Enabling 24/7 carbon-free energy

Modeling tools and decision frameworks

June 2024

Executive summary

As the global push towards a sustainable energy future accelerates, a growing number of market players are focused on securing carbon-free energy sources around the clock. Industrial players, such as data centers and hydrogen producers, are at the forefront of this shift, driven by legislative and internal mandates and technological advancements. Likewise, many electric utilities are evaluating how to incorporate hourly clean generation goals as part of their resource planning. In this paper, we delve into the complexities and opportunities inherent in transitioning to a 24/7 carbon-free energy (24/7 CFE) grid. We propose a new metric—Loss of Green Hours (LoGH)—to help decision makers achieve the optimal balance between meeting decarbonization goals and investing in a carbon-free resource mix. We demonstrate that entities with aggressive LoGH targets will have to substantially overbuild their resource mix or look to next generation carbon-free technologies to achieve their goals.

In this paper, we provide insights into the challenges of achieving 24/7 CFE goals for large, high-load factor demands. We present a holistic approach for assessing clean power pathways to meet these demands, demonstrated with a case study of the American desert Southwest. Our findings indicate that aggressive CFE goals require substantial overbuild of renewable resources. To meet a constant load using wind, solar, and lithium-ion batteries at 99% of hours, the nameplate capacity of the required resources would be *12 times that of the load*. This level of capacity overbuild poses significant challenges, including substantial capital costs, land requirements, and labor needs. We conclude that advanced clean technologies, such as small modular reactors, advanced geothermal, and long-duration energy storage, are more viable resources to achieve 24/7 clean energy under aggressive LoGH targets. However, we find that substantial decarbonization can still be achieved with current, widely used technologies like wind, solar, and lithium-ion batteries, and further decarbonization can be achieved by harnessing emerging technologies, like long-duration energy storage.

Introduction

The pursuit of a sustainable energy future has bolstered demand for around-the-clock-carbon-free energy. Decarbonization goals, combined with stringent legislation around tax credit qualifications have created opportunities to drive decarbonization beyond annual targets by looking at carbon-free energy accounting on a more granular basis. Transitioning to 24/7 carbon-free energy (24/7 CFE) creates new incentives and complexities to procuring renewable energy resources.

In this paper we discuss our new proprietary models that incorporate uncertainty into decision-making and help decision makers protect themselves against long-duration, low renewable events while not overbuilding capacity. We also introduce a novel decision metric—Loss of Green Hours—to help developers find the right balance between achieving decarbonization goals and renewable overbuild.

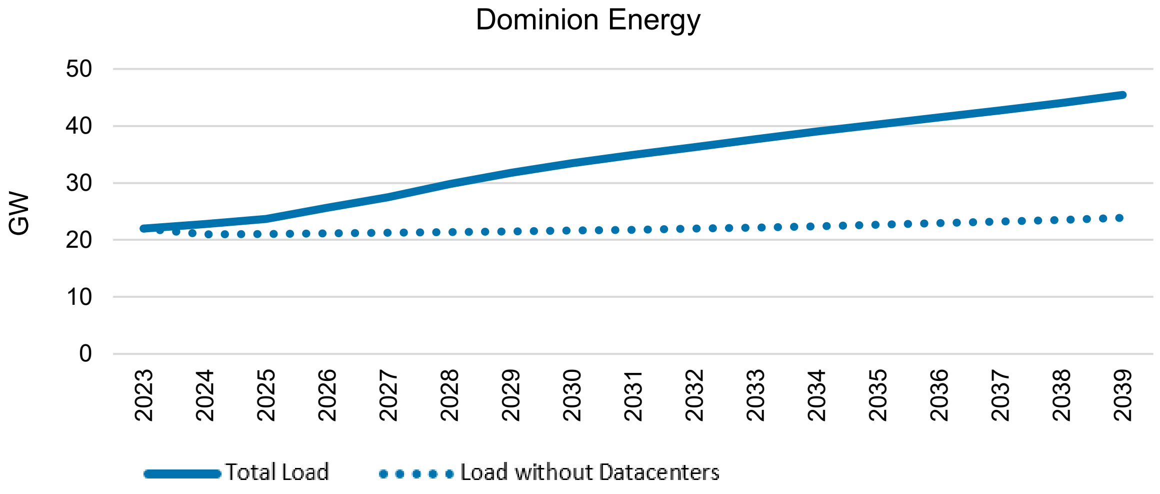
Industrial players are driving toward 24/7 CFE

Through a mix of legislative guidance and voluntary targets, many industries are driving the shift towards a 24/7 CFE grid. These include but are not limited to data centers and clean hydrogen producers.

Data centers

The growth of artificial intelligence (AI) computing is creating challenges and opportunities for the energy sector. Rising energy demand—particularly demand driven by data center growth within the next five years—has the potential to strain energy systems already navigating challenges associated with transmission, interconnection, and achieving existing carbon-free targets. For example, Dominion Energy in Virginia is projected to double its peak demand over the next 15 years, primarily due to data center development in its footprint, as shown in Figure 1.

Figure 1: PJM data center load impacts[1]



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[1] Dominion Energy, Data Center Demand Forecasting Process, https://www.pjm.com/-/media/planning/res-adeq/load-forecast/dominion-documentation.ashx, PJM Load Forecast Report, January 2024, revised February 1, 2024, https://www.pjm.com/-/media/library/reports-notices/load-forecast/2024-load-report.ashx.

Governmental organizations are already concerned about the environmental effects of compute-intensive tasks like cryptocurrency data mining. Large load data centers are falling under the same scrutiny. In early February 2024, congressional delegates from multiple states introduced legislation to require a study on the environmental impacts of AI and create a voluntary reporting system for entities developing and operating AI data centers to document and report their environmental impacts.[2]

Clean hydrogen and CFE tax credits

Proposed guidance from the US Department of the Treasury (US Treasury) clarified that in order for hydrogen production to qualify for the Section 45V tax credits from the Inflation Reduction Act (IRA), the energy it uses must be time-matched, in addition to being produced from a new carbon-free energy source within the same balancing authority.[3] While the hourly matching of renewable production and consumption is not required until 2028, it has already affected near-term procurement decisions that favor the three pillars of “incrementality,” “deliverability,” and “hourly-matching.” Table 1 shows the applicable tax credit available to a hydrogen producer based on the carbon intensity of the hydrogen produced, with the assumption that energy is hourly matched and sourced from the same regional authority as that of the electrolyzer.

Table 1: Production tax credit for clean hydrogen[4]

Life cycle GHG emission rate	<0.45kg CO2e/kg-H2	0.45 – 1.5kg CO2e/kg-H2	1.5 – 2.5kg CO2e/kg-H2	2.5 – 4kg CO2e/kg-H2
Applicable %	100%	33.4%	25%	20%
Base credit rate	$0.60/kg-H2	$0.20/kg-H2	$0.15/kg-H2	$0.12/kg-H2
Bonus credit rate	$3/kg-H2	$1/kg-H2	$0.75/kg-H2	$0.60/kg-H2

While the final guidance from the US Treasury may deviate from what has been presented in the proposed guidance, project developers, off-takers, and investors need to understand how different power procurement strategies will impact a project’s operating cost, potential tax credit qualification, and profitability.

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[2] Congress.gov, “S.3732 - Artificial Intelligence Environmental Impacts Act of 2024,” May 2024, www.congress.gov/bill/118th-congress/senate-bill/3732/text.

[3] Federal Register, “Section 45V Credit for Production of Clean Hydrogen,” December 2024, https://www.federalregister.gov/documents/2024/04/11/2024-07644/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen#:~:text=1818%20(August%2016%2C%202022),and%20investment%20in%2C%20clean%20hydrogen.

[4] “Hydrogen project commercialization in the United States: 45V guidance and assessing operating risk for electrolyzer projects,” Charles River Associates, January 2024, https://www.crai.com/insights-events/publications/hydrogen-project-commercialization-in-the-united-states-45v-guidance-and-assessing-operating-risk-for-electrolyzer-projects/.

Modeling considerations in a renewable future

The inherent challenge in providing 24/7 carbon-free energy is that mature, cost-competitive clean energy technologies, like wind and solar, have intermittent generation. Their output at any given hour depends on weather conditions. Currently, system planners combine two main methods for resource planning to hedge against such uncertainty and provide reliable power: using a planning reserve margin (PRM) and incorporating effective load carrying capacity (ELCC). A PRM is the percentage of excess capacity needed to maintain resource adequacy in a utility-scale electrical system in the event of excessive load. The ELCC is a concept in which system planners only count a portion of the nameplate capacity from variable and energy limited resources toward meeting installed capacity needs.

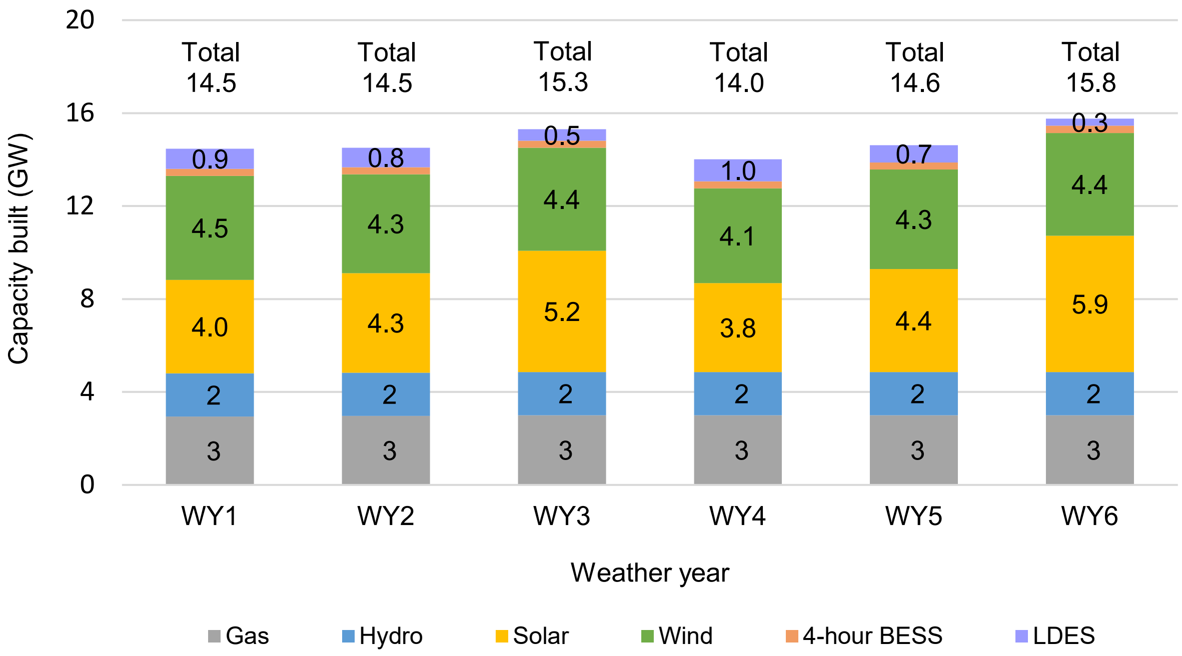
These methods to design a reliable generation portfolio have been effective in markets with primarily firm, dispatchable generating resources. However, these approaches are not adequate for systems with very high renewable penetration and flat load shapes. New approaches will be needed to support utilities in their efforts to accommodate new high load factor demand for clean energy. To mitigate risks in these future energy systems, we recommend 1) incorporating stochastic risk management with multi-weather year optimization, 2) evaluating “loss of green hours”, and 3) embracing geographic diversity when making procurement decisions for 24/7 CFE applications.

Stochastic risk management with multi-weather year optimization

Transitioning from thermal-driven to renewables-driven portfolios will leave developers increasingly exposed to risk from atypical weather conditions. Consequently, making portfolio decisions based on a single or typical weather year could lead to suboptimal investment decisions and potential reliability issues during extreme weather events that could cause long periods of low renewable generation.

Figure 2 shows the impact different weather year profiles have on the optimal mix of wind, solar, and long duration energy storage (LDES) in a sample utility system. As shown in this figure, the total capacity of wind and solar generation, and their relative proportion in the resource mix, can vary substantially based on the weather year (WY). Optimizing a resource mix based on a year with high solar generation could leave the system exposed to a 2 GW solar shortfall in a low-solar year (e.g., WY4 compared to WY6). Using stochastic optimization to simulate multiple weather years can quantify the uncertainty around weather conditions. Incorporating uncertainty in renewable output into resource planning can help identify high-risk hours and ensure reliable systems.

Figure 2: Weather year impact on built capacity



Evaluating loss of green hours: Trade-offs between capacity build-out and decarbonization goals

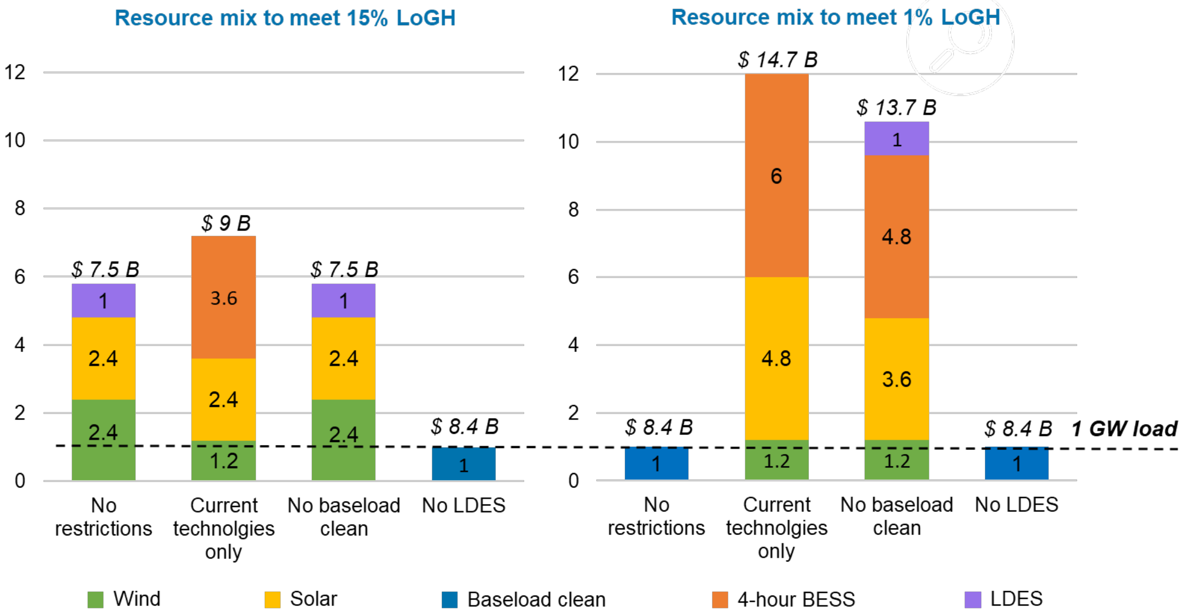
Meeting every hour of load in a year with carbon-free energy requires a resource mix with an installed capacity substantially higher than peak load. Overbuilding carbon-free generating capacity in the pursuit of 24/7 CFE can be prohibitively expensive. To help evaluate the trade-offs between (i) overbuilding intermittent carbon-free generation and (ii) meeting all hours of load with clean electricity, we propose a new metric: Loss of Green Hours (LoGH). LoGH quantifies the portion of hours not met by power produced from a carbon-free resource. Selecting a 'target' LoGH value requires reckoning with the trade-off between meeting clean energy goals and the overall costs associated with building out sufficient capacity.

In Figure 3, we show how different LoGH tolerances affect the necessary installed capacity and total capital costs for a resource mix to meet the load of a hypothetical data center in the US Southwest. We model a mix of current and next generation technologies. For each target, we modeled four generation technology scenarios to demonstrate the differences in resource mixes when different technologies are available:

1. **No restrictions:** Build out for all technologies is not restricted. This scenario will result in the most cost-optimal mix to meet LoGH goals using current technologies (wind, solar generation, 4-hour batteries) and next generation technologies (long-duration storage and advanced baseload clean technologies, such as small nuclear reactors, next generation geothermal, or carbon capture).
2. **Wind/solar generation and LIB only:** Demonstrates resource mix using only current, widely adopted technologies – wind, solar, and 4-hour batteries.

3. **Wind/solar generation, LIB, and LDES only:** No advanced baseload clean technologies (SMR, geothermal, hydrogen, etc.) are allowed. Seasonal gaps in renewables can be filled by 4-hour lithium-ion storage and long-duration energy storage (LDES).
4. **No LDES:** To assess the value of LDES and simulate potential technology bottlenecks, no LDES is allowed in this scenario. Other technology types, including advanced baseload clean energy technologies are allowed.

Figure 3: Resource adequacy analysis by technology



In this example, we model a constant, 1 GW load requirement to determine the least-cost resource mix to meet the demand, under each tech scenario and LoGH target.[5] With a 1 GW load, meeting a 15% LoGH target using only current technologies requires an installed nameplate generation capacity of more than 7x the load. When LDES is an option, the required capacity is reduced by about 20%. This indicates that LDES can be a powerful resource to offset long-duration, low-renewable events. While this resource mix only meets the hourly demand in 85% of hours, it produces 1.54x the total energy consumed by the proposed 1 GW load over the entire year. This indicates that projects with most LoGH targets may result in substantial decarbonization across the wider grid. Decision makers should consider how to further benefit from this excess carbon free energy, such as selling it on the market or allocating it toward other energy needs.

In the 'No LDES scenario,' the optimal solution is to build baseload clean. The flat load shape does not lend to synergies between baseload clean technologies and wind/solar/LIB resources. For developers with more typical load shapes (i.e., with hourly and seasonal variations), there will be synergies between these technologies. Baseload clean generation can be used to meet the

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[5] This stochastic programming-based optimization finds the lowest cost resource mix to meet the LoGH target. The optimization seeks the lowest cost solution across eight weather-year scenarios. The cost associated with this optimization is the net present value of costs over 15 years. The optimization also models solar and storage performance in their degraded condition to protect decision makers against declining performance over a 10-year useful life.

minimum load levels and some combination of wind/solar/LIB resources can be leveraged to meet the variable portion of the load.

Meeting a 1% LoGH goal using only current technologies requires an installed nameplate generating capacity that is 12x the load. This is substantially higher than the 15% LoGH target. For this stringent LoGH target, a baseload clean technology could become the most economic option for meeting this high-capacity factor load. In addition to being more costly than a baseload clean technology, the required large-scale renewable developments bring challenges such as tackling supply chain limitations, acquiring land, and managing interconnection access. These challenges may be so substantial that meeting a 1% LoGH target may not be feasible, using only current technologies.

Figure 4 shows the technology mix with no baseload clean technology at three LoGH targets and demonstrates that the optimal resource mix at different targets may not be intuitive. For example, LDES appears in both the 15% LoGH case and the 1% LoGH case, but not in the 5% LoGH case. This is because different LoGH targets require different total installed capacity and relative ratios of those resources for optimal operation.

- In the 15% LoGH case, an even split between wind generation and solar generation is the optimal solution. Lithium-ion batteries are not needed to achieve the LoGH target, and LDES is selected to protect against long-duration low wind events.
- In the 5% LoGH case, the optimal portfolio is primarily a solar resource mix. As such, LDES is no longer needed, but lithium-ion batteries are required to ‘fill-in’ the missing solar hours in the evening.
- In the 1% case, LDES is added to the 5% LoGH portfolio’s resource mix to further protect the system from low renewable events that are too long to be covered by the lithium-ion batteries.

Stricter targets require higher capacity. The stricter the LoGH target is, the more practical it becomes to rely on baseload clean technologies to meet clean energy targets due to increasing costs to procure the last few hundred MWhs of clean energy. Technological innovation and the location of the development may change which of the emerging baseload clean technologies is the most suitable resource. However, developers with less stringent LoGH goals can still achieve significant decarbonization using current technologies. This may be the preferred decarbonization pathway for developers with near-term decarbonization goals, concerns about technology-related risks, or less stringent LoGH targets.

We note that these optimal resource mixes are highly dependent on cost assumptions. Technological breakthroughs or delays may change the costs of developing and operating new and emerging technologies like LDES, SMRs, and others. Changes in the pricing and timing constraints of bringing baseload clean technologies to market will change the optimal resource mix. We recommend decision makers consider a number of possible cost and technology futures when developing their strategy for reaching 24/7 clean to protect themselves against technology risks.

Figure 4: Cost-optimal resource mix at decreasing LoGH targets

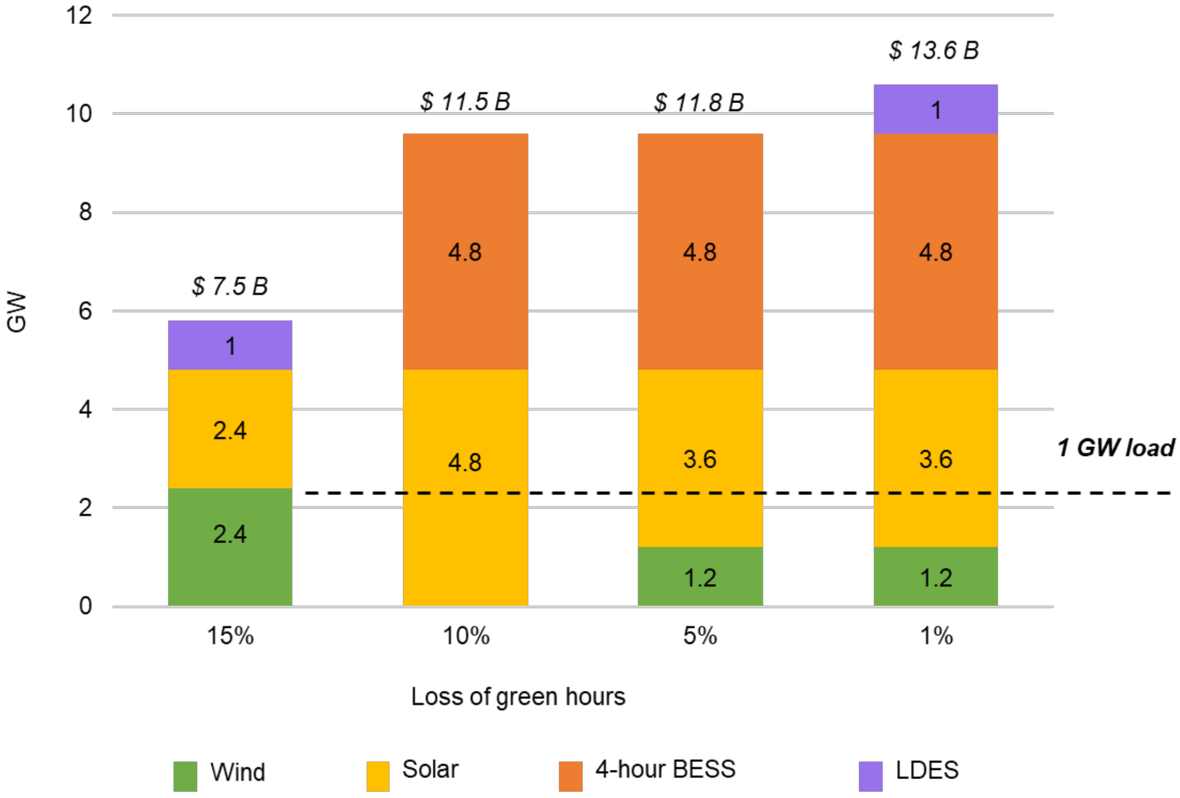
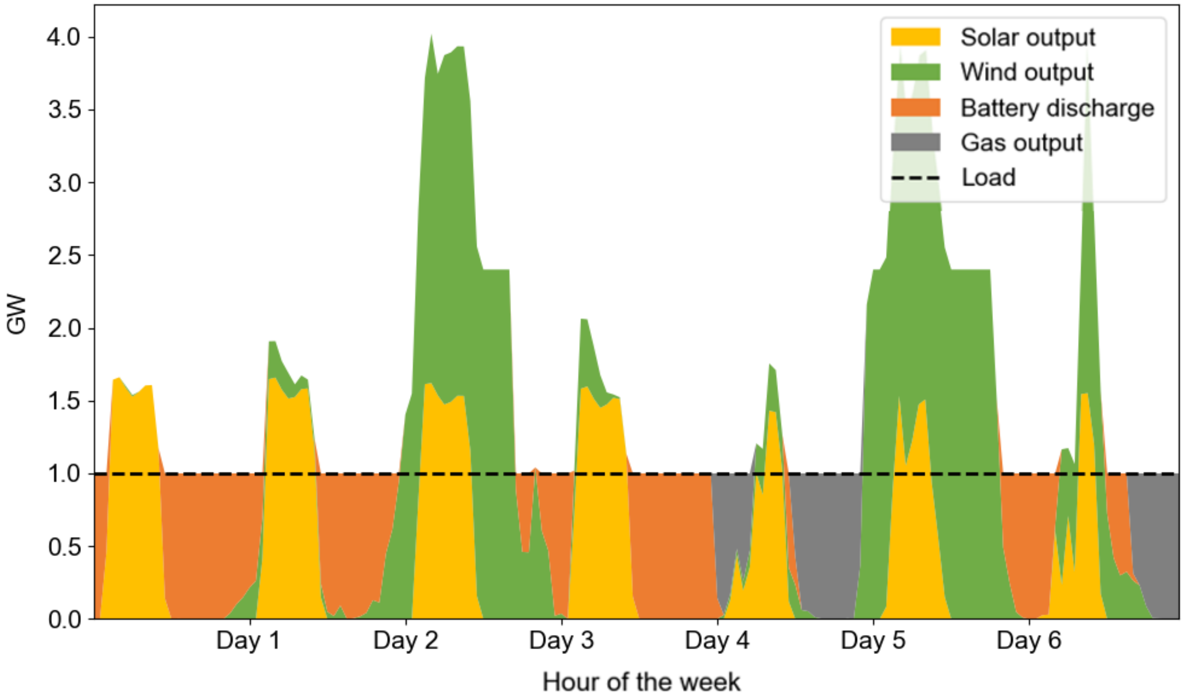


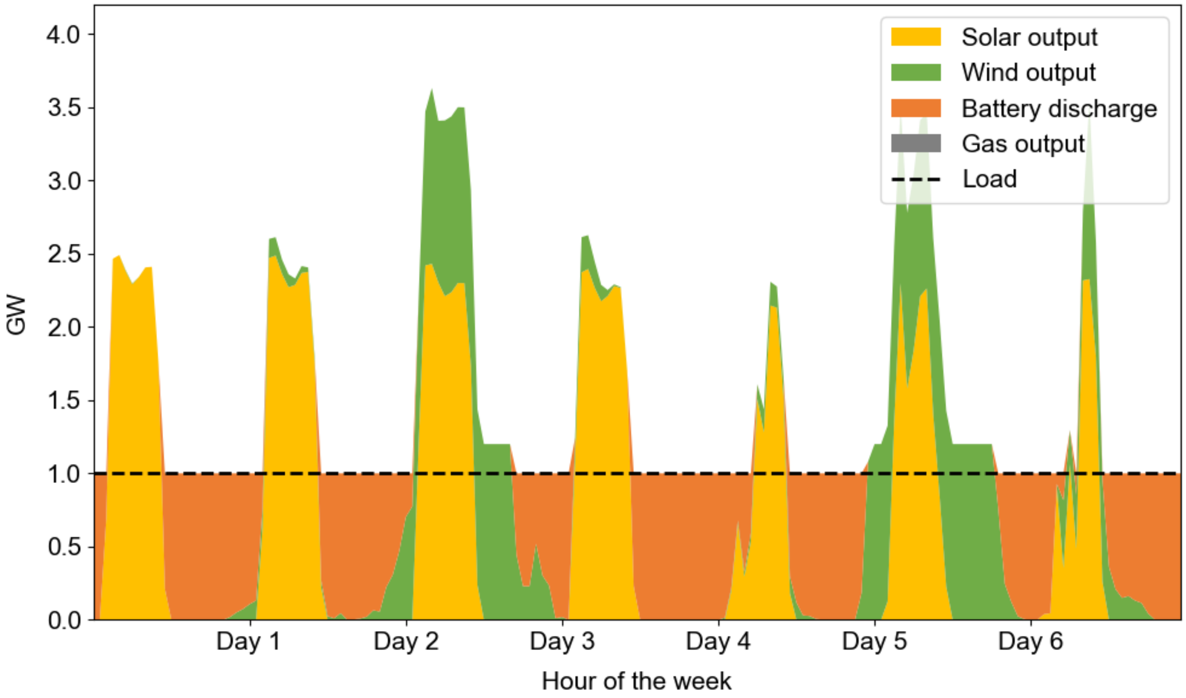
Figure 5 demonstrates hourly generation in a sample week at different LoGH targets. At a 15% LoGH target, load is not met by renewables or storage at all hours. Unmet load is met by another resource, such as gas, as demonstrated in Figure 5.a. We find that 21% of the wind and solar generation is curtailed because this portfolio has limited storage capacity. Conversely, at a LoGH target of 1%, load is met by carbon-free resources during nearly all hours. We find minimal renewable curtailment since this portfolio has substantial storage capacity.

Figure 5: Hourly generation in a sample week at different LoGH targets

(5a) Generation at 15% LoGH goal



(5b) Generation at 1% LoGH goal

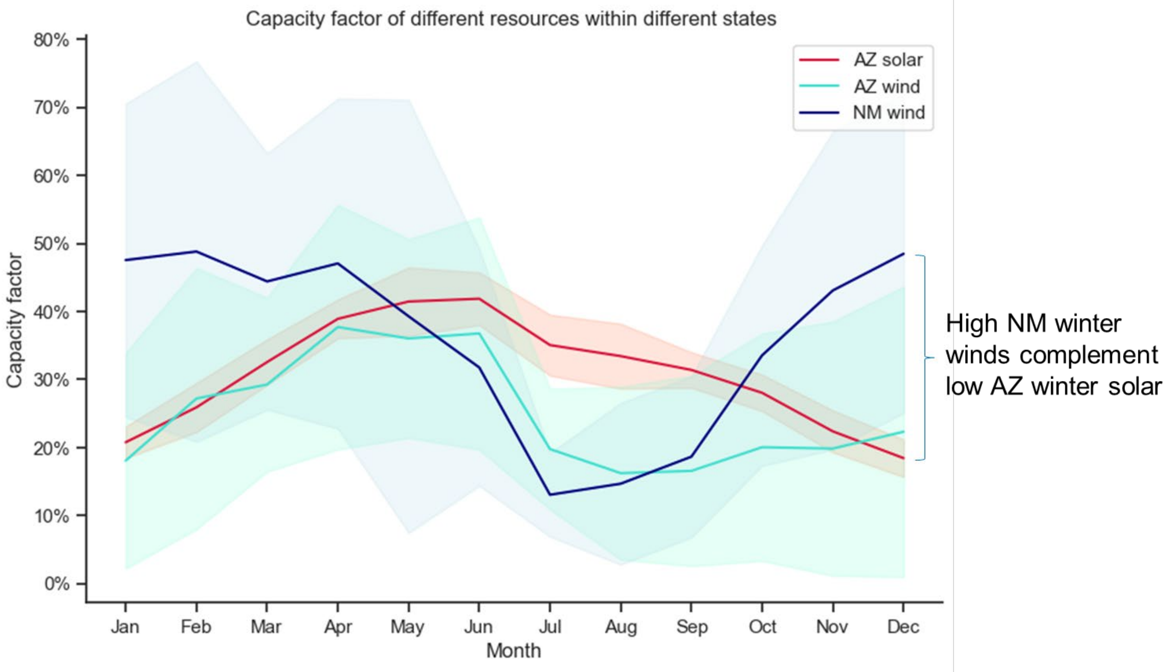


Diversify geographic footprint of resources

A primary reason to diversify the geographic footprint of a resource mix is to cover the hourly and seasonal gaps in renewable generation in a single area. In most of the US, wind and solar are generally complementary on an hourly level throughout the day: solar output peaks during the day and wind output mostly peaks at night, resulting in some renewable production at most hours of the day. However, wind and solar also have seasonal patterns. Depending on the location, wind and solar output may follow similar generation patterns across the seasons (such as peaking in the summer and lowering in the winter) or follow more complementary patterns (such as having solar peak in the summer and wind peak in the winter). The more correlated wind and solar generation is in an area, the more difficult it is to meet hourly generation targets. Daylong periods of no renewable production require overbuilding renewables and battery storage to ensure these gaps are met with clean energy.

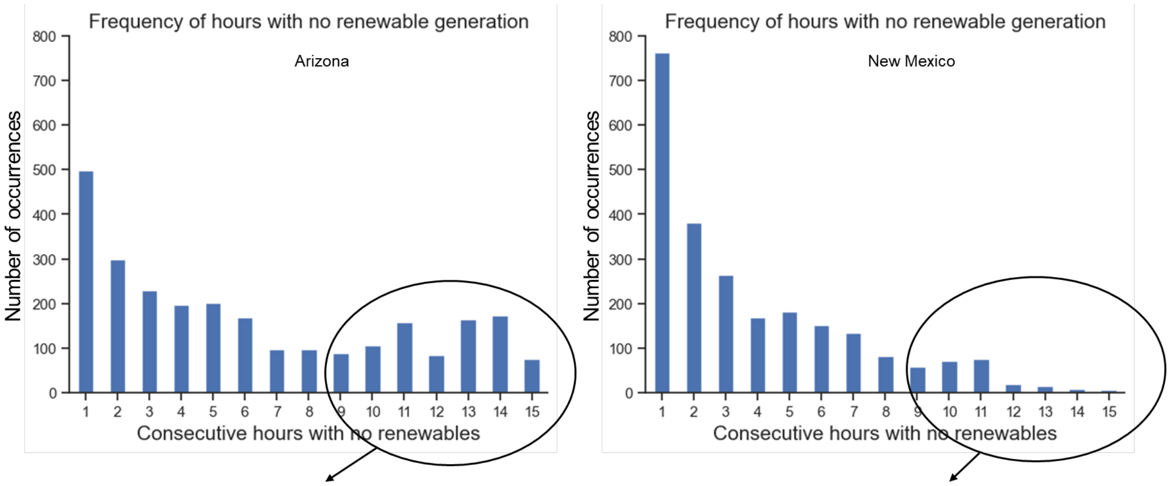
A potential solution is to diversify the geography of a renewable portfolio to include assets with complementary generation patterns. By managing the seasonal risks associated with energy production, transmission, and distribution infrastructure in specific locations, companies can minimize the likelihood of disruptions and optimize resource allocation. Incorporating production from neighboring regions with different seasonal weather patterns make it possible to strategically offset seasonal variation in resource availability. Figure 6 details an analysis conducted in the Southwest, demonstrating how wind assets from New Mexico can help cover winter generation gaps in Arizona's portfolios.

Figure 6: Complementary assets in the Southwest United States



In Arizona, wind and solar generation peak simultaneously in the early summer, leaving a large generation gap in the winter. Due to differences in its atmospheric patterns, New Mexico's wind peaks in the winter. Importing New Mexico's wind resources can offset periods of low solar and wind generation in Arizona in the winter and early spring. Procuring renewable resources in different geographies could open lower capacity, cheaper 24/7 clean portfolios. This is illustrated further in Figure 7, which shows the difference in consecutive hourly gaps of clean energy generation in states with and without complementary renewable resources. The graph on the left demonstrates the frequency of consecutive days of no renewable output in Arizona over the 8-year study period. The graph on the right incorporates wind from New Mexico and solar from Arizona; the complementary generation patterns between these states result in significantly fewer periods of long renewable outage events. Developers could seek renewable resources with complementary generation patterns to achieve 24/7 clean goals. If possible, developers could also look for opportunities to leverage existing and developing transmission to capitalize on regional weather diversity and differing peak solar times from East to West.

Figure 7: Reduced renewables outages with complementary assets



Frequent events of more than 10 hours of no generation, requiring more energy storage

Fewer long duration generation outages due to complementary solar and wind

Looking forward toward a resilient, carbon-free future

In this *Insights*, we highlighted the critical challenges and opportunities involved in transitioning to a 24/7 CFE grid, especially for large, high-load factor demands such as data centers and hydrogen production facilities. The proposed metric—Loss of Green Hours (LoGH)—offers a valuable tool for decision-makers to balance decarbonization goals with the practicalities of resource investment.

Our findings indicate that aggressive LoGH targets require substantial overbuilding of renewable resources or the adoption of advanced clean technologies. Through a detailed case study in the American desert Southwest, we demonstrated the challenges of meeting stringent LoGH goals with current technologies alone due to the significant costs and resource requirements. In the short term, fully reaching 24/7 CFE may remain infeasible due to the substantial overbuild required to reach aggressive loss-of-green-hour targets with existing technologies. Instead, the integration of next-generation technologies, such as small modular reactors, advanced geothermal, and long-duration energy storage, may present more feasible pathways toward aggressive 24/7 CFE efforts.

To achieve 24/7 CFE, developers should evaluate multiple weather years to protect themselves from long-duration renewable droughts, pursue resource mixes with synergistic weather patterns, capitalize on existing and future transmission infrastructure to gain East-West solar diversity, and design creative incentives to shift demand to peak periods of renewables. Unlocking the greatest value renewable assets will also likely require substantial investment in the transmission system. As emerging carbon-free base load technologies materialize within the next decade, these will be powerful tools toward the pursuit of 24/7 CFE, particularly for high-capacity factor loads.

Market and technological innovations will be critical for achieving 24/7 CFE. Developments in power purchase agreements to incorporate storage offtake and green premium pricing will be necessary to bridge the gap between intermittent renewable energy sources and consistent power demand. As companies strive to achieve a clean energy future, the convergence of these solutions not only promises to revolutionize our power grids but also to pave the way for a cleaner, more resilient future.

Key applications of 24/7 clean analysis include the following:

- **Hydrogen production:**
  - Assess the feasibility of integrating renewable energy sources for electrolysis to produce green hydrogen on a 24/7 basis
  - Determine the optimal resource mix to qualify for Section 45V tax credits and profitability
- **Data centers:**
  - Strategize how to power data centers around the clock, ensuring uninterrupted operation while meeting sustainability goals
  - Assess the potential for on-site renewable energy generation coupled with energy storage solutions
- **Electric utilities:**
  - Develop integrated resource plans with portfolios capable of meeting 24/7 CFE objectives
  - Identify opportunities for demand side management to align consumer electricity usage with peak periods of renewable energy generation
  - Implement power purchase agreements (PPAs) to facilitate the transition to 24/7 carbon-free energy while ensuring financial viability for utilities

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