reveals a clear economic and environmental advantage of the multi-year approach compared to the other scenarios. In the Utility-only case, the LCOE discounted for the project length is highest with $0.4704 /kWh. In the Utility with SMR only case, the LCOE discounted for the project length is $0.1153 /kWh, while the Multi-Year Approach that considers also DERs achieves a significantly lower LCOE of $0.0383/kWh, inclusive of all investment costs. This difference is driven by the strategic integration of Distributed Energy Resources (DERs), starting in 2025, which results in **79.66% operational expenditure (OPEX) savings** and an **8.69% reduction in emissions** over the project period. Relative to the Utility-Only Case, the multi-year approach achieves an OPEX savings of 306.12% and an emission reduction of 173.66%.

Operational Expendature (OPEX) Savings

79.66%

8.69% Reduction in Emissions

In 2025, the utility with SMR case relies solely on the electric chiller for cooling, with no further investments for a decade. In contrast, the multi-year approach incorporates gas generators, and absorption chillers, thereby reducing utility dependence and setting a foundation for SMR implementation. By 2035, additional DERs complement SMRs, ensuring cost-effective energy production and significant sustainability gains.

Figure 2, Figure 3, Table 1, and Table 2 illustrate the capacity investments across the Utility with SMR only, and the Multi-Year cases in 2025, 2035, and 2040. In the Utility with SMR only case, in 2025 only the investment in the electric chiller to satisfy the cooling is made, and the data center relies on the utility for the first 10 years of operation. On the contrary, in the multi-year approach, in 2025 investments in gas generator, electric chiller, cold storage, and absorption chiller are made. These technologies allow to decrease the reliance on the utility and provide a path to the SMR implementation, while reducing operational costs. Figure 3 shows the installed electric capacity of the installed generators by year for the Utility with SMR only and the multi-year approaches.

These results highlight the cost-effectiveness and sustainability of the multi-year approach, demonstrating that proactive DER integration significantly lowers LCOE and operational expenses compared to relying solely on SMRs and utility electricity.

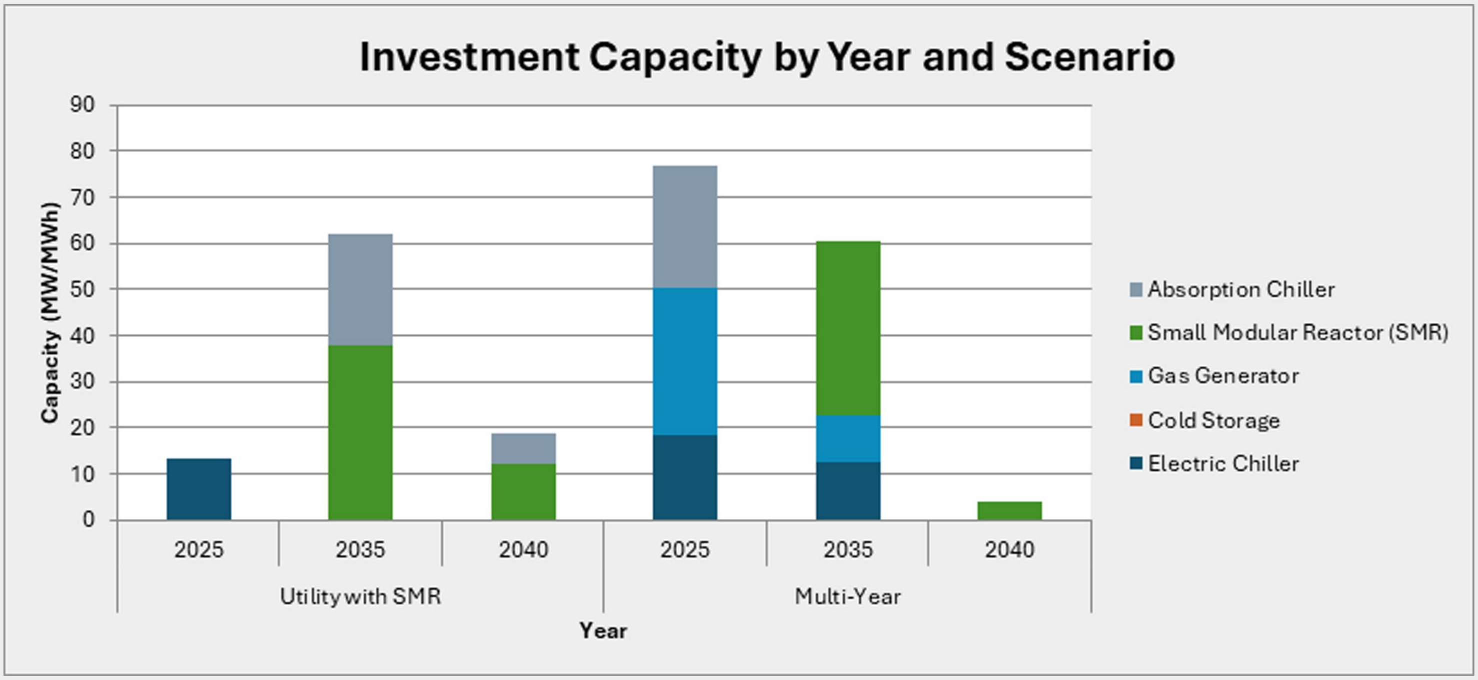


Figure 2. Optimal investment schedule for the Utility with SMR only and the Multi-Year Approaches for the Data Center in Santa Clara, CA. Please note that the utility-only case has no investments, and therefore, is not shown here.

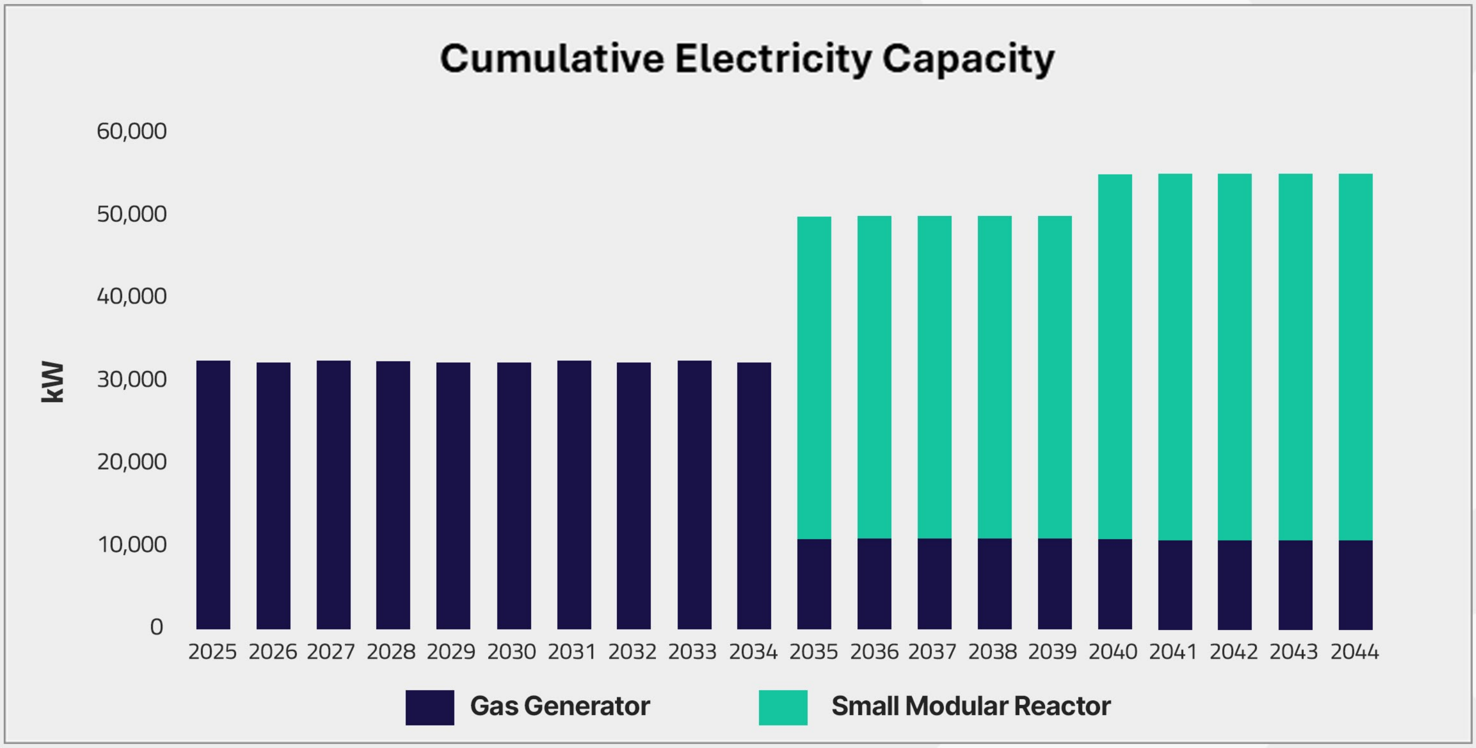


Figure 3: *Electric Capacity by Year, Multi-Year Approach for the Data Center in Santa Clara, CA*

Utility with SMR Only

Year	Technology	Capacity
2025	Electric Chiller	13.4 MW_{th}
2035	Small Modular Reactor (SMR)	38 MW (19 units)
	Absorption Chiller	24.1 MW_{th}
2040	Small Modular Reactor (SMR)	12 MW (6 units)
	Absorption Chiller	6.81 MW_{th}

Table 1. *Case optimal investment schedule for the Data Center in Santa Clara, CA*

Multi-Year Approach

Year	Technology	Capacity
2025	Gas Generator	32 MW (16 units)
	Electric Chiller	18.2 MW_{th}
	Absorption Chiller	26.2 MW_{th}
	Cold Storage	268 kWh_{th}
2035	Gas Generator	10 MW (5 units)
	Small Modular Reactor (SMR)	38 MW (19 units)
	Electric Chiller	12.5 MW_{th}
2040	Small Modular Reactor (SMR)	4 MW (2 units)

Table 2. *Optimal investment schedule for the Data Center in Santa Clara, CA*

Data Center Alley (Ashburn, VA)

Ashburn, VA, demonstrates similar advantages for the multi-year approach, albeit with region-specific dynamics. In this case, the Utility-Only scenario yields the highest discounted LCOE, reaching $0.1409/kWh over a twenty-year period. The Utility with SMR case produces a discounted LCOE of $0.0486/kWh, compared to $0.0350/kWh for the Multi-Year Approach. This includes **59.51% OPEX savings** and a **23.86% reduction in emissions** over the project period. Compared to the Utility-Only Case, the multi-year approach achieves an **OPEX savings** of 95.82% and an **emission reduction** of 58.76%.

Operational Expendature (OPEX) Savings

59.51%

23.86% Reduction in Emissions

As in Santa Clara, the Utility with SMR case in Ashburn relies entirely on utility power for the first 10 years, with minimal investments in 2025. The Multi-Year Approach, again, strategically introduces DERs, including gas generators and absorption chillers in 2025, to minimize operational costs and prepare for SMR integration.

Comparative Insights: Santa Clara vs. Ashburn

While both locations show a significant economic and environmental advantage for the Multi-Year Approach, some notable differences emerge:

• **Cost impact:** Santa Clara benefits more from DER integration due to its higher electricity rates, achieving a larger percentage of OPEX savings (79.66%) compared to Ashburn (59.51%).

• **Emissions Reduction:** The Multi-Year Approach in Ashburn achieves a greater percentage reduction in emissions (23.86%) compared to Santa Clara (8.69%), likely due to differences in grid emission factors. Xendee uses marginal time-dependent CO2 emissions (as opposed to average emissions) for the energy imported through the local utility.

• **Investment Dynamics:** Initial investments in Santa Clara are higher, driven by greater reliance on DERs to offset expensive utility electricity, while Ashburn's lower rates provide more flexibility in initial DER adoption.

The findings emphasize the importance of location-specific strategies when optimizing microgrid investments.

Conclusions

The sole reliance on the utility grid with no DER and/or SMR investments always delivers the highest Levelized Costs of Electricity (LCOE). Xendee's multi-year adaptive optimization methodology has demonstrated enormous potential for guiding data center energy planning in diverse regional environments and grids. The results from Santa Clara, CA, and Ashburn, VA, highlight the superiority of a phased, strategic approach that balances Distributed Energy Resources (DERs) and utility reliance to achieve significant cost savings, emissions reductions, and lower LCOE. By leveraging advanced algorithms, planners can anticipate future energy challenges, optimize technology deployment timelines, and minimize stranded investments.

For Santa Clara, the Utility-only case is the least economical, with an LCOE of $0.4704 /kWh. The multi-year approach led to 79.66% OPEX savings and 8.69% reduction in emissions but also achieved an LCOE of $0.0383/kWh, significantly lower than the $0.1153/kWh observed in the Utility with SMR-only case. These impressive LCOE reductions, inclusive of all investment costs, underscore the financial efficiency of the methodology.

For Ashburn, the lower electricity rates are reflected in the overall lower LCOE values. However, the utility-only case is also the most expensive with an LCOE of $0.1409/kWh, while the multi-year approach led to 59.51% OPEX savings, a more substantial 23.86% reduction in emissions, and an LCOE of $0.0350/kWh (compared with the $0.0486/kWh for the Utility with SMR-only case), further demonstrating the regional adaptability of Xendee's methodology. These findings emphasize the importance of tailoring strategies to local conditions, highlighting how location-specific challenges and opportunities can influence outcomes.

This study underscores the importance of proactive planning in addressing surging energy demands driven by AI and digital transformation. The innovative application of multi-year optimization not only aligns with decarbonization goals but also ensures financial viability by reducing LCOE and enhancing investment efficiency. This approach represents a paradigm shift in microgrid planning, offering a flexible, scalable blueprint for sustainable and resilient energy infrastructure tailored to both high-cost and low-cost regions.

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Nishaant Sinha is a recent graduate from Cal Poly Humboldt, where he completed his Masters in Environmental Systems. With over 7 years of experience, his professional journey has primarily revolved around transmission and distribution projects. However, his true passion lies in renewable energy and microgrids. As a Graduate Research Assistant at the Schatz Energy Research Center, he delved into the intricacies of two tribal microgrid projects, fostering a deep appreciation for sustainable energy solutions. His involvement in the SETI Project, a collaboration between Cal Poly Humboldt and UC Denver, further emphasized his commitment to improving clean cooking access in remote areas of India.

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