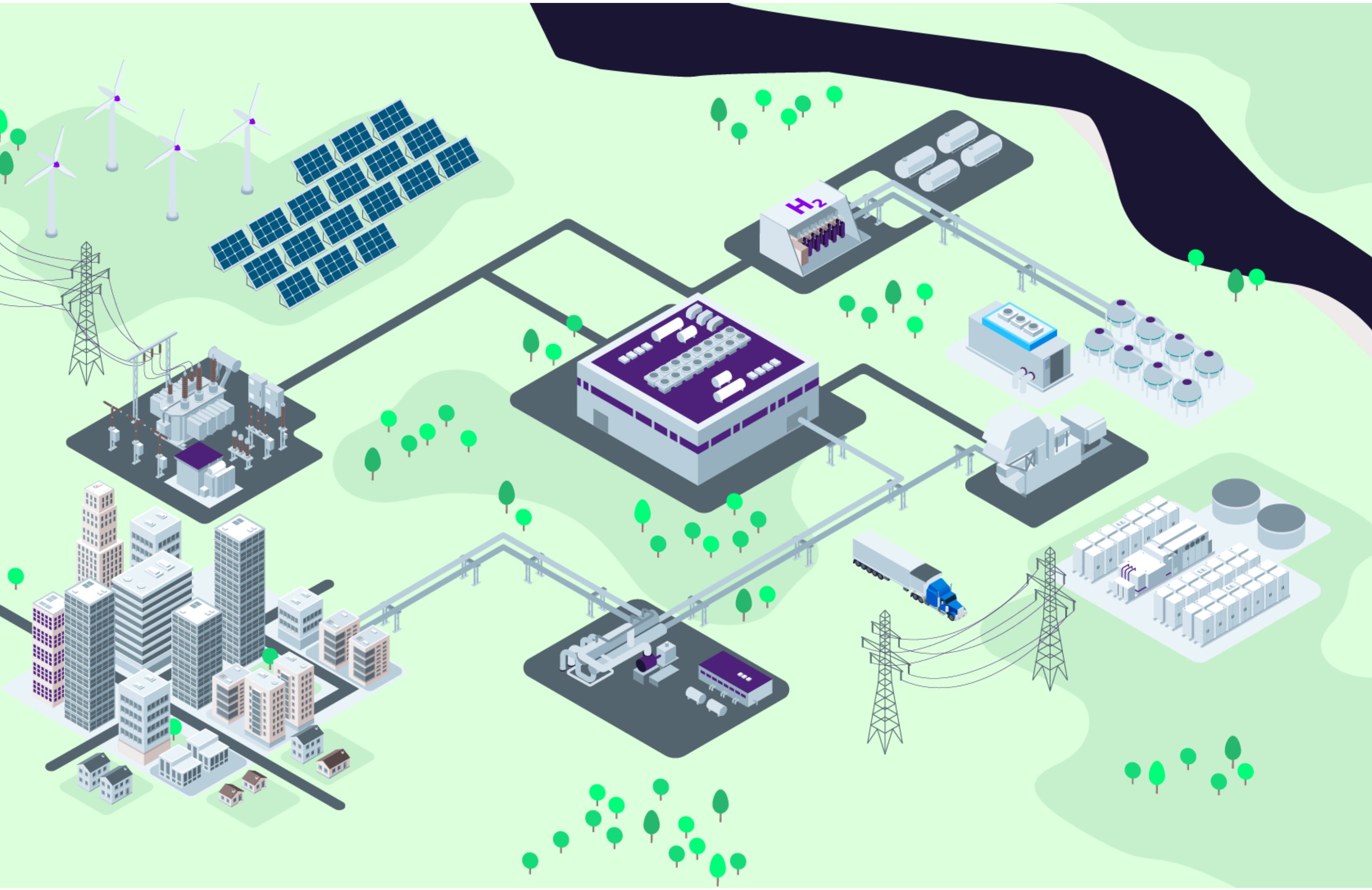

Optimization of data center power systems using energy system design

Page

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Executive summary

Data center power demand is growing at an unprecedented rate. The rapid development and deployment of Generative Artificial Intelligence (GenAI) and the growing demand for cloud storage to fuel our digital lifestyles are driving this boom in data center demand and require electricity and cooling power at availability levels beyond what our power infrastructure was built to supply. At the same time, nearly all major GenAI industry giants have pledged to limit their carbon footprint toward future net zero emissions. **Reliability, affordability, sustainability, and security will be critical to the success of data center energy systems.**

Siemens Energy has developed an optimization method for energy system designs that holds the potential to markedly enhance the reliability, cost-effectiveness, and environmental footprint of powering data centers. This design strategy helps the industry to minimize costs, curb carbon emissions, boost grid independence, and elevate the operational performance and reliability of their energy systems.

This whitepaper discusses data center power demands and the technologies used to generate, store, and dispatch this power. Siemens Energy's Energy System Design method is introduced as a holistic approach to identifying energy system designs which meet the technical, financial, and environmental targets of our customers. A case study details the Energy System Design process at work in designing the energy system for a real customer's data center power supply project. The study demonstrates multiple hybrid solutions that satisfy strict reliability requirements, where in each solution the cost of electricity and its attributed carbon intensity are detailed and discussed. A system performance boundary is delivered by identifying cost-optimized energy system designs with progressively lower CO_2 emissions. This work considers hourly-matched CO_2 emissions accounting to identify energy system designs which show a progressive decrease in CO_2 emissions, ultimately leading to the development of a so-called 24/7 carbon-free energy system. Finally, a dispatch profile is included, and operating strategies are discussed. **This exercise offers customers a practical tool for understanding the cost of decarbonization and what technologies and operating strategies may be required for their data center energy system.**

Energy System Design supports the optimization of energy systems. This powerful tool delivers concepts for turnkey energy system solutions complete with technology selection, sizing, operation, and cost within one integrated optimization procedure. A successful energy transition requires balancing affordability, reliability, security, and sustainability. Siemens Energy works with our customers to exploit each of these in their current and future energy systems by guiding the selection and configuration of energy conversion and storage assets and producing world class energy generation, transmission, and storage technologies.

Powering data centers

Data centers require terrific amounts of power, and their demand is growing. The International Energy Agency (IEA) estimates that in 2024 the global electricity consumption of data centers was 415 terawatt-hours (TWh), or between one and two percent of the global total demand [1]. **This demand could grow to over 940 TWh by the end of 2030** [1]. In the United States alone, data centers were estimated to consume about 4.4% of the total national electricity generation in 2023 with some sources projecting this value to rise to as much as 12% of national electricity generation by 2028 [2]. Datacenters are critical to supporting global economic growth via the growth of GenAI and other cloud and internet services and the expansion of the Internet of Things (IoT). Operating these in a sustainable and reliable way will require collections of solutions from the way power is used on-site to how it is obtained in the first place.

Purchasing power

Historically, datacenters have sourced most of their primary power supply from the electrical grid, outsourcing production to the power generation industry. To accommodate the projected growth in demand, the electrical grid is preparing to modernize its transmission infrastructure and introduce hundreds of gigawatts of new capacity in the coming decades [3]. Transmission network upgrades including advanced reconductoring efforts and expanded energy storage and the introduction of high-voltage direct current (HVDC) transmission lines will allow increased capacity and access to a broader portfolio of traditional and renewable power sources. At the same time, new renewable generation complemented by reliable gas power generation and modern nuclear systems will aim to add reliable and affordable power to the grid.

Purchasing electricity exclusively from the electrical grid carries a unique set of challenges. Current projected demand may outpace the new generation introduction and transmission infrastructure upgrades required to mitigate severe capacity limitations. In addition, each interconnection location imposes a carbon intensity according to the real time power generation profile of the local electrical grid. For example, power produced from coal contributes approximately 2,200 lbs CO_2/MWh whereas power produced from a combined cycle natural gas power plant carries about three times less CO_2 (about 800 lbs CO_2/MWh). As carbon-free renewables vary throughout the day and year, other, often fossil-based power sources, must provide the missing power. Data centers with exclusively grid power are therefore beholden to the carbon intensity of this mixture. Also, data centers often face long wait times in order to permit and execute interconnection to the electrical grid for buying such large volumes of power. Finally, the price of electricity is projected to rise with the modernization of transmission and distribution infrastructure and with the replacement of aging coal and other generation assets with modern renewable, gas, nuclear and other emerging generation systems. This is all compounded by increasing demand and the growing expectation of consumers, driven by the datacenter market, to have reliable access to power. Data center customers must therefore consider the potential impact to operating cost of uncertain electricity rate futures against the opportunity and challenge of self-generating power.

Generating power

The alternative to purchasing power from the electrical grid is self-generating power using gas, nuclear, renewable or other emerging generation systems. Self-generation offers data center customers greater control over the operation, maintenance, availability, and carbon intensity of their energy supply. **With projections of electricity rate growth out-pacing natural gas and other fuel prices, self-generation offers potentially long-term lower cost power and the opportunity to sell excess power from redundant units as well as resilience capability into the electrical grid.** Decarbonization opportunities can be managed "behind-the-meter" using low-carbon generation and storage technologies.

Exclusively self-generating electricity carries challenges of its own as well. Data center developers and operators have historically not been in the business of owning and operating large power generation assets. Self-generating power requires significant upfront capital investment, ongoing regulatory compliance and maintenance cost, and operational expertise. Third-party operators, and co-location contracts can alleviate this concern, but the consideration is significant. In addition, as traditional power generation and data center markets grow simultaneously, the availability of generation assets may be limited, leading to long lead times.

Making the right choice

Purchasing power from the grid, self-generating power, and hybrid solutions carry benefits and risks for data center operators. Data centers must therefore weigh the costs, complexities, uncertainties, and logistical implications of each power system alternative against their overall strategic objectives. **Siemens Energy's Energy System Design studies help data center customers to quantify and improve the cost, carbon intensity, and reliability of their energy systems.**

Energy system design

Siemens Energy has introduced Energy System Design (ESD) to help data centers make the right decisions for energy system expansions, upgrades, and new system designs, in light of the need for low-cost and decarbonized energy, the current incentive landscape, and the broad range of technologies available. ESD is a model-based engineering optimization study that selects and sizes energy conversion and storage assets to supply datacenter thermal and electrical power. Figure 1 summarizes the ESD process.

Energy System Design Inputs:

- Energy system loads: electrical and chilled water demand on an hourly or sub-hourly basis.
- Options for purchasing and/or selling commodities including pricing: electricity, natural gas, etc.
- Local climate conditions to account for asset impacts such as gas turbine or chiller performance.
- Existing data center assets for potential integration within the energy system design.
- Local renewable potentials such as solar PV or wind turbine generation profiles

In addition to these design inputs, Siemens Energy works with customers to understand their technology preferences, the overall objective of the study, and what constraints must be considered. Traditionally, customers are looking for energy systems with a minimum total cost of ownership, but ESD studies can also target improved carbon intensity, primary energy use, energy-system specific water consumption or other attributes, and any combination of these.

Once the customer's energy needs, targets, and site-specific boundary conditions are thoroughly understood, a collection of energy conversion and storage technologies is defined and modeled regarding performance and cost. Each technology is then included as an option within an optimization model. The model evaluates many different collections of these, including their interconnections, to identify the most competitive energy system and asset dispatch strategy for powering the mill.

Energy System Design Results:

- Most suitable set of technologies (assets)
- Optimized capacity for each asset
- Most suitable dispatch strategy for each asset

ESD study results are subject to the evaluation period (single or multiple representative year(s)) and provided model data. Since each input to the study is subject to uncertainty, a collection of scenarios is strategically defined, and a few parameters are selected to inform a collection of sensitivity analyses. These sensitivity analyses help identify the most robust possible energy system design against a mill's requirements, targets, and the uncertainty of future information.

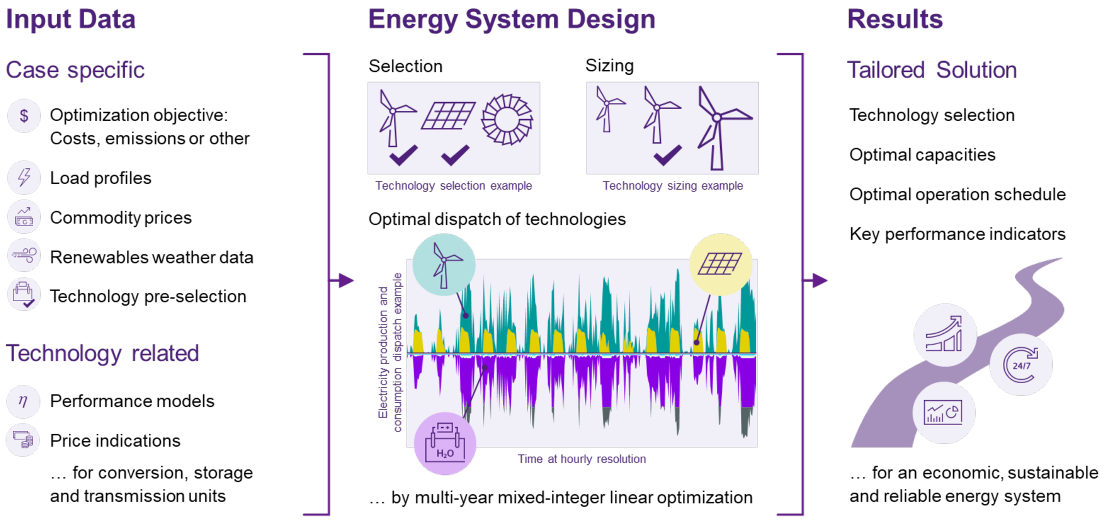


Figure 1 Energy System Design is a model-based, optimized selection, sizing, and dispatching of technologies to best comprise an energy system.

Case study: Optimizing data center energy

Siemens Energy has worked with data center customers to reduce the cost and carbon emissions of their overall energy systems. An ESD study was performed to help one such customer who was considering powering a 500 MW data center at 99.99% availability using a mix of on-site generation, renewables, and interconnection to the grid. **Siemens Energy was tasked with producing a collection of turnkey solutions which included not only the lowest cost option but also those which reduced carbon emissions and the cost associated with each.** The presented case study is a simplification of the complete study performed for the customer. The results are anonymized and do not directly reflect the customer's actual proprietary data and study results.

Reference case

The ESD study began by establishing a reference case for comparison against all other energy system designs. The customer's originally proposed energy system design concept consisted of a grid connection including both a regular utility purchase agreement and a wind power PPA with a large nearby wind farm. The wind power PPA is structured with priority data center access to the first 500 MW of power generated by the nearby wind farm. The reference system was modeled using Siemens Energy's own optimization tool and verified to match the customer's expected performance based on the data center's loads, assets' performance, and costs.

Cost optimization

Having established both a reference case and agreement on the customer's energy needs, targets, and site-specific boundary conditions, a set of energy conversion and storage technologies was defined and modeled with respect to performance and cost. The complete collection of energy system design options is shown in Figure 2. In addition to the assets included in the reference system, the ESD study considered:

- Green (carbon-free) fuel, Hydrogen here.
- Gas turbine systems in both simple cycle and combined cycle configurations.
- Solar photovoltaic (PV) and wind turbine power generation
- Battery energy storage systems
- Dedicated transmission line for power export

These technologies are considered based on their potential to positively interact within the system, as well as their commercial maturity and customer preference. Performance models define conversion efficiencies between incoming and outgoing energy or material streams, capacity and energy limitations, ramp rates, and other properties. Cost models define investment costs, operation and maintenance costs, and tax opportunities.

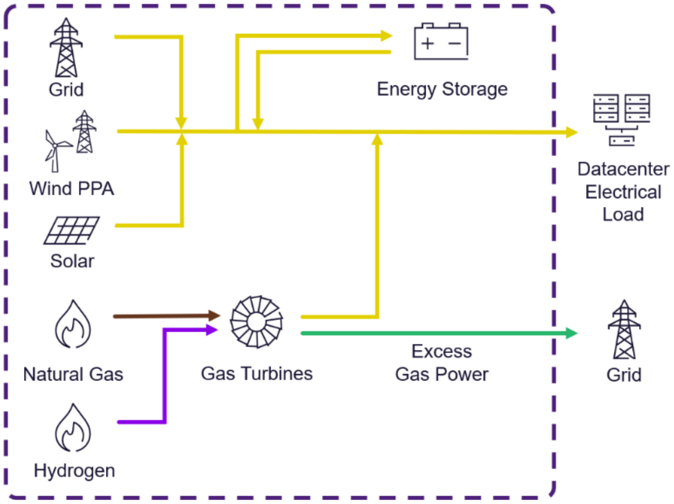


Figure 2 Complete optimization design space of technologies.

The optimization environment was used to identify the lowest cost system by comparing many combinations of the available assets, the interconnections between them, and their operation. An additional constraint ensured a minimum amount of backup generation capacity to satisfy the data center's 99.99% power availability requirement for gas turbine systems. Importantly, this work does not include the added capital and maintenance costs associated with backup power systems required to ensure grid electricity at 99.99% availability.

The lowest cost system, a combined cycle gas turbine power plant operating using natural gas, was estimated to be 8.4% cheaper and nearly twice as carbon intense as the reference design. This design emerged because of its lower cost relative to the estimated grid and wind power PPA electricity. To compare the cost of energy between the gas turbine power plant and other generation options, the capital, operating, and maintenance costs as well as the system's dispatchability and ramp rate constraints are considered.

Decarbonization

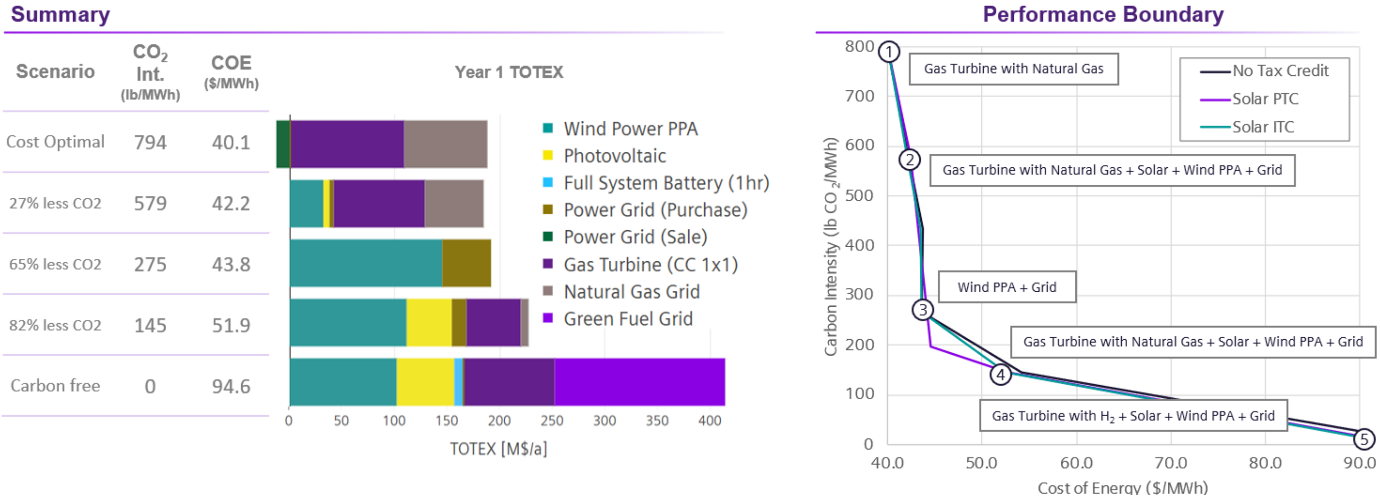
The ability to make decisions based on both cost and CO_2-intensity is an imperative for data center developers, owners, and operators. To support this reality, the collection of design options shown in Figure 2 was re-optimized with the objective of finding the lowest cost design across a series of constraints on the maximum allowable CO_2 emissions. Figure 3 compares the cost and CO_2 emissions of the energy system designs, including asset-specific cost contributions, developed across progressively more severe CO_2 emissions constraints.

The ESD study first identified the lowest cost design, consisting of a combined cycle gas turbine system, at an estimated cost and CO_2-intensity of 40.1 $/MWh and 794 lb CO_2/MWh, respectively. This design assumes the gas plant, oversized precisely to ensure 99.99% availability, runs continuously. The optimization was re-performed to find the lowest cost energy system with a maximum CO_2-intensity of 579 lb CO_2/MWh. This new design costs 5.2% more, emits 27% less CO_2, and consists of a smaller combined cycle gas turbine system alongside a large amount of purchased wind PPA power, a small solar farm, and a small amount of grid electricity.

The optimization exercise was re-evaluated at a maximum allowable CO_2-intensity of 275 lb CO_2/MWh. The resultant design is identical to the reference design, costing 9.2% more than the cost-optimal design with a large 65% reduction in CO_2-intensity. Another evaluation was performed at a maximum CO_2-intensity of 145 lb CO_2/MWh. Interestingly here, the resultant design re-introduces the combined cycle gas turbine system with a much larger share of wind PPA and solar power, and a small amount of grid power. The design costs 29.4% more than the cost-optimal design but offers a significant 82% savings in CO_2 emissions. Finally, optimization was performed with no allowable CO_2 emissions. This new design consists of a large, combined cycle gas turbine system burning hydrogen as a carbon-free fuel, as well as a large amount of wind PPA and solar power and a one-hour battery energy storage system for firming. **This design is carbon-free but costs 136% more than the cost-optimal design.** This result considers hourly time-matched CO_2 emissions accounting and exemplifies a so-called 24/7 carbon-free energy system design.

The plot on the right of Figure 4 illustrates the data center's energy system performance boundary. **This shows the collection of "optimal" designs as a function of the system designer's prioritization of cost against CO_2 emissions.** The cost-optimal design is to the top (high CO_2-intensity) and left (low cost) of the plot. As CO_2-intensity becomes a larger priority, the energy system design must move to the right (higher cost) and add or remove collections of technologies along the way. Under this study's specific assumptions and constraints, no system designs can exist to the left of and below the performance boundary. This boundary is re-constructed for both solar production (PTC) and investment (ITC) tax credit opportunities. The results discussed thus far are specific to the solar ITC case as this outperformed the PTC case in this study.

These results are specific to the unique boundary conditions and requirements considered in this study but demonstrate ESD as a powerful tool for energy cost and carbon planning at the data center level. Under different conditions, for example with the consideration of markets for renewable energy certificates (RECs) or Guarantees of Origin (GO) for produced electricity, a different specific pathway to decarbonization could emerge. **ESD helps stakeholders understand the actual costs of reducing CO_2 emissions.**



Scenario	CO_2 Int. (lb/MWh)	COE ($/MWh)
Cost Optimal	794	40.1
27% less CO2	579	42.2
65% less CO2	275	43.8
82% less CO2	145	51.9
Carbon free	0	94.6

Figure 3 Summary of energy system designs across decarbonization assessment.

Dispatch opportunities

Each optimization exercise conducted within an ESD study identifies the strongest collection of assets and the best dispatch strategy for operating these on an hourly or sub-hourly basis across the modeling period. Figure 4 shows this recommended dispatch strategy for the lowest-carbon emission design identified in the optimization exercise for a single week in the summer. The design relies heavily on renewable energy, which generates large swings in power as solar irradiation and wind changes throughout the day. The gas generation system is designed to respond to this intermittency and maintain load. The battery energy storage system charges when excess renewable power is available and discharges to cover transient periods when the gas generation starts or during rapid load changes.

The carbon-free design is especially attractive because the same gas turbines which it depends upon for continuous power today may be transitioned to accommodate a variety of fuels.

Currently, hydrogen and other sustainable drop-in fuels are in many cases more expensive than natural gas or unavailable in the volumes needed. As future advancements make sustainable fuels more affordable and reliably available, the carbon-free and cost-optimal design from the ESD study today, is positioned well to become the carbon-free and cost-optimal design of tomorrow. In the meantime, this design may be constructed and operated using natural gas. In addition, access to a power market using this customer's dedicated transmission line offers the potential to reduce costs further by operating the gas turbine system within this same design at a higher capacity factor while exporting the excess power. The table below compares these operating situations for the same carbon-free energy system design.

Operation	Fuel	Power export	Cost of energy ($/MWh)	CO_2 Int. (lbs/MWh)
Scenario 1	H_2	No	94.6	0
Scenario 2	CH_4	No	60.9	431
Scenario 3	CH_4	Yes	41.7	431

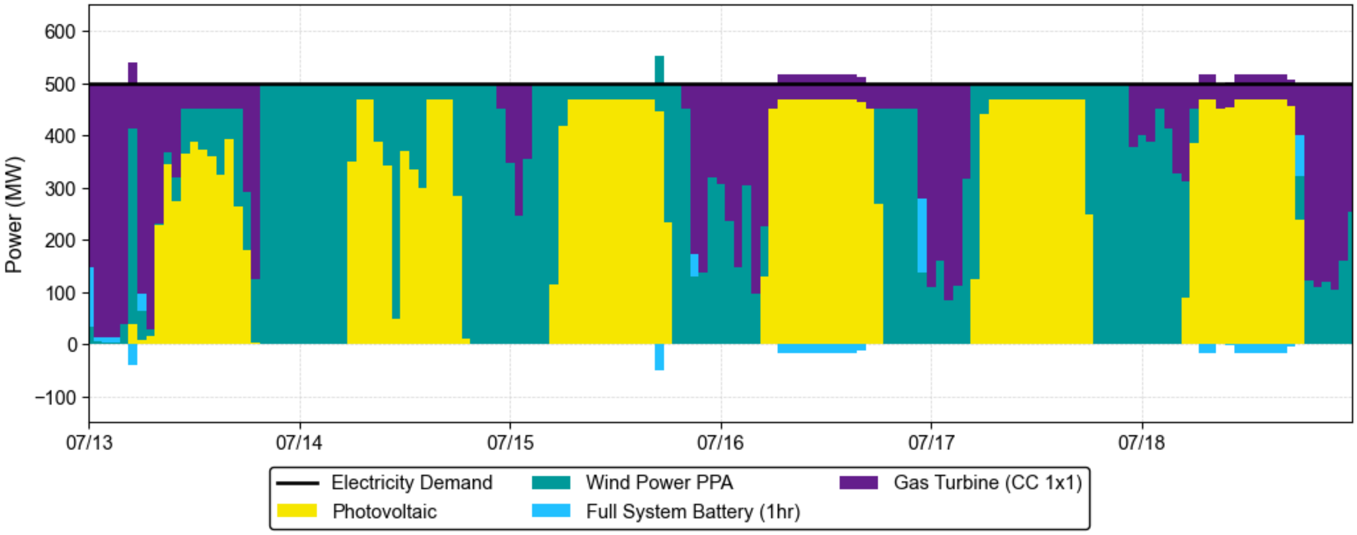


Figure 4 Hourly asset dispatch profile for carbon-free design.

Conclusion

The exponential growth in data center power demand, driven by advancements in Generative AI and the increasing reliance on cloud services, presents both challenges and opportunities for the energy sector.

As data centers strive to meet their operational needs while adhering to sustainability commitments, the optimization of energy systems becomes paramount. Siemens Energy has introduced Energy System Design to address these challenges, enabling data center customers to make informed decisions around energy sourcing, generation, and management.

The case study presented illustrates the effectiveness of Energy System Design in identifying cost-optimized energy solutions which consider carbon intensity. By evaluating a range of technologies and operational strategies, data centers can achieve a delicate balance between reliability, affordability, security, and sustainability. **The findings underscore the importance of integrating advanced generation technologies, renewable energy sources, and energy storage to create resilient and low-carbon energy systems.**

As the energy landscape continues to evolve, the insights gained from Energy System Design studies will be invaluable for data center operators seeking to navigate the complexities of energy procurement and management. The ability to model various scenarios and assess their implications on both cost and carbon emissions empowers stakeholders to develop tailored decarbonization pathways that align with their strategic objectives.

Ultimately, the transition to a more sustainable energy future for data centers is not only feasible but essential. By leveraging innovative energy system designs and embracing a holistic approach to energy management, data centers can play a pivotal role in reducing their carbon footprint while supporting the growing demands of the digital economy. **Siemens Energy remains committed to partnering with industry leaders to drive this transformation, ensuring that data centers can operate efficiently, securely, sustainably, and reliably in the years to come.**

Source-list

1. International Energy Agency: Energy and AI World Energy Outlook Report, 2024
2. Berkely Laboratory: 2024 United States Data Center Energy Usage Report, 2024
3. US Department of Energy: Clean Energy Resources to Meet Data Center Electricity Demand, 2024

Published by

Siemens Energy
Transformation of Industry, Energy System Design

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