MARCH 2023

Enabling a True 24/7 Carbon-Free Resource Portfolio for Great River Energy with Multi-Day Storage

About the authors

Great River Energy is a not-for-profit wholesale electric power cooperative that provides electricity to 27 member-owner distribution cooperatives. Together, the cooperatives provide power to approximately two-thirds of Minnesota geographically and to parts of Wisconsin. With $3.9 billion in assets, Great River Energy is the second largest electric power supplier in Minnesota and one of the largest generation and transmission cooperatives in the nation.

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Form Energy is an American energy storage technology and manufacturing company that is developing and commercializing a pioneering iron-air battery capable of storing electricity for 100 hours at system costs competitive with legacy power plants. Form's multi-day battery will address variability concerns of a renewable heavy power grid and enable a fully decarbonized electric grid that is reliable and cost-effective year-round, particularly during periods of grid stress caused by winter storms, heat waves, and multi-day renewable lulls. Form Energy was founded by energy storage veterans who came together in 2017 with a unified mission to reshape the global electric system by creating a new class of low-cost, multi-day energy storage systems.

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The Humphrey School of Public Affairs at the University of Minnesota is a nation-leading policy school. Its Science, Technology, and Environmental Policy (STEP) department offers research along with graduate majors and minors to help prepare students to work on issues at the intersection of science, technology, environment, and society that shape human well-being, environmental sustainability, and social justice in a complex and diverse world.

Great River Energy has partnered with Form Energy to develop the first commercial deployment of Form Energy's iron-air energy storage system – a 1.5 MW/150 MWh pilot project to be located in Cambridge, Minnesota.

Executive summary

On February 7, 2023, Governor Tim Walz signed legislation that sets Minnesota utilities on a path to carbon-free energy by 2040. While wind and solar have accounted for the majority of new installed capacity in Minnesota over the past several years,[1] the intermittent nature of these technologies poses a challenge to 24/7 time-matching of renewable energy supply with demand for electricity. Battery storage is one way to manage this intermittency, storing renewable energy during periods of excess and discharging during periods in which output is low.

This whitepaper provides a case study about how a new class of multi-day battery storage can broadly support the firming of renewables. Using Form Energy's iron-air technology as a case study, we demonstrate how this new asset class can supply reliable, cost-effective, 24/7 carbon-free electricity to new demand from data centers or other commercial and industrial customers within Minnesota utility Great River Energy's (GRE's) service territory.

In this study, Form Energy evaluated how the inclusion of iron-air batteries in a resource portfolio can impact GRE's ability to deliver time-matched renewable energy to new load in 98 percent and 100 percent of hours compared to portfolios with only lithium-ion storage. This analysis was conducted using Form's state-of-the-art, least-cost capacity optimization and production cost tool, Formware™, which has been designed from the ground up to capture the chronology and multi-scenario optimization necessary to accurately model grids with substantial renewables and storage. In this analysis, we used Formware to select the optimal resource additions in 2030 to meet 400 megawatts (MW) of new data center load with 100 percent renewable energy in GRE's service territory. The modeled resource additions included new wind, solar, and storage technologies that would be incremental to GRE's existing resources to serve new data center load. We modeled two scenarios: a *Without Iron-Air* scenario that included 4-, 6-, and 8-hour lithium-ion batteries as storage options, and a *With Iron-Air* scenario that also included iron-air batteries. In each scenario we evaluated optimal resource needs to match 24/7 carbon free electricity to a hypothetical large electric customer's demand in 98 percent and 100 percent of hours of the year, the high standard that portfolios must achieve to credibly claim to deliver 24/7 carbon-free energy.

Through its participation in this case study analysis, GRE was interested in learning more about how a multi-day energy storage resource like iron-air batteries could support its growing renewable portfolio and benefit members.[2] This study provided the opportunity to learn more about both the drivers of multi-day storage adoption in capacity optimization modeling, as well as the operation of that particular asset class in a high renewable scenario. GRE will be able to use these insights as it continues to plan along with its member-owners for future resources to meet Minnesota's carbon-free energy targets while best serving customer needs. Although GRE's current 2023 filing of its Integrated Resource Plan does not include a multi-day storage asset as a selectable option, the findings and information garnered from this collaboration begin to build the groundwork for doing so, and provide insights that GRE can bring to its planning process.

The results of this analysis demonstrate key benefits of including a multi-day storage asset in time-matched clean energy portfolios. Specifically, we find that iron-air batteries:

- Reduce the total resource needed in a 400 MW peak load 24/7 carbon-free portfolio by 723 megawatts (MW), or 25 percent, relative to a lithium-ion only portfolio.
- Lower renewable curtailment in time-matched renewable portfolios by 80 percent relative to portfolios that depend exclusively on lithium-ion storage.
- Meet 69 percent of the net load during renewable lull periods, despite providing only roughly 50 percent of the power capacity in the least-cost portfolios.
- Reduce the cost to deliver time-matched renewable energy by 25 percent relative to a lithium-ion only portfolio.
- Enable an increase from 98 percent to 100 percent time-matched renewable energy at an incremental cost increase of only 13 percent, as opposed to a lithium-ion only portfolio in which the cost increase is approximately 60 percent.
- Provide resiliency benefits across weather years by reducing the variance in year to year optimal resource builds.

The focus of this white paper is on the value of multi-day storage to future commercial and industrial loads that are seeking to serve loads with 24/7 carbon-free energy. Results of this analysis demonstrate that a multi-day storage offering like iron-air provides benefits to those members located within GRE's territory, making time-matched clean energy more affordable and reliable.

1 Minnesota Department of Commerce. May 2022. Minnesota Energy Data Dashboard. Available at: https://mn.gov/commerce-stat/pdfs/mn-energy-data-dashboard.pdf.
2 Technology types with a discharge duration at rated capacity of greater than 24 hours are considered to be part of the "multi-day storage" asset class. This is in contrast to long-duration storage (LDES), which we consider to be resources that can discharge at rated capacity for 8 to 24 hours.

Introduction

After more than a decade of mostly flat demand for power from electric utilities across the United States,[3] future electric loads are expected to rise at a comparatively greater rate in the future with increased electrification, greater penetration of electric vehicles, and demand from new data centers. Owners of these data centers often have ambitious renewable energy goals and are thus planning to meet demand with new solar and wind resources – a challenge due to the inability of intermittent renewable resources to serve near-constant hourly data center load.

The limits of typical renewable energy targets: substantial portfolio emissions

In the recent past, entities seeking to be supplied by a target percentage of renewable energy have simply summed their total energy consumption over the course of the year and procured Renewable Energy Certificates (RECs)[4] in sufficient volume to match that consumption regardless of whether the renewable energy was generated coincident with actual energy demand. However, this annual approach often produces substantial carbon dioxide emissions due to the inherent variability in renewable energy supply and the mismatch in timing between output and energy demand.[5] An entity that purchases RECs to cover its annual electricity consumption actually meets its hourly demand using carbon-free resources only 40 to 70 percent of the time.[6]

Towards time-matched 24/7 carbon-free electricity to load in all hours

The concept of "24/7 carbon-free energy" promises clean energy that is time-matched to customers' energy demand, meaning that both renewable energy and flexible capacity are used to provide dispatchable, zero-carbon power that is available to meet demand in every hour. Costs of 24/7 resource portfolios that rely exclusively on renewables and lithium-ion batteries have been more expensive than the current "annual REC" approach – sometimes prohibitively so – as a substantial overbuild of resources is often necessary to meet demand in all hours, particularly during periods of extended lulls in renewable output.[7]

Variability of GRE's renewable energy portfolio in all hours and conditions

Wind energy makes up a majority of GRE's existing renewable portfolio, and enabled the utility to meet Minnesota's 25 percent Renewable Energy Standard by 2017 – eight years ahead of schedule – while providing cost-effective power to its members. As penetrations increase to even greater levels, however, the intermittent nature of the resource means that, in the absence of adequate storage, periods of high output can lead to a need to curtail the resource, while periods of low output will require that generation from other sources be called upon to fill in during these hours.

Figure 1 (see next page) identifies the timing and duration of wind lulls identified in the generation profiles for Lyon County, Minnesota that were derived from the National Renewable Energy Laboratory's (NREL) System Advisor Model (SAM).[8] Each of the bubbles shown in Figure 1 represents a lull period of 12 hours or more. Lulls are defined as having output that is 75 percent or less of the annual average (alternatively, a 25 percent reduction in output compared to the annual average).

The size of each bubble represents the duration of the lull event. While the most frequent wind lulls often last 48 hours or less, there are several weather years in which the duration of a single renewable lull exceeds 100 hours, and there are multiple 100+ hour lull events in a single year. Finally, the color of each bubble represents the number of gigawatt hours (GWh) of energy lost during each lull event, with more GWh being lost as the duration of the event increases.

3 Normalized for weather.
4 Renewable energy projects generate both energy and Renewable Energy Certificates, with one REC being equal to 1 MWh. RECs can be sold to any entity and can be used to meet that entity's renewable energy targets.
5 de Chalendar, J.A. and Benson, "Why 100% Renewable Energy is Not Enough," Joule 3:6, 2019, 1389-1393. Available at: https://doi.org/10.1016/j.joule.2019.05.002.
6 Long Duration Energy Storage Council. 2022. A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements.
7 N. Sepulveda, J. Jenkins, F. de Sisternes, R. Lester, "The Role of Firm, Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation," Joule 2:11, 2018, 2403-2420. Available at: https://doi.org/10.1016/j.joule.2018.08.006.
8 Available at: https://sam.nrel.gov/download.html.

Figure 2 presents the wind lull data as a histogram that plots the number of occurrences of multi-day wind lulls (greater than 24 hours) alongside their duration. We see that, across all years of data, wind lulls ranging from 24 to 50 hours are most common, but that there are also a number of lulls that are greater than 50 hours in duration. Notably, the longest wind lull in our dataset is approximately 140 hours. We do not see wind lulls that last for multiple weeks or months.

The frequency and magnitude of these wind generation droughts suggests that resources like multi-day energy storage can help capture periods of excess generation and fill in wind generation droughts, with the benefit of reducing overall needs for generation capacity, and improving the dispatchability and availability of wind portfolios under a wide range of weather conditions.

FIG 1. Historical periods of lower than average wind output, 2007-2013

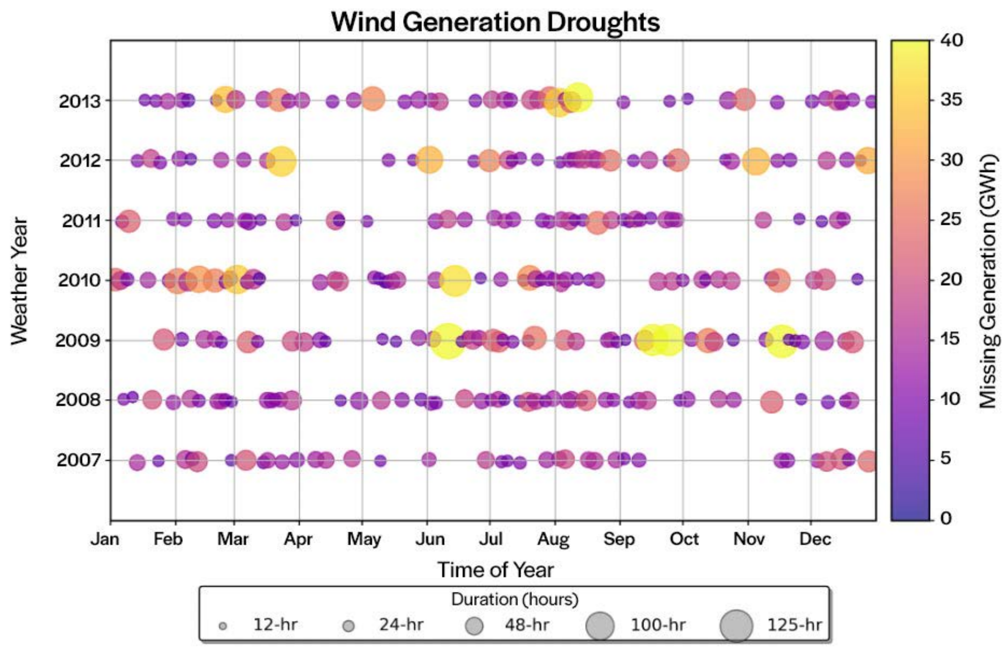
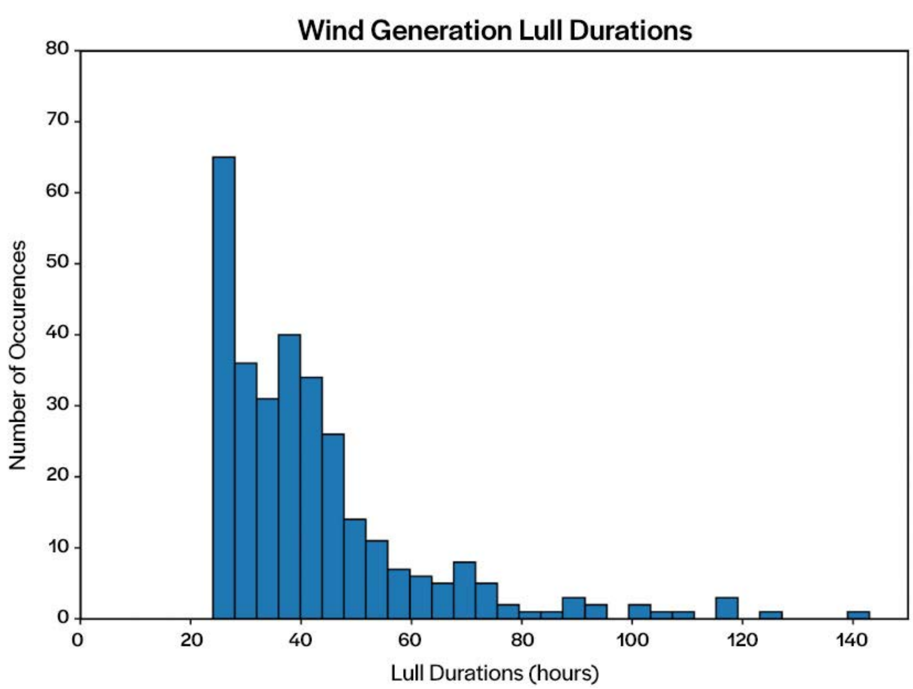


FIG 2. Number of events with lower than average wind output and duration of these events, 2007-2013



Case study scope and motivations

This white paper provides a case study on the resource portfolios that could supply data center or other commercial and industrial load within GRE's service territory with 24/7 carbon-free energy using new, incremental renewable and storage resources, including both lithium-ion and multi-day, iron-air technologies. This study compares resource portfolios that rely exclusively on lithium-ion storage with portfolios that include iron-air batteries to evaluate the impact of multi-day storage technologies in providing time-matched renewable energy under load factors of 98 percent and 100 percent, respectively. The following sections describe the assumptions and modeling methodology used in this analysis, detail the optimized capacity expansion results and corresponding resource portfolio costs, and discuss the key conclusions that can be drawn from this analysis.

Looking to the future, GRE is interested in learning more about how a multi-day energy storage resource could support its growing renewable portfolio. This study provided the opportunity to learn more about multi-day storage dispatch in a high renewable scenario. GRE was also looking to explore the drivers of multi-day storage adoption through this modeling exercise. GRE will be able to use these insights as it continues to plan along with its member-owners for future resources to best serve customer needs, and looks forward to expanding the analysis around multi-day storage in future work.

Rendering of a 56 MW Form Energy battery system

Assumptions and modeling methodology

Form Energy modeled portfolios of incremental new resources to provide 24/7 carbon-free electricity to a hypothetical data center to meet demand in every hour of the year. The analysis was predicated on the concept that in this situation, no existing renewable energy in GRE's portfolio would be used to satisfy the renewable demands of a new load, thus incremental resources would be needed to serve the 24/7 clean energy needs. This analysis was conducted using Form's state-of-the-art, least-cost capacity optimization and production cost tool called Formware, which has been designed from the ground up to capture the chronology and multi-scenario optimization necessary to accurately model grids with substantial renewables and storage. Formware finds the least-cost mix of assets, and the operational strategies of those assets, necessary to meet system requirements on an hourly basis across diverse weather, load, and contingency scenarios. The model is highly customizable, allowing Form Energy to create bespoke analyses of utility systems and integrated markets.

In this analysis, we used Formware to select the optimal resource portfolio in our modeled year of 2030 to meet 400 megawatts (MW) of new load in GRE's service territory.[9] We modeled two load shapes with high load factors, which are consistent with load associated with data centers. The first load shape has a 98 percent load factor and is modeled in Formware as an interruptible load, meaning that load is shed during the top 2 percent of hours in which energy prices are the highest over all of 2030.[10] The second shape has a 100 percent load factor, meaning that load must be met in all hours of the year. GRE provided hourly generation profiles for solar and wind for each year from 2007 to 2013 for Lyon County, with the profiles for 2008 being used as the base year for capacity optimization modeling.

The modeled resource portfolios included new wind, solar, and storage technologies that would be incremental to GRE's existing resources to serve new data center load. At GRE's request, wind and solar were modeled as power purchase agreements (PPAs) with pricing at $35/MWh and $45/MWh respectively, inclusive of tax credits associated with the Inflation Reduction Act. Portfolio costs were also calculated for an alternative, lower wind and solar cost scenario, in which wind and solar PPAs are priced at $20/MWh and $30/MWh respectively. Lastly, portfolio costs were calculated in a scenario in which total capacity is valued in the market, reducing net costs to customers.

Lithium-ion battery technologies were offered to the model in 4-, 6-, and 8-hour durations. Capital and operating costs were taken from the National Renewable Energy Laboratory's 2022 *Annual Technology Baseline*. Form Energy's 100-hour iron-air battery was included in the analysis as an option of a multi-day storage asset class, and Form provided pricing data for 2030. An Investment Tax Credit (ITC) of 30 percent was applied to each of the storage technologies included in the analysis. A summary of storage cost assumptions under Low, Moderate, and High pricing assumptions (pre-ITC) is shown in Table 1.[11]

TABLE 1. Summary of input assumptions and scenarios

	Pre-ITC All-in Capital Cost ($/kW)			FOM ($/kW-yr)
Scenario	**Low**	**Moderate**	**High**	**All**
4-hour LI	$580	$700	$1,065	$25
6-hour LI	$824	$968	$1,485	$35
8-hour LI	$1,067	$1,237	$1,905	$44
Iron-air	$1,700	$1,900	$2,400	$19

Financial assumptions underlying this analysis include a discount rate of 8 percent and an inflation rate of 2 percent. Portfolio costs were calculated using a 25-year net present value. In addition to the 98 percent and 100 percent load factor cases mentioned above, we also performed a multi-scenario optimization, in which we varied the generation profiles of solar and wind, using the profiles for each year between 2007 and 2013,[12] to produce seven different resource portfolios that are representative of the optimal capacity build-out under a variety of weather conditions.

9 This analysis optimized the resource portfolio necessary to meet load in the required number of hours and did not include a planning reserve margin. We note that MISO has moved to a seasonal construct for capacity accreditation of resources, and, depending on the capacity value given to wind and solar resources, it is possible that our modeled portfolios might not contain sufficient capacity to meet a given reserve margin in a specific season.

10 In practice, load in this remaining 2 percent of hours could be supplied by grid energy.

11 Cost assumptions used for iron-air in this analysis are representative, and should not be considered to be indicative of Form Energy's pricing for commercial projects in 2030.

12 Generation profiles were derived by GRE from the National Renewable Energy Laboratory's System Advisor Model. At the time they were derived, data availability was limited to the years 2007 to 2013.

Results - 98 percent load factor

Capacity optimization and resource selection

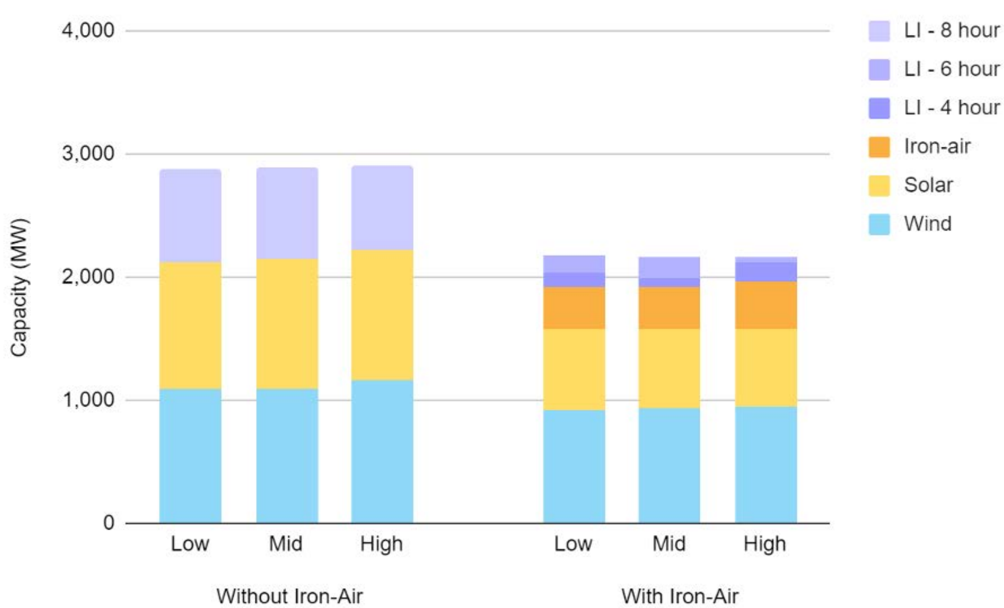
In the 98 percent load factor case, the availability of iron-air batteries lowers the overall resource build necessary to supply 24/7 clean energy to serve new load, while also increasing the diversity of the storage technologies that make up the least-cost portfolio. Figure 3 shows the resource selection in both the *Without Iron-Air* and *With Iron-Air* scenarios under high, mid, and low forecasts of future storage costs. When iron-air batteries are available for selection by the model, the total resource build required under each of the cost sensitivities is at least 700 MW less than in the *Without Iron-Air scenario*. When we look at capacity additions by type, we see that the presence of iron-air results in approximately 15 percent less wind, 18 percent less total storage, and 38 percent less solar on a MW basis than in portfolios that rely exclusively on lithium-ion batteries.

Iron-air results in approximately 15 percent less wind, 18 percent less total storage, and 38 percent less solar on a MW basis than in portfolios that rely exclusively on lithium-ion batteries.

Given the limited number of resources in this analysis, and the need to serve near-constant energy demand, the variability in storage costs has a limited effect on overall resource selection. In the *Without Iron-Air scenarios*, 756 MW of 8-hour lithium-ion batteries are selected when costs are low, which declines to 682 MW when storage costs are high. As storage costs increase and fewer resources are selected, the model instead adds additional wind and/or solar to make up the energy deficit.

Finally, the addition of iron-air as a resource allows for a more diverse portfolio of storage technologies, with the model selecting both 4- and 6-hour lithium-ion batteries as a supplement to iron-air's 100-hour duration in the *With Iron-Air* scenario. The *Without Iron-Air* scenario, by contrast, relies exclusively on 8-hour lithium-ion batteries. This indicates that the model is seeking some portion of longer duration resources. Without iron-air, the model is forced to stack 8-hour storage capacity in order to achieve that goal while still meeting the need that could otherwise be met by 4- and 6-hour duration batteries.

FIG 3. Total installed capacity by scenario and cost sensitivity, 98 percent load factor, 2030



Hourly Operation and Dispatch

In addition to selecting the optimal resource portfolio to meet projected demand, Formware also simulates the least-cost dispatch of that portfolio across all hours of the year. Of particular interest to this analysis is how iron-air operates across days, weeks, and seasons as part of a larger resource portfolio with renewable output specific to Minnesota's weather patterns.

Iron-air batteries minimize curtailment and fill in during renewable energy lulls

Figure 4 and Figure 5 provide a snapshot of the annual operation of the resources that are selected in the *With Iron-Air* scenario under the mid-cost sensitivity. Figure 4 presents the weekly sum of energy generated to serve gross load (load served plus energy consumed for charging storage minus energy discharged from storage) over the span of the year. Solar output is greatest during the summer weeks, while wind output is at its highest during the fall and winter weeks. Storage charges over all weeks of the year, largely as a result of solar and wind having complementary output profiles, with solar at its maximum production during the day and wind at its maximum overnight. Curtailment tends to be highest during the spring months due to increased amounts of both solar and wind generation.

FIG 4. Energy generated to serve gross load, summed by week, *With Iron-Air* scenario

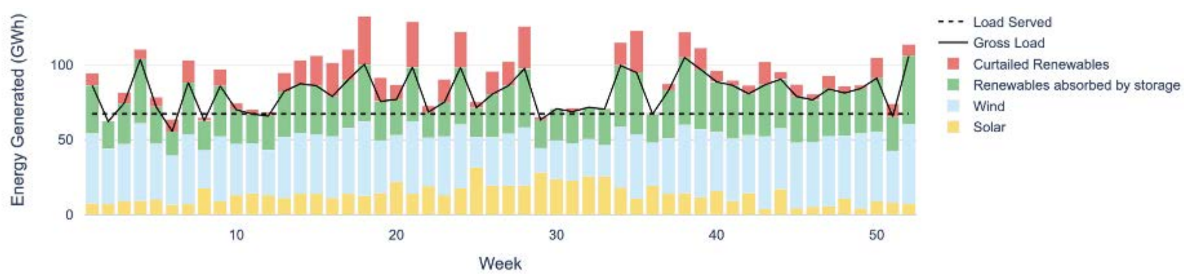
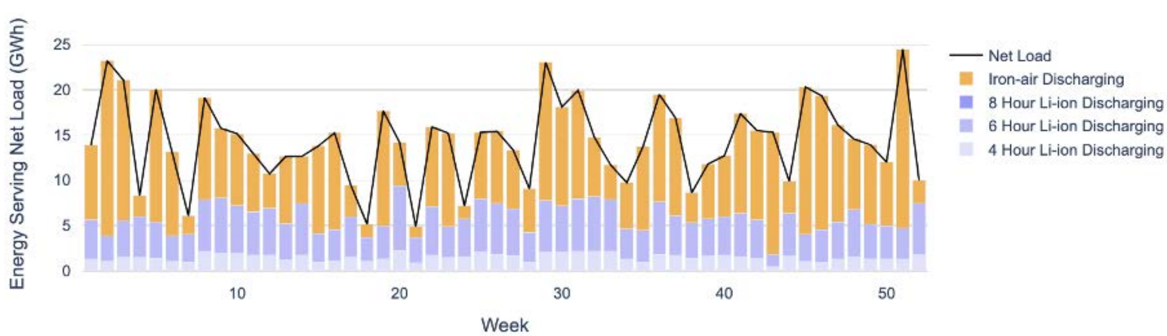


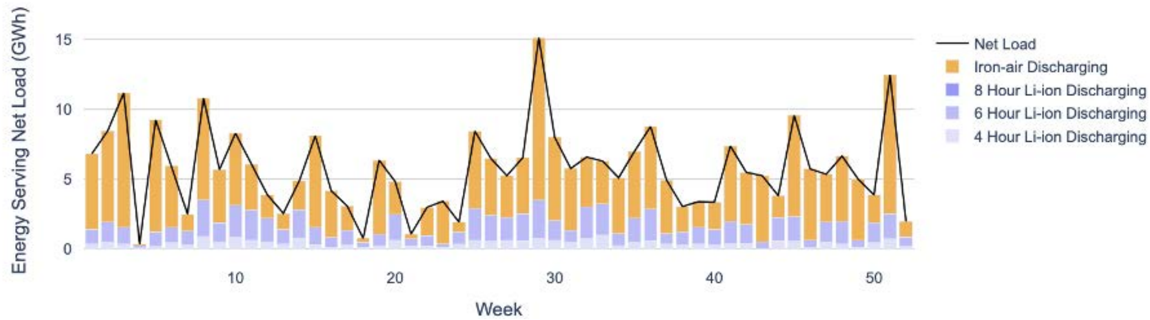
Figure 5 shows energy storage dispatch to serve net load (load served minus solar generation minus wind generation) over all the weeks in the modeled year in the *With Iron-Air* scenario. The resource portfolio relies heavily on dispatch from iron-air in almost every week of the year, due largely to the battery's 100-hour duration and its unique ability to fill in during renewable lull periods that last for only a few hours to periods lasting for several days. Dispatch from iron-air is higher during the winter months at both the beginning and end of the year.

FIG 5. Energy dispatched from storage to serve net load, summed by week, *With Iron-Air* scenario



In contrast to Figure 5, above, which looks at energy dispatched from storage to serve load across all hours, Figure 6 examines the ratio of lithium-ion to iron-air that is dispatched to meet load during renewable lull periods. In Figures 1 and 2, lull periods are defined as those periods in which output falls below 75 percent of annual average output. Figure 6 looks at more severe lull periods, in which output falls below 10 percent of the annual average. Iron-air batteries play an outsized role in maintaining high availability during these periods. Over the course of the year, iron-air meets 69 percent of net load during these identified lull periods, and as much as 90 percent at its maximum, as compared to lithium-ion technologies. This occurs despite the fact that iron-air batteries make up only roughly 50 percent of battery power capacity in the portfolio.

FIG 6. Energy dispatched to serve net load, summed by week, during variable renewable energy lulls, *With Iron-Air scenario*



Figures 7 through 10 show hourly operation of our resource portfolios during summer and winter weeks with renewable lulls. As was shown in Figure 1, the Lyon County wind profiles show a number of lull periods that vary in terms of both timing and duration. In the *Without Iron-Air* and *With Iron-Air* scenarios, we see the different volumes of renewables and durations of storage resources in each portfolio operating in unique ways in order to meet load. Figure 7 and Figure 8 show dispatch of the resource portfolios during a typical summer week in the *Without Iron-Air* and the *With Iron-Air* scenarios, respectively. The dotted line represents the constant 400 MW of hourly load, and generation above that line is used to charge the battery resources. In the event that those resources are fully charged, additional excess generation (shown in red, below) is curtailed in the model.

FIG 7. Hourly portfolio dispatch, *Without Iron-Air* scenario, summer

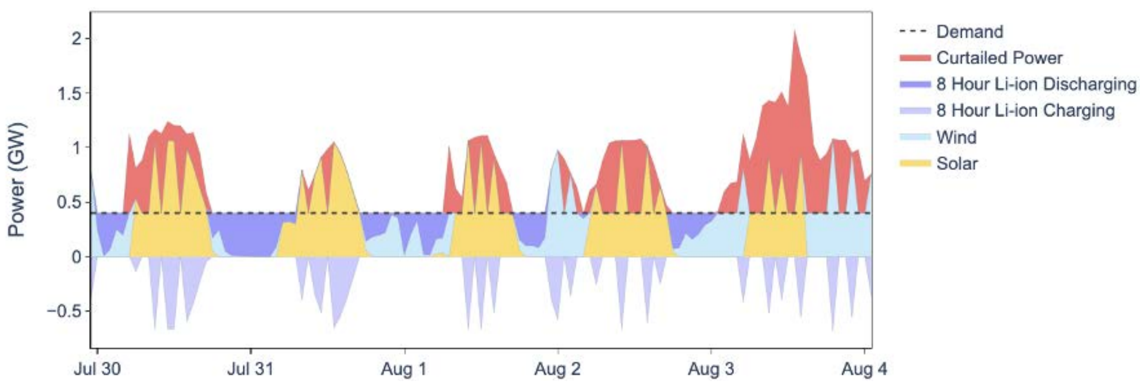
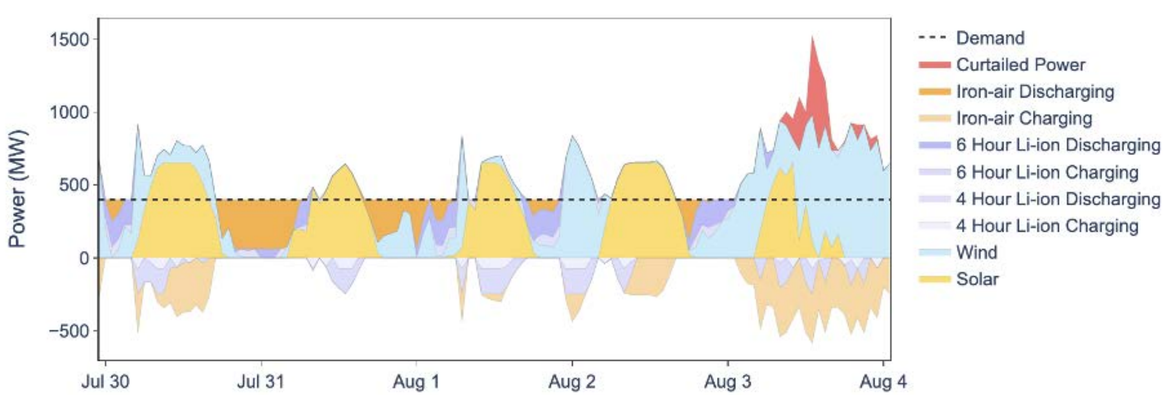


FIG 8. Hourly portfolio dispatch, *With Iron-Air* scenario, summer



In the *Without Iron-Air* scenario, shown in Figure 7, we see higher volumes of excess energy due to the greater number of megawatts of wind and solar needed in the portfolio to meet demand across a majority of hours. As a result, there is increased curtailment in that scenario relative to the *With Iron-Air* scenario shown in Figure 8. From an operational standpoint, during the summer months iron-air batteries are dispatching during overnight periods when solar resources are not producing energy and wind output is low. Iron-air is cycling more frequently during these summer weeks, operating in conjunction with 4- and 6-hour lithium-ion batteries to meet demand during low to no-solar periods.

Figure 9 and Figure 10 show hourly dispatch of both portfolios during a sample winter week in which there is a wind lull that spans multiple days. The resource portfolio in the *Without Iron-Air* scenario, shown in Figure 9, is able to use 8-hour lithium ion batteries to meet demand in the initial hours of this lull period but chooses to shed load in the remainder of the hours, consistent with the requirement to maintain a 98 percent load factor. There is excess wind generation near the end of the week, and, while a portion of that excess is used to recharge lithium ion batteries, the bulk of that excess generation is curtailed due to insufficient energy storage capacity.

FIG 9. Hourly portfolio dispatch, *Without Iron-Air* scenario, winter

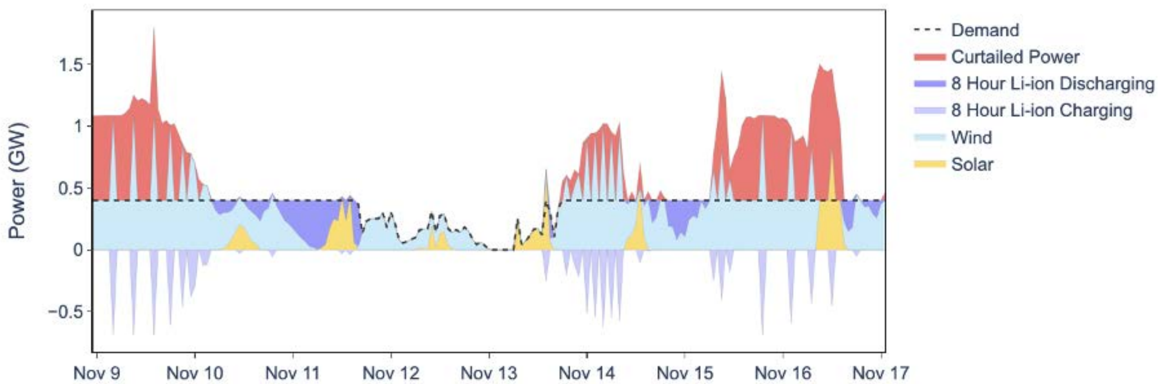
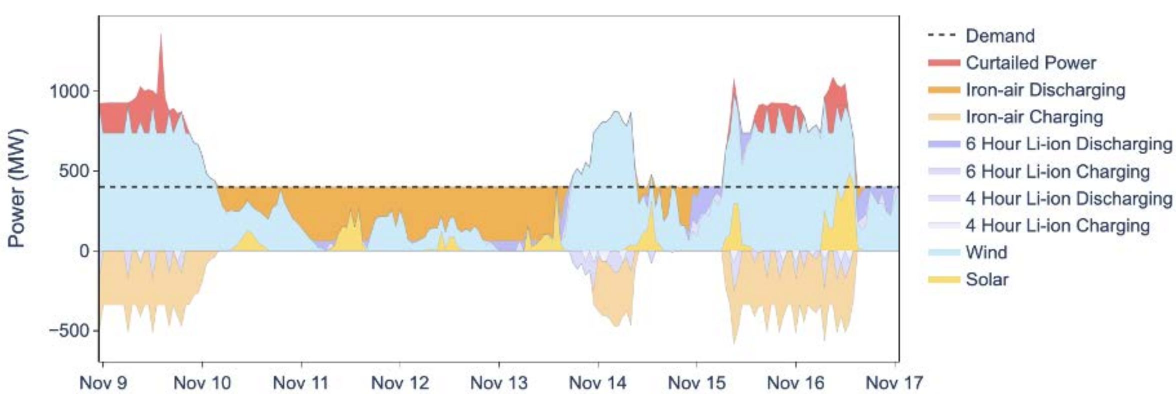


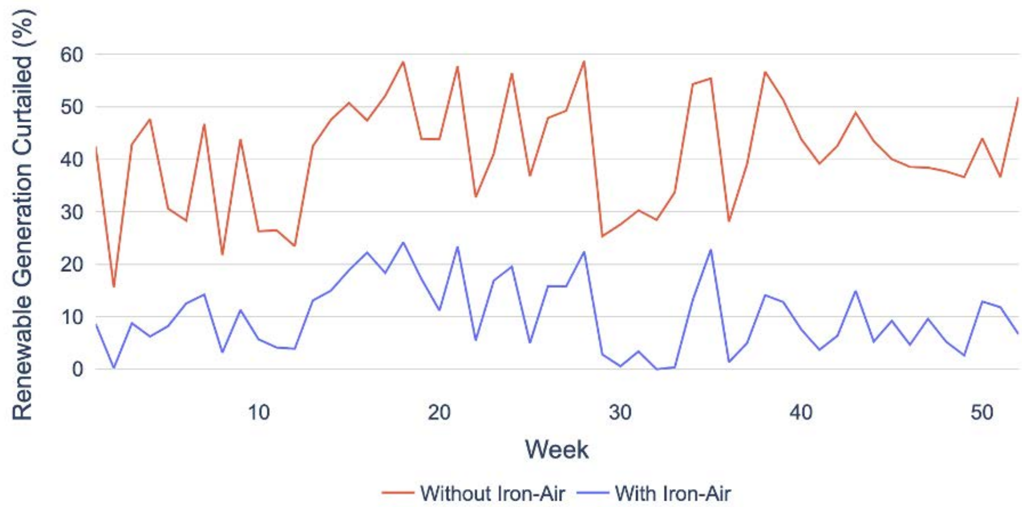
FIG 10. Hourly portfolio dispatch, *With Iron-Air* scenario, winter



In contrast, Figure 10 shows dispatch over that same winter week when iron-air is included in the optimal resource portfolio. Rather than shedding load, the model is instead able to meet demand during the wind lull period by dispatching stored energy from the multi-day asset. Periods with excess wind at both the beginning and end of the week are used to recharge battery storage with 80 percent less curtailment than in the *Without Iron-Air* scenario. Curtailment over the course of the year is shown in Figure 11 for both scenarios.

Periods with excess wind at both the beginning and end of the week are used to recharge battery storage with 80 percent less curtailment than in the Without Iron-Air scenario.

FIG 11. **Percent of energy curtailed, 98 percent load factor, 2030**



Total portfolio costs

We calculate the value of iron-air in the 24/7 clean resource portfolio by subtracting the total cost of each resource (capital plus operating costs) in the portfolios that include multi-day storage from those that do not, and dividing the resulting number by the total number of installed kilowatts of iron-air batteries. The sum of these values is equal to the value of iron-air in $/kW, and is shown in Figure 12 for the mid-cost sensitivity.

The majority of the value of iron-air results from the displacement of 8-hour lithium-ion storage, with additional value accruing from reductions in necessary wind and solar capacity. In addition to the cost of iron-air, there are additional costs for 4- and 6-hour lithium-ion batteries that are included in the value calculation of Form's battery technology as part of this 24/7 clean portfolio.

FIG 12. **Value of iron-air, mid-cost sensitivity, 98 percent load factor**

Total portfolio costs for each scenario under each of the three cost sensitivity cases, inclusive of the ITC, are shown in Table 2. Costs are lower for those portfolios that include iron-air given that the overall resource requirement to meet demand is lower. Notably, the range of portfolio costs within scenarios, taking into account the various cost sensitivity cases, is narrower in the *With Iron-Air* scenarios, with the range from high to low being only $0.32 billion, compared to a range of $0.64 billion in the *Without Iron-Air* scenarios. A portfolio that includes iron-air is 25 percent less expensive than a lithium-ion only portfolio under low and mid storage costs, and 28 percent less expensive under high costs. This calculation of total portfolio cost assumes that any excess renewable energy production is curtailed rather than sold into the bigger Midcontinent Independent System Operator (MISO) market.

A portfolio that includes iron-air is 25 percent less expensive than a lithium-ion only portfolio under low and mid storage costs, and 28 percent less expensive under high costs.

TABLE 2. **Net present value of total portfolio cost, by scenario and cost sensitivity**

Cost sensitivity	With Iron-Air ($B)	Without Iron-Air ($B)	Net Savings with Iron-Air ($B)
Low	$3.25	$4.34	$1.09
Mid	$3.34	$4.47	$1.13
High	$3.57	$4.98	$1.41

Portfolio costs for 24/7 carbon-free energy products are highly dependent on the cost of the underlying wind and solar. We analyzed a low cost wind and solar PPA case to highlight this dependence.[13] In this case, 2030 wind and solar PPA prices are assumed to be $20/MWh and $35/MWh respectively. Further, because the *capacity* provided by these 24/7 products can be monetized in the MISO market, we examined a scenario in which this capacity is valued.[14] These cost sensitivities are shown in Table 3, which highlights how low cost wind and solar, combined with capacity value monetization, can result in dramatic cost reductions for 24/7 carbon-free PPA prices.

TABLE 3. **24/7 carbon-free PPA price sensitivities**

Iron-Air Cost Sensitivity	Iron-Air Case	24/7 PPA Price, Base Wind/Solar ($/MWh)	24/7 PPA Price, Low Wind/Solar ($/MWh)	24/7 PPA Price, Low Wind/Solar Plus Capacity Payment ($/MWh)
Low	With Iron-Air	$74	$53	$44
	Without Iron-Air	$99	$72	$63
Mid	With Iron-Air	$76	$55	$46
	Without Iron-Air	$102	$75	$65
High	With Iron-Air	$81	$60	$51
	Without Iron-Air	$113	$85	$76

While the base model in this analysis does not assume that excess renewable energy is sold into the MISO market, the resource portfolios in all scenarios and cost sensitivities do produce excess energy above what is needed to serve load. Hourly MISO market prices in 2030 and beyond are highly uncertain, as they are dependent on both regional loads and the resources that exist across a number of states to meet that load. In addition to our base assumption, we evaluated two sensitivity cases that assume that all excess energy can be sold at market energy prices of $25/MWh and $45/MWh in 2030, which grow at the rate of inflation over our 25-year analysis period. Table 4 presents the total portfolio costs for the *With Iron-Air* and *Without Iron-Air* scenarios, under the mid-cost assumption, inclusive of market sales at our three assumed market prices. Iron-air batteries result in net savings to the new load relative to a lithium-ion portfolio except in the case of a constant market energy price of $45/MWh. This is driven by the assumption that the higher volume of excess energy could all be sold at the higher market price.

TABLE 4. **Net present value of total portfolio cost ($billions), inclusive of market sales**

Market Energy Price	With Iron-Air ($B)	Without Iron-Air ($B)	Net Savings with Iron-Air ($B)
$0/MWh	$3.34	$4.47	$1.13
$25/MWh	$3.16	$3.58	$0.42
$45/MWh	$3.01	$2.86	($0.15)

This calculation of portfolio costs inclusive of market sales is illustrative only. Market prices vary considerably from hour to hour, and it is likely that market prices would be lower in hours in which there is excess energy in our resource portfolio because wind and solar output would be similarly high across the MISO market. High market prices would reflect hours of generation scarcity – hours in which battery storage would discharge stored energy and protect GRE customers from price shocks.

13 In order to isolate the impact of lower wind and solar PPAs on 24/7 product economics, we changed wind and solar PPA prices but held portfolio builds the same. That is, we did not optimize portfolios for lower wind and solar costs, which would change the mix of wind, solar, and storage.

14 We assumed a capacity value for each portfolio of $80/kW-yr, applied to the full 400 MW product.

Results - 100 percent load factor

Results follow a similar pattern to those described above when the load shape models a 100 percent load factor, meaning that load must be served by carbon-free energy in all hours of the year, but they differ in two notable ways. While total resource build and system portfolio cost increase in both the *With Iron-Air* and *Without Iron-Air* cases as we increase the load factor from 98 to 100 percent, those differences are much smaller in the cases that include iron-air batteries. The increase in total resource build in the *With Iron-Air* case is only 218 MW, while the increase in the *Without Iron-Air* case is more than 1,300 MW. As a result, the increase in total portfolio cost required to serve load in all hours is $0.44 billion in a scenario that includes iron-air, as compared to an increase of $2.66 billion in the *Without Iron-Air* scenario.

As mentioned above, the $/MW cost of a portfolio that includes iron-air is 25 percent lower than a portfolio that relies exclusively on lithium-ion batteries under a 98 percent load factor. When the load factor increases to 100 percent, the iron-air portfolio is 47 percent less expensive per MW than the lithium-ion portfolio. Put another way, when iron-air is included as a resource option, costs per MW increase by approximately 13 percent to move from serving load in 98 percent of hours to serving load in 100 percent of hours. When we rely exclusively on lithium-ion batteries, costs per MW in the 100 percent load factor case are almost 60 percent higher than in the 98 percent load factor case. The presence of a multi-day storage asset like iron-air therefore allows achievement of incrementally greater levels of time-matched clean energy with a smaller resource build and at a lower cost relative to resource portfolios that lack multi-day storage. A comparison of the results in the 98 percent and 100 percent load factor cases is shown in Table 5.[15]

TABLE 5. **Comparison of results from 100 percent and 98 percent load factor cases, mid-cost sensitivity**

Case	98 Percent Load Factor		100 Percent Load Factor	
Scenario	**With Iron-Air**	**Without Iron-Air**	**With Iron-Air**	**Without Iron-Air**
Wind selected (MW)	928	1,086	1,059	1,437
Solar selected (MW)	653	1,064	620	678
Lithium-ion selected, 4-hour (MW)	73	–	44	–
Lithium-ion selected, 6-hour (MW)	172	–	170	–
Lithium-ion selected, 8-hour (MW)	–	738	–	2,082
Iron-air selected (MW)	338	–	490	–
Total resources selected (MW)	2,165	2,888	2,383	4,197
Total portfolio cost ($B)	$3.34	$4.47	$3.78	$7.13

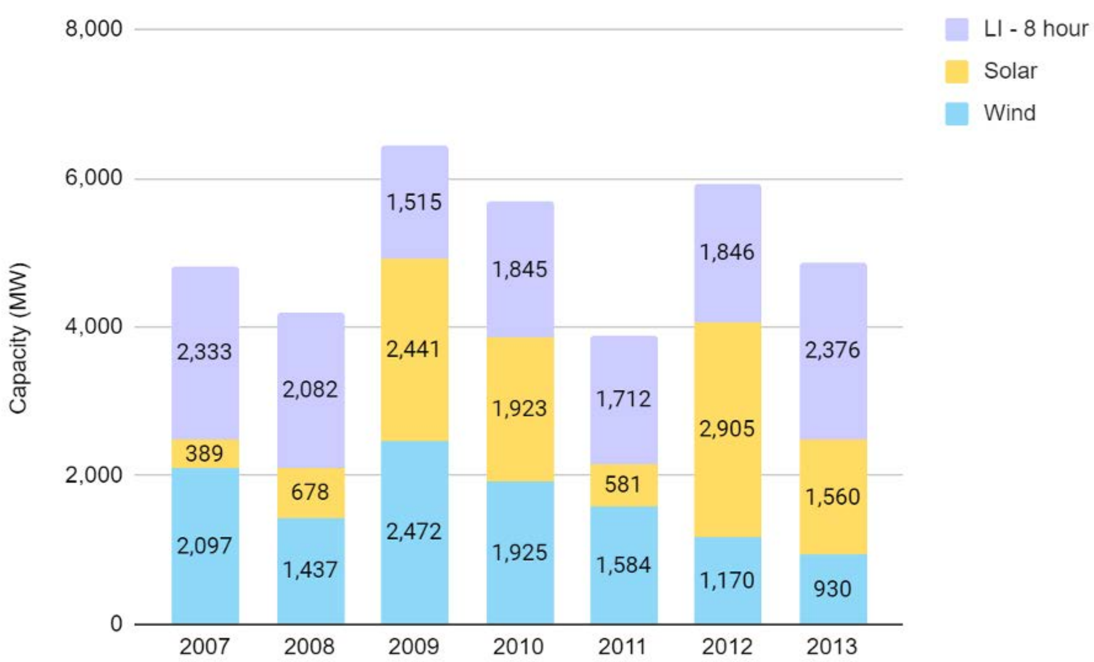
15 We can contextualize the capacities required to supply 24/7 clean energy with wind, solar, and storage with some quick and simple math. At a high level, renewables operate anywhere from 20 to 40 percent of hours. To make things easy, we can use an average output of 33.3 percent. This means that each MW of wind or solar provides, on average, 0.333 MWh of energy in each hour (ignore for a moment the reality of hour to hour variation). In order to supply 1 MWh of renewable energy in every hour, then, we need to build 3 MW of renewable energy (0.333 MWh times 3 MW equals 1 MWh). We very quickly see that supplying 24/7 wind and solar requires some degree of building wind and solar capacity in excess of demand - typically 3 to 5 times demand. Of course, wind and solar do not generate in every hour. Sometimes they generate at their full output - in this example, 3 MW - while other times they generate 0 MW. This is where storage comes into play. Storage capacity is needed to soak up excess generation when supply exceeds demand (in this case, supply would sometimes exceed demand by 2 MW), and provide energy when demand exceeds supply. In this simple example, we may end up with 5 MW total to supply 1 MW of demand. Some readers may be thinking, "doesn't this mean 24/7 carbon-free energy would be very expensive?" As the analysis in this paper shows, the answer is, of course, that it depends. With the right mix of low cost wind and solar and sufficiently low cost and long duration storage, these products can be very compellingly priced.

Multi-scenario optimization

Industry-standard capacity optimization and production cost models typically simulate a single annual generation profile for each type of renewable generator included in the model. A set of solar and wind profiles for a single year were included in the modeled load factor cases described above, with the annual generation profiles for solar and wind taken from 2008 for sites in Lyon County, Minnesota. Total output from solar and wind generators varies year to year, however, as do the hourly and seasonal production patterns of those generators. This variability in renewable output will lead to different least-cost resource portfolios, depending on which weather year is selected as an input to the optimization.

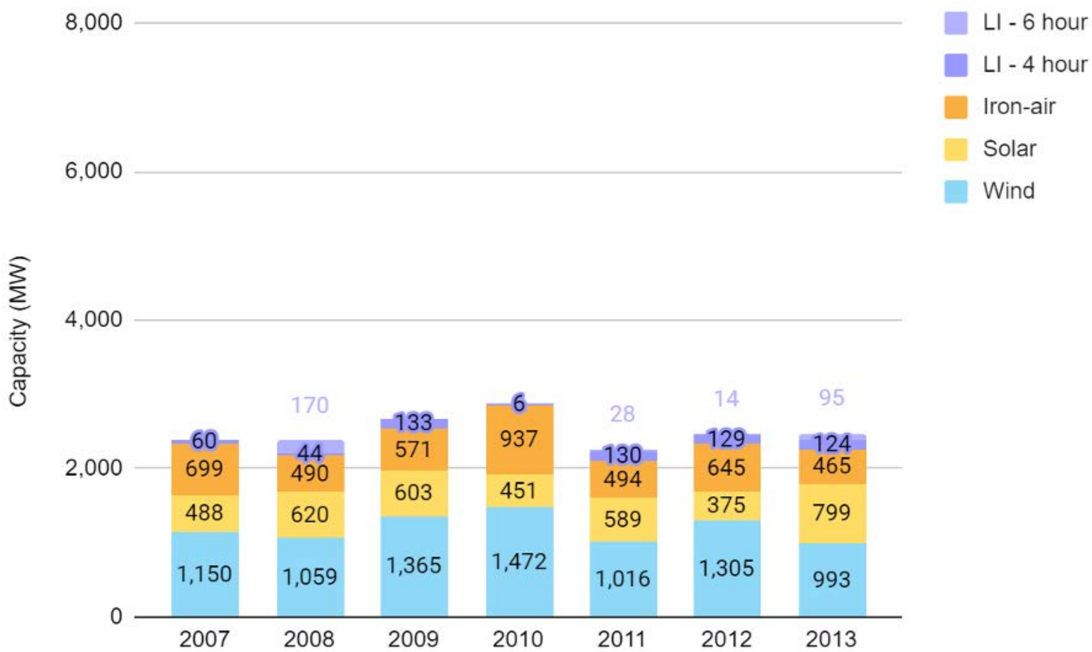
In order to determine how resource build might change as a function of the input renewable generation profiles in our model, we compared seven different capacity optimization simulations that each use renewable generation profiles for solar and wind from a single weather year between 2007 and 2013. The total resource build that occurs when the different annual profiles are used is shown in Figure 13 for the *Without Iron-Air* scenario and Figure 14 for the *With Iron-Air* scenario. Note that each weather year case shown below assumes a 100 percent load factor.

FIG 13. **Total installed capacity needed under varying annual renewable profiles (MW), *Without Iron-Air* Scenario, 100% load factor**



In a scenario that does not include iron-air as a resource option, the total installed capacity that is needed to meet load is highly variable depending on which annual renewable profiles are used as input assumptions. Profiles from 2011, for example, result in the lowest volume of total installed capacity required at 3,877 MW while profiles from 2009 result in the highest volume of installed capacity at 6,428 MW – a difference of more than 2,500 MW. While total load is the same from hour to hour across our modeled time horizon, a fixed resource build that is determined using 2011 generation profiles would likely not meet that load in all hours in any other weather year. In the reverse case, a portfolio that was determined using 2009 profiles would have substantial excess renewable generation over the course of the year under any other weather year, resulting in curtailment of the resource in the majority of years in this analysis.

FIG 14. **Total installed capacity required under varying annual renewable profiles (MW), *With Iron-Air* scenario, 100 percent load factor**



Total installed capacity in scenarios with iron-air as a resource option, by comparison, experience less variability in the optimized resource build as a result of the difference in annual generation profile. In order to serve a hypothetical 400 MW load with 24/7 carbon-free energy demands, the total installed capacity in 2011 is 2,257 MW, which represents the smallest required capacity build in our set of scenarios, compared to 2,867 MW in 2010, which represents the highest required capacity build. The net difference between highest and lowest required builds in scenarios that include iron-air is 610 MW, compared to a net difference of 2,551 MW in scenarios that do not include iron-air batteries.[16] Inclusion of iron-air as a multi-day storage asset in a resource portfolio better allows an optimized resource portfolio based on a single year's weather profile to meet load in other years in which weather and renewable output differ from the modeled year.

16 The highest total resource build occurs in 2009 in the *Without Iron-Air* scenario and in 2010 in the *With Iron-Air* scenario. The hourly generation profiles for wind and solar are unique to each individual weather year and drive the resource selection in that year. Referring back to Figure 1, we see that the timing and duration of wind lulls differs when we compare the 2009 and 2010 weather years. The longest lull periods occur in the summer and mid to late fall in 2009, but occur mostly in the winter in 2010. The contributions of the renewable and storage resources during these events in particular cause the differences in portfolio builds across years and scenarios.

Discussion and conclusions

These results demonstrate that a multi-day storage resource that offers firm and dispatchable capacity to a 24/7 resource portfolio has a number of benefits.

Iron-air reduces the total resource need in 24/7 carbon-free portfolios by 25 percent

In the 98 percent load factor case, inclusion of iron-air results in a smaller total resource build required to serve 400 MW of new load with 24/7 carbon-free energy. Under the mid-cost case for storage, the total required resource build is 2,165 MW in the *With Iron-Air* scenario, as compared to 2,888 MW in the *Without Iron-Air* scenario – a reduction of 723 MW, or 25 percent. The *With Iron-Air* portfolio includes 338 MW of iron-air batteries, 73 MW of 4-hour storage, and 172 MW of 6-hour storage, which displaces 738 MW of 8-hour lithium-ion storage, 158 MW of wind, and 411 MW of solar.

Iron-air lowers renewable curtailment in time-matched renewable portfolios by 80 percent

As noted above, the modeled resource portfolio that relies exclusively on lithium-ion storage technologies requires an overbuild of resources to meet load in all hours. This results in 43 percent of renewable energy being curtailed in the *Without Iron-Air* resource portfolio. Our analysis demonstrates that iron-air contributes to serving load reliably across all hours of the year with fewer total resources, and with this lower total resource build, we see 80 percent less curtailment of renewable resources in the *With Iron-Air* scenario relative to the scenario *Without Iron-Air*.

Iron-air plays an outsized reliability role during renewable lulls

In those hours in which solar and wind generation is lower than 400 MW in a given hour, storage resources discharge stored energy to fill the generation gap. In this analysis, we identified renewable lull periods in which generation fell to 75 percent or below of the annual average, and deep lulls in which generation fell to 10 percent or below of the annual average. Over the course of the year, iron-air meets 69 percent of net load during these identified deep lull periods, and as much as 90 percent at its maximum, as compared to lithium-ion technologies.

Iron-air reduces the cost to deliver time-matched renewable energy by 25 percent

Under the assumption of mid-storage costs, we find that a 24/7 carbon-free portfolio, inclusive of iron-air and meeting a 98 percent load factor is 25 percent - or roughly $25/MWh - cheaper than a portfolio that relies exclusively on lithium-ion batteries.

Iron-air enables an increase to 100 percent time-matched renewable energy at a lower incremental cost

When the load factor increases to 100 percent, the iron-air portfolio is 47 percent less expensive per MW than the lithium-ion portfolio. Put another way, when iron-air is included as a resource option, costs per MW increase by approximately 13 percent to move from serving load in 98 percent of hours to serving load in 100 percent of hours. When we rely exclusively on lithium-ion batteries, costs per MW in the 100 percent load factor case are almost 60 percent higher than in the 98 percent load factor case. The presence of a multi-day storage asset like iron-air therefore allows achievement of incrementally greater levels of time-matched clean energy with a smaller resource build and at a lower cost relative to resource portfolios that lack multi-day storage.

Iron-air provides resiliency benefits across weather years

Multi-day storage assets like iron-air also offer a resiliency benefit that is demonstrated but not explicitly quantified in this study. When we examine the results of capacity optimization modeling done across a range of weather years, we find that inclusion of an iron-air resource leads to less variability in the volume of resources needed to serve load across those different years, thereby increasing the resiliency value of the resource portfolio itself. As extreme weather events increase in both frequency and severity, multi-day storage can thus help utilities like GRE to serve load across different types of weather events while also minimizing the costs to members of such events. The pricing of energy in the MISO market during a multi-day weather event can be substantially higher than average pricing, and the presence of a resource with the ability to dispatch throughout the duration of a reliability event could create additional financial benefits beyond those quantified here.

Iron-air batteries offer a viable pathway to deliver 24/7 carbon-free energy to customers

The focus of this case study analysis is on the value of multi-day storage to future commercial and industrial loads that are seeking to serve loads with 24/7 carbon-free energy, and demonstrates that a multi-day storage offering like iron-air could provide benefits to those members located within GRE's territory.

Future analysis

Future studies of multi-day storage and other dispatchable carbon-free resources should examine the value of these assets as part of GRE's total resource portfolio, as they act as grid resources, particularly in light of recent legislation mandating that Minnesota's electricity be carbon-free by 2040. This would allow for a further assessment of the effect of load factor on multi-day storage selection and demonstrate the competitiveness of multi-day storage with both more traditional peaking plants and also various load management technologies. Recent changes to the capacity construct in MISO also warrant further discussion with respect to multi-day storage. As critical reliability hours become more of a focus, and the ability of resources to provide energy to the system during these times continues to be a priority, it will be of interest to understand how these resources can fit into current and future reliability constructs of MISO and other ISO / RTOs.

In the context of multi-day storage as a grid resource, GRE can also seek to understand the locational value of iron-air and other storage resources, analyzing the confluence of transmission charges, avoidable or deferrable transmission and distribution projects, and differences in regional wholesale or retail energy and capacity prices with and without these assets. To move beyond simulation modeling, GRE could employ an experimental approach to multi-day storage deployment and could, for instance, site multi-day storage across the member co-ops systems and evaluate different operational strategies and outcomes over time. GRE could also account for the non-energy benefits of multi-day storage (such as creating resiliency hubs or improving economic development) and seek to involve member co-op and end-use member-consumer needs in deployment.

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