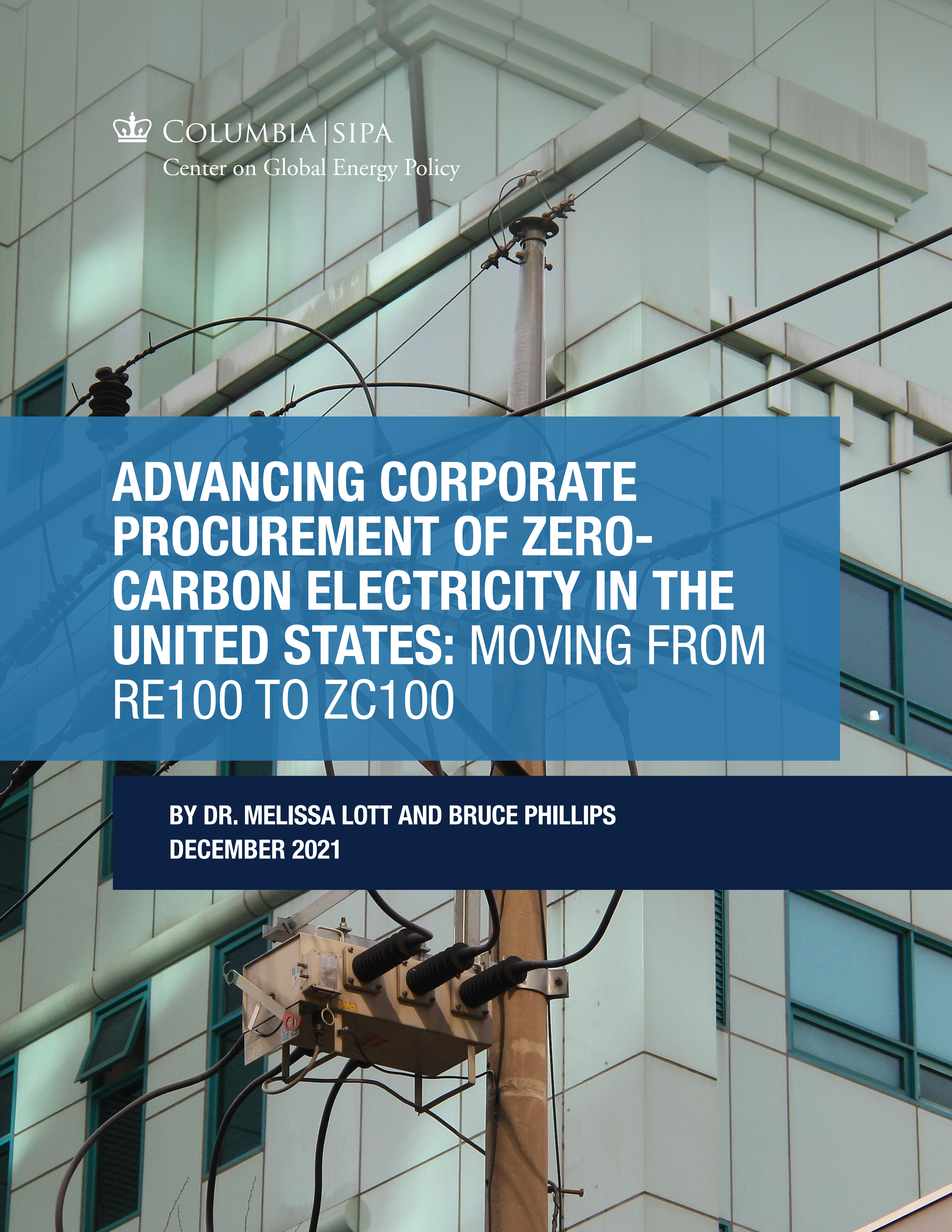

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ADVANCING CORPORATE PROCUREMENT OF ZERO-CARBON ELECTRICITY IN THE UNITED STATES: MOVING FROM RE100 TO ZC100

BY DR. MELISSA LOTT AND BRUCE PHILLIPS

DECEMBER 2021

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EXECUTIVE SUMMARY

Corporate pledges to purchase renewable electricity have led to significant new solar and wind capacity investments and driven down the carbon intensity of the power sector in the United States. Participating companies have increasingly procured this power, many with a goal of procuring quantities that are equal or proportional to the amount of electricity that they consume at their facilities on an annual basis.[1] Corporate buyers can reap many benefits from renewables procurement, including hedging against power price fluctuations and enjoying positive brand association, helping them meet shareholder demands around climate or other environmental, social, and governance (ESG) goals. However, the reality is that commitments to buy 100 percent renewable electricity may not equate to a company actually reducing its power carbon footprint to zero.

This report from Columbia University's Center on Global Energy Policy quantifies the mismatch between companies' contracted variable renewable electricity (VRE) and their actual use of electricity to highlight the degree to which these companies still rely on a partially fossil-fueled power grid to bridge the gap. A modeling exercise and analysis done in collaboration with The NorthBridge Group reveals a significant shortfall between electricity demand and VRE supply, leaving companies that contract for 100 percent renewables to in fact draw between 20 percent and 50 percent[2] of their annual electricity from the regional electric grid, depending on their location, demand profile, and mix of contracted renewable supplies.

This disparity presents a number of challenges to corporations that wish to achieve deep decarbonization and are unable to curtail operations to match renewable energy supplies. There are several approaches to get closer to a true zero-carbon power footprint. Installing storage capacity either on-site or at the power plant to provide stored electricity when renewables are not sufficient, such as with a battery,[3] is one option. However, this only reduces the minimum shortfall by half, requiring a customer to continue to rely on electricity from the regional electric grid for 10 percent to 28 percent of its annual load.[4] Resolving the shortfall by procuring extra renewable power (e.g., to 150 percent of annual electricity demand with renewables) can drive costs up substantially without closing the gap.

The authors instead suggest companies can take the following steps to better meet zero-carbon electricity goals and avoid accusations of greenwashing:

- Employ procurement methods that match a company's demand with low-carbon supplies on an hour-by-hour basis using local resources.
- Move beyond supply targets exclusively centered around variable renewable energy and batteries to diverse portfolios of low-carbon resources, including variable renewable energy and also firm low-carbon electricity generation resources (e.g., large hydropower, nuclear, fossil fuels with carbon capture and sequestration systems, and geothermal) and long-duration energy storage (e.g., zero-carbon hydrogen and other seasonal storage options).

Companies that advance procurement practices that reflect these recommendations would increase the demand for firm low-carbon generation and long-duration energy storage technologies, sending stronger price signals to drive investment in zero-carbon technologies that better coincide with the timing of customer electricity demand and accelerate carbon emission reductions. These practices could also improve the performance, reduce the cost, and accelerate the commercialization of advanced technologies that are needed to achieve the goal of full decarbonization in a practical and affordable manner.

I. INTRODUCTION

As the collective awareness of the impact of climate change has grown, some corporate buyers of electricity have tried a variety of strategies to position themselves both in the present and the future. In particular, pledges to purchase 100 percent of electric power from renewable sources were largely led by tech companies (e.g., Google and Apple) and companies in other sectors, such as retail (e.g., Walmart), apparel (e.g., Nike), finance (e.g., Citi and Barclays), insurance (e.g., Swiss Re), and manufacturing (e.g., 3M and BMW). As a result, many of these companies have signed long-term power purchase agreements (PPAs) as part of this strategy.[5] This type of target is similar to the renewable portfolio standards used in some states, which mandate that a fraction of the electric supply delivered to customers be generated by legislatively defined sources of renewable energy (commonly wind and solar and sometimes hydropower).[6]

There are many benefits to 100 percent renewable pledges, targets, and purchases for corporate buyers. Renewables can provide a hedge against cost fluctuations in the price of power and, in some cases, can reduce overall power bills. Many companies also believe that these types of pledges help brand the company positively and avoid (or forestall) shareholder challenges around climate or other environmental, social, and governance (ESG) goals.[7]

However, moving forward, these strategies present limits to companies that want to reduce the emissions associated with their electricity supplies. In reality, companies with 100 percent renewable procurement targets (inevitably) have drawn power from the regional grids when their contracted renewable electricity was unavailable and the facility did not curtail its operations. This grid-based power, which includes unabated fossil fuel combustion, has generated and continues to generate greenhouse gas (GHG) emissions and pollution. This gap was highlighted in a white paper published in December 2016 by Google, one of the early adopters of a 100 percent renewable electricity target, which showed that despite contracting for 100 percent or more of a data center's annual consumption from renewable energy supply, its data centers around the world relied on regional grid supply for a significant portion of their consumption, ranging from 6 percent to 82 percent of a data center's annual consumption depending on its location and corresponding demand profile.[8]

For data centers located in the United States, 40 percent to 60 percent of its annual consumption relied on regional grid supply over the course of the year. Google also showed substantial grid-related emissions associated with the electric generation supplies needed to satisfy the electricity consumption at its data centers and acknowledged that these supplies from the grid are not carbon-free. While these emissions can be offset—for example, through purchasing renewable energy certificates (RECs) or carbon offsets—these methods pose risks to companies that wish to avoid accusations of greenwashing or overstating their environmental commitment.[9] Furthermore, they do not directly incentivize the development of the power mix that is needed to achieve deep decarbonization targets.

Growing recognition of this gap has contributed to policies requiring zero-emission credits and clean energy standards (CES). Several states have already set a timetable to achieve 100 percent power sector decarbonization and have accommodated a wide set of zero-carbon emissions technologies, including nuclear power generation, geothermal power, and fossil power systems with high levels of carbon capture and storage. In Congress, the Climate Leadership and Environmental Action for our Nation's (CLEAN) Future Act includes a CES component in its overall framework for achieving net-zero greenhouse gas emissions in the United States by no later than 2050.[10]

For companies to adopt 100 percent zero-carbon (ZC100) electricity procurement standards, they ultimately will have to conclude that the benefits of ZC100 are larger than 100 percent variable renewable (RE100) electricity targets. This report outlines the limitations of a variable renewables-focused approach in providing reliable power and decarbonizing scope 2[11] emissions for companies and demonstrates the likely financial, environmental, and societal benefits of ZC100 portfolios.[12] The report begins with discussion of the near-term impacts of today's renewables-focused procurement practices. It then presents a framework for advancing corporate electricity procurement that could better support deep decarbonization ambitions.

II. NEAR-TERM CONSEQUENCES OF TODAY'S PROCUREMENT PRACTICES

A. Procurement Has Been Successful but Is Limited Due to Its Design

In recent years, many large companies have set public goals to increase the amount of their electricity consumption that can be supplied by renewable sources. These companies have largely procured this renewable electricity in quantities that are equal or proportional to the amount of electricity that they consume at their facilities on an annual basis.

Four main methods are currently used by companies to meet their stated goals relating to renewable electricity procurement.[13]

1. Deploying distributed renewable generation resources (e.g., rooftop solar panels) on-site
2. Purchasing renewable energy certificates (RECs) that are generated by renewable electricity generation sources
3. Purchasing electricity from local utility distribution companies via green tariff programs designed to provide compensation for renewable energy sources that the utilities have procured directly
4. Entering into PPAs with new renewable electricity generation suppliers

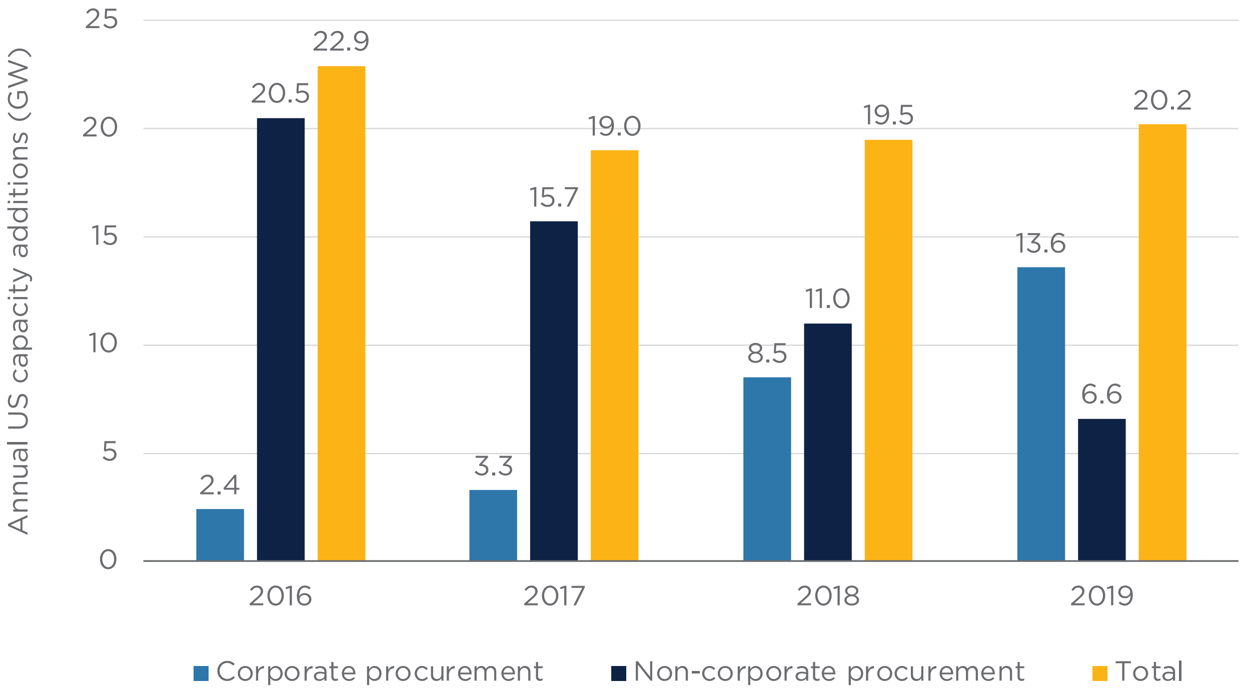
In a deregulated market, a buyer can purchase either all or a portion of the electricity output from a new wind or solar facility for a fixed length of time (i.e., via PPAs). Alternatively, a retail access customer in a deregulated market can choose a 100 percent renewable or "green" contract from a competitive retail supplier, who in turn would contract with renewable developers or purchase and retire renewable energy certificate (i.e., a "REC" purchase or indirect PPA).

In some regulated markets, a buyer can indirectly purchase either all or a portion of the electricity output from a new wind or solar facility for a fixed length of time with a green tariff or sleeved contract[14] from the incumbent utility. In each of these examples, large corporate buyers enter into an agreement with renewable energy generators (directly or indirectly) to purchase some or all their facilities' output. The RECs associated with the output of these renewable generation units provide generators an additional revenue stream to facilitate the development and operation of these renewable energy plants.[15]

While buyers undertake different purchasing strategies to meet their goals, most buyers have focused on purchases of wind and solar generation (e.g., via power purchase agreements or green tariff arrangements) and/or the environmental attributes (e.g., renewable energy credits) associated with wind and solar generation.[16] Whereas unbundled RECs have become less popular due to criticisms of their inability to support new, additional renewable resources in the electricity sector, PPAs have gained traction over the past several years.[17] This "additionality" principle was highlighted by Google in its December 2016 white paper[18] as a key component in its procurement structure.

By procuring renewable energy through PPAs and the like, companies have enabled the development of many gigawatts (GW) of new renewable generation capacity. From 2014 to 2018, large companies announced transactions with off-site renewable energy projects representing over 15 GW of generating capacity—roughly equal to one-quarter of all renewable capacity installed across the United States during that time.[19] Furthermore, corporate-driven procurement of renewables has offset declines in non-corporate (e.g., utility or retail supplier) renewable procurement in recent years as shown in Figure 1.

Figure 1: Corporate-driven procurements of renewables have offset the decline in non-corporate procurements of renewables



Note: Corporate procurement includes all categories of corporate procurement, including PPAs and green tariffs.

Source: James Kobus, Ali Nasrallah, and Jim Guidera, "The Role of Corporate Renewable Power Purchase Agreements in Supporting US Wind and Solar Deployment," Center on Global Energy Policy, Columbia University SIPA, March 24, 2021, https://www.energypolicy.columbia.edu/research/report/role-corporate-renewable-power-purchase-agreements-supporting-us-wind-and-solar-deployment based on data from Business Council for Sustainable Energy and Bloomberg New Energy Finance, 2020 Sustainable Energy in America Factbook (Bloomberg, 2020), https://data.bloomberglp.com/professional/sites/24/BNEF-BCSE-2020-Sustainable-Energy-in-Amercia-Factbook_FINAL.pdf.

The demonstrated ability of corporate purchasers to meaningfully increase the deployment of renewable energy is clear. But the degree to which current procurement methods are aligned with efforts to achieve full decarbonization of the power sector and the economy is limited, as discussed in the analysis presented in this report.

B. Timing Matters: Widespread Mismatches between Variable Renewable Energy Supply Profiles and Customer Demand Profiles Lead to Continued Reliance on Fossil Fuel Generation

While the deployment of new wind and solar capacity in the near term can help reduce carbon emissions, the hourly time pattern during which wind and solar produce electricity (i.e., the supply profile) does not match the hourly time pattern of customer consumption of electricity (i.e., the demand profile). This mismatch means that customers who only procure variable renewable energy (VRE), most importantly wind and solar energy, which are variable since the timing and amount of their output depends on the weather, are in fact frequently taking power from the regional electric grid, often from carbon-emitting fossil fuel generation.

Many companies have achieved their sustainability goals to date by purchasing variable renewable energy supplies and/or RECs so that the quantity of solar and wind electricity that is supplied is roughly equal to the amount of electricity that is consumed by that customer on an annual basis.[20] However, a company does not typically require the supply profile of these contracted VRE resources to match the company's demand profile. The degree of mismatch between the supply and demand profiles was quantified in this analysis, revealing that while the degree of mismatch is sensitive to both the type of company that is purchasing the electricity and the mix of variable renewable energy resources that are purchased, combinations of wind, solar, and battery storage by themselves are not enough to close the gap between supply and demand on an hourly basis in any of the markets that were analyzed.

This analysis compared the electric consumption profile of a typical corporate buyer over the course of a year to the annual supply profiles of variable renewable generators with hourly resolution to better understand how corporate purchases of variable renewable energy impact the carbon footprint of these companies and how they align with longer term deep decarbonization objectives. Key components of this analysis include the following:

- Hourly chronological demand profiles over the course of a year that were constructed using hourly data of a representative big box store and a commercial office building.[21] These representative corporate buyers were assumed to have an average hourly demand of 1 MW over the year with total consumption of 8,760 MWh on an annual basis. The customer demand profiles were constructed separately for three regions: New England, California, and Texas.[22]

- Assumptions that these corporate buyers procured new solar and/or wind generation in sufficient quantity over the course of the year to match 100 percent of their annual electricity demand (i.e., to meet a RE100 type goal) and that these supply sources were produced within the regional transmission organization (RTO) in which the corporate buyer was located.

- A range of supply portfolios reflecting different combinations of wind and solar generation (e.g., 100 percent wind, 100 percent solar, 50 percent wind, and 50 percent solar). Each supply mix was analyzed both with and without integrated battery storage.[23] A total of nine supply portfolios were analyzed for each of the six customer/region combinations, for a total of 54 scenarios.

Scenario Outputs: Degree of Mismatch and Its Implications for a Company's Carbon Dioxide (CO_2) Emissions

The temporal mismatch between renewable supply and customer demand profiles means that a company that voluntarily decides to purchase 100 percent of its annual consumption from variable renewable supplies still relies on supplemental electricity from the regional electric grid, which typically contains a large fraction of carbon-emitting fossil fuel–generated electricity. Overall, the analysis presented in this report found the following:

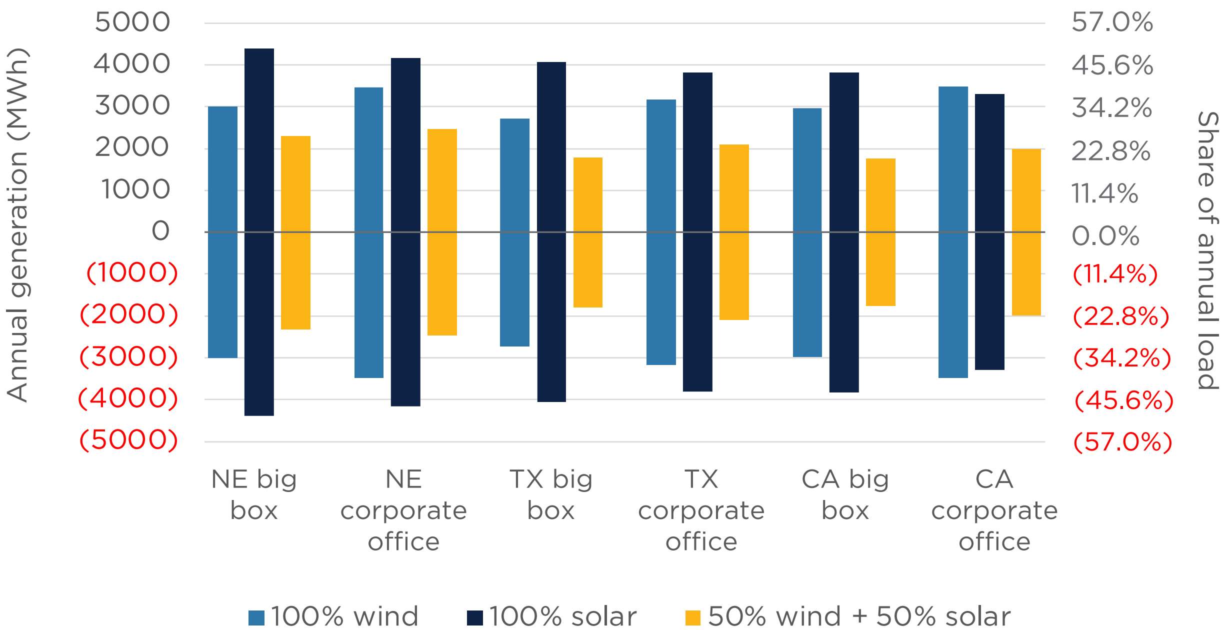
- Significant mismatches were seen between supply and demand in all scenarios for all regions and both customer types, demonstrating that this outcome is robust.[24]
- The mismatches were reduced, but not eliminated, using a combination of renewable electricity resources (i.e., with a mix of wind and solar) and the adoption of battery storage.
- While RE100 targets led to reductions in the carbon footprint of each company's electricity supply in the regions analyzed, no scenario fully eliminated the carbon emissions associated with a company's electricity demand.

With regard to the first point, both hourly and longer-duration mismatches and resulting reliance on carbon-emitting supplies from the regional electric grid were seen across the first six supply mixes (100 percent wind, 100 percent solar, 50 percent wind + 50 percent solar, and a variant for each of those that included battery storage), all three regions, and both customer types. While this analysis was not comprehensive of all regions in the United States or all customer types, it is reasonable to expect that the observed gaps between hourly supply and hourly demand during the year will be problematic for almost all US corporate customers looking to contract for variable renewable energy.

According to this analysis, without battery storage, total annual surpluses and deficits range between 20 percent and 50 percent of annual customer demand (Figure 2). While adding a battery improves intraday (daytime versus nighttime) matching, the timing mismatch exists over longer durations of multiple days, multiple weeks, and even seasonally, as discussed later in this report. Solar output is greater during the summer, and the seasonal pattern of wind output varies across the country. Mismatches can also happen in shoulder seasons during times of extended calm and cloudiness that are not the result of expected seasonal variations.

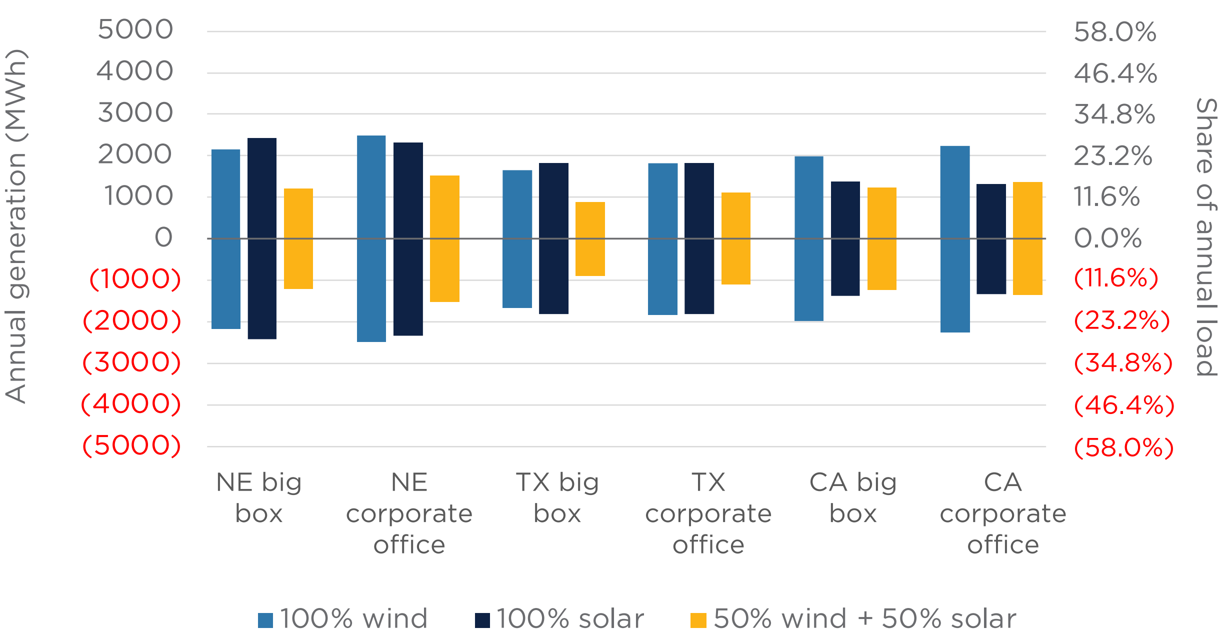
Adding an advanced battery allows for the time-shifting of excess supply during some periods to others where the renewable resources are not supplying enough electricity to meet demand in real time. In this analysis, the impact of an advanced 1 MW/8 MWh battery was examined, reflecting a battery capable of storing 8 MWhs of usable electricity and discharging that at a rate of 1 MW per hour, which is the average hourly demand assumed for the representative corporate buyers in this analysis. The advanced battery is therefore assumed to be capable of supplying a corporate buyer's average hourly demand for up to eight consecutive hours. However, even with this advanced battery capacity, the gap between buyer demands and renewable energy supply is only reduced, not eliminated. In turn, companies continue to rely on electricity from the regional electric grid for 10 percent to 25 percent of their annual load (Figure 3).[25]

Figure 2: Annual surpluses and deficits without a battery



Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

Figure 3: Annual surpluses and deficits with a battery (1 MW/8 MWh)



Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

For buyers, the results of this analysis showed that current corporate procurement practices will not typically provide energy that is sufficient to meet all of a company's load for significant portions of the year. This gap means that, in reality, buyers continue to rely heavily on electricity from their regional electric grid, which often has a significant fossil fuel component and corresponding carbon footprint. Even with the addition of battery storage, the mismatch between variable renewable energy supplies and customer load is only reduced, not eliminated.[26]

C. Adding Renewable Electricity Reduces Carbon Emissions to Varying Degrees, Depending on the Power Mix

As previously mentioned in this report, companies primarily procure renewable electricity to meet either all or a set portion of their annual demand, without consideration for the hourly (or sub-hourly) variation in their demand or the corresponding variability in their contracted electricity supplies. While new variable renewable electricity generation resources (e.g., wind and/or solar) can reduce the greenhouse gas emissions that are associated with a company's electricity demand, the amount of reduction depends on three primary factors.

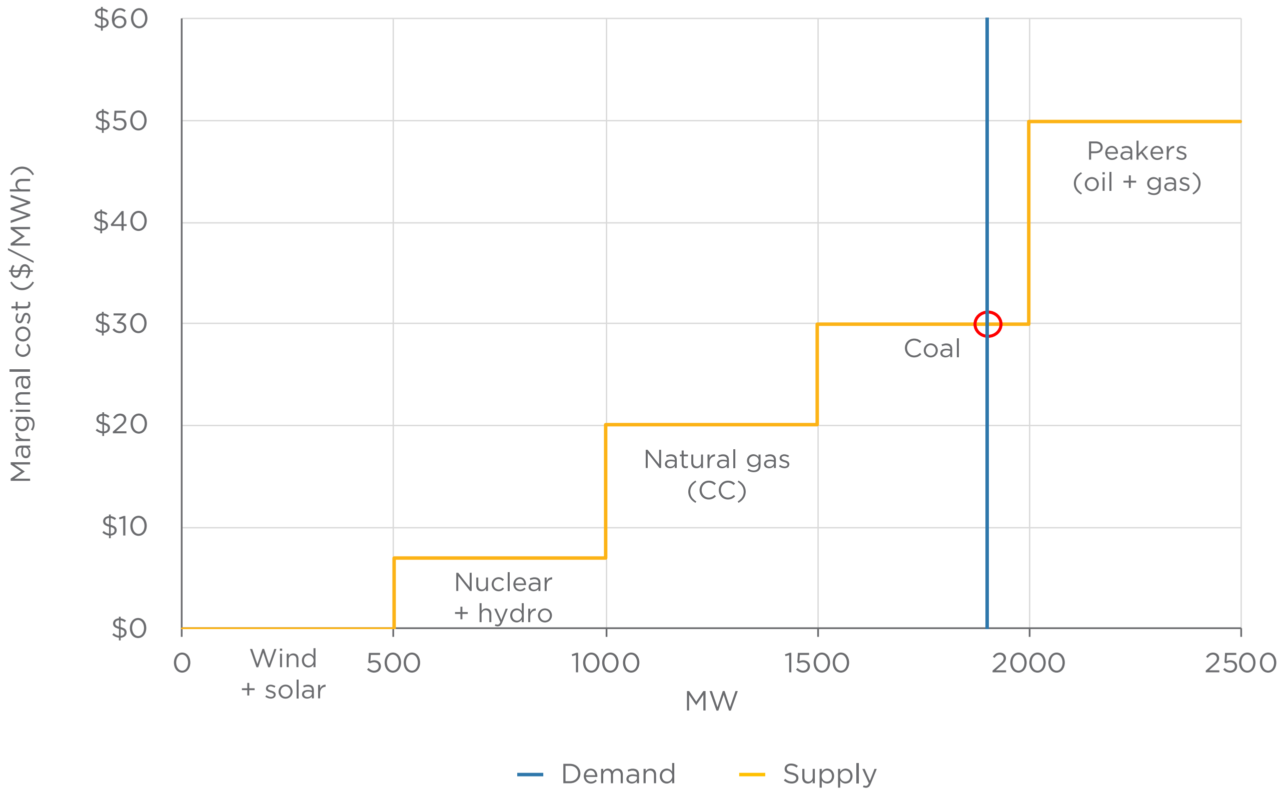
1. The supply profile of the renewable generation resources that have been procured
2. The demand profile of the company that is procuring the electricity
3. The carbon footprint of generation in the regional electric grid

Existing electricity generation resources are typically dispatched based on which resources have the lowest marginal cost, subject to possible transmission constraints associated with moving electricity from generators on the grid to customers. Because wind and solar facilities have a marginal cost of close to zero, they can be broadly expected to operate whenever they are capable of generating electric output (i.e., when the wind is blowing or the sun is shining with sufficient strength to produce electricity) and ahead of carbon-emitting generation resources, which must burn fuel to operate and therefore have a marginal cost greater than zero. When new renewable generation capacity is added to the electricity system, their output typically displaces the output of other generating resources with higher marginal costs, often carbon-emitting fossil resources. In this manner, additional solar and wind resources can reduce the carbon footprint of generation in the grid.

The supply curve (sometimes referred to as a "supply stack") used to dispatch electric generating resources in a regional electric grid is shown in Figure 4. The supply stack shows the order in which the available generating units are "turned on" or dispatched to satisfy customer demand at any given time. Absent transmission or operating restrictions, generating resources are sorted from the lowest marginal cost (on the left) to the highest marginal cost (on the right). As seen in Figure 4, wind and solar generation (with their nearly $0/MWh marginal cost) operate whenever the sun shines or the wind blows, followed by other zero-carbon generating resources (in this example, hydroelectric and nuclear), and then by carbon-emitting natural gas and coal,[27] and, finally, by higher-cost fossil-fueled peaking plants, which typically only operate a small number of hours in the year.[28]

In this illustrative figure, the carbon-emitting coal plant is the marginal generator, as a slight increase or decrease in demand will change the amount of output needed from coal plants. Adding more solar and wind generation on the left side of the figure would "push out" the supply curve to the right, leading to less generation from the coal plant and lower emissions from the system.

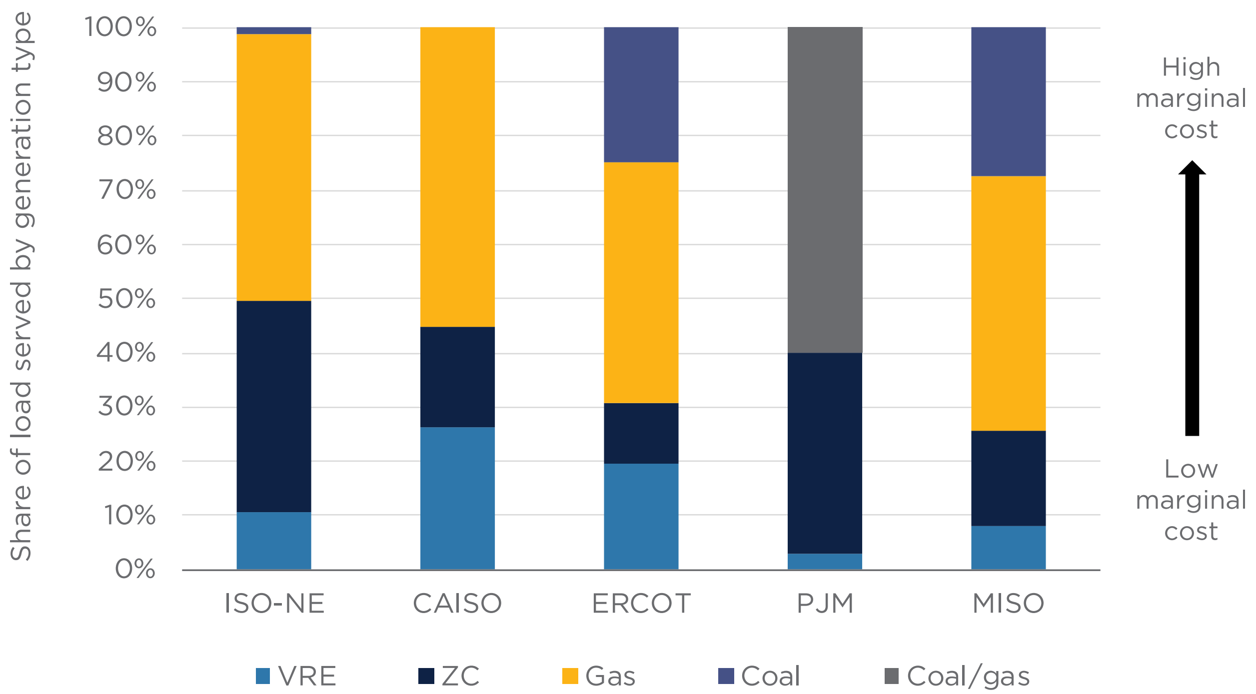
Figure 4: Illustrative electric system supply curve or "supply stack"



Source: Representative fuel and variable operating costs from the NorthBridge Group.

In the United States today, the deployment of new wind and solar resources will almost always be climate beneficial in the near term, as all regions of the country currently have nontrivial carbon footprints with carbon-emitting resources on the margin for significant portions of the year. Figure 5 shows the relative composition of generation in several regional transmission organizations across the country. In these RTOs, carbon-emitting coal and/or natural gas power plants are the marginal generators during significant portions of the year.

Figure 5: Total and marginal generation mix in several RTO regions of the country, 2018[29]



Note: ZC includes hydro.

Source: NorthBridge Group analysis based on data from EPA eGRID, "eGRID Summary Tables 2016," February 15, 2016, https://www.epa.gov/sites/production/files/2018-02/egrid2016_summarytables.xlsx; SO-NE, "Net Energy and Peak Load by Source," December 2018, https://www.iso-ne.com/static-assets/documents/2018/02/2018_energy_peak_by_source.xlsx; CAISO, "Imports Assumed to be Gas," accessed via ABB Energy Velocity, http://www.caiso.com/todaysoutlook/pages/supply.aspx; ERCOT, "Demand and Energy 2018," March 7, 2019, http://www.ercot.com/content/wcm/lists/144927/DemandandEnergy2018.xlsx; PJM, "2018 State of the Market Report for PJM," March 14, 2019, https://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2018/2018-som-pjm-volume2.pdf; and MISO, "Historical Generation Fuel Mix 2018," https://docs.misoenergy.org/marketreports/historical_gen_fuel_mix_2018.xlsx.

New wind and solar plants are also generally lower cost sources of energy than other forms of new low-carbon generation. New onshore wind plants typically cost between $25 per MWh and $55 per MWh on a levelized cost of energy (LCOE) basis, and new solar photovoltaic plants typically cost between $30 per MWh and $45 per MWh LCOE, depending on the region. By way of comparison, the LCOE of a new nuclear plant today is at least $120 per MWh, and a conventional natural gas combined cycle (NGCC) plant without carbon capture and sequestration capability has an LCOE of between $40 per MWh and $70 per MWh.[30] Of course, these cost estimates are not directly comparable since nuclear and NGCC provide firm dispatchable electricity (i.e., both energy and capacity), while variable wind and solar resources provide non-firm electricity (i.e., primarily energy). But they show why onshore wind and solar can displace both carbon-emitting energy and other forms of low-carbon power in the electricity system.[31]

D. Location Matters: The Quantity of Renewable Generation Is Not Always a Reliable Proxy for Carbon Reductions

As previously mentioned, the amount of carbon reductions driven by new solar and wind depends on the type of generation that it displaces. This value varies largely between fuel types and the emissions factor of the marginal power plant in the supply stack, which varies regionally. Indicative carbon emissions factors for power plants are shown in Table 1.[32] In turn, the quantity of wind and solar generation (in MWh) a buyer purchases is not a reliable proxy for carbon impact. Rather, more information is needed to reliably estimate the emission reductions enabled by corporate procurement of renewables.

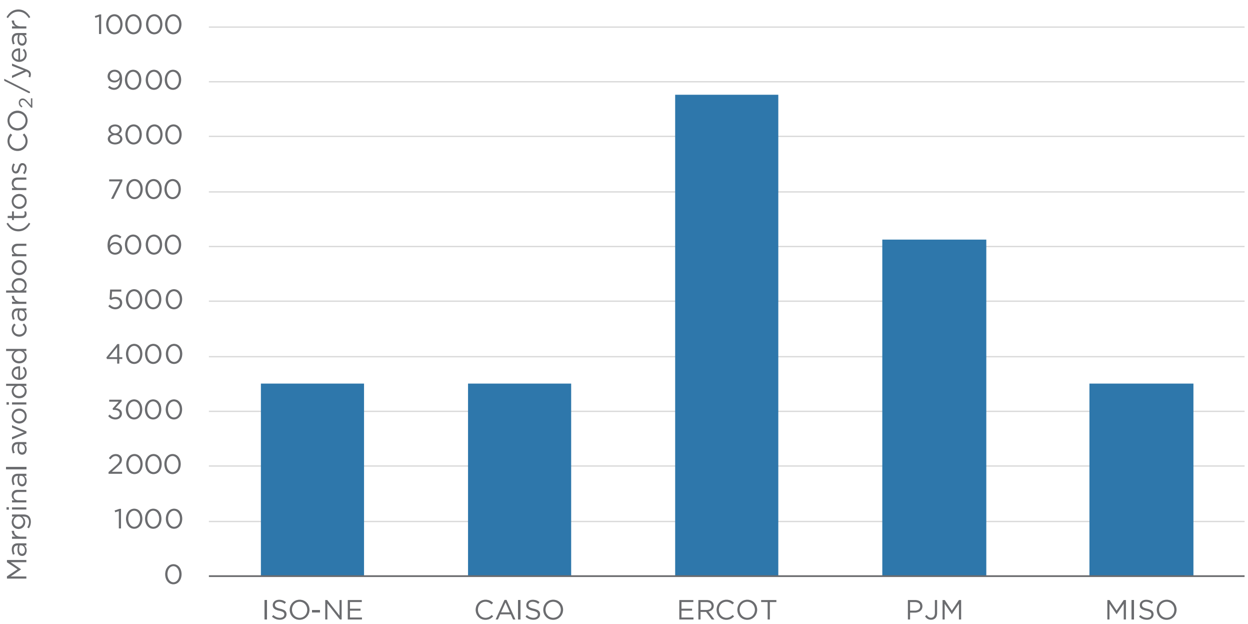
Table 1: Indicative emissions factors by fuel type and technology

Fuel—Technology	Emissions Factor (tons CO_2/MWh)
Wind, Solar, Nuclear, and Hydro	0.0
Natural Gas Combined Cycle	0.4
Oil or Gas Combustion Turbines	0.8
Coal	1.0

Source: US Energy Information Administration, Electricity: Emissions by plant and by region—Final annual data for 2019, October 22, 2020, https://www.eia.gov/electricity/data/emissions/; U.S. Environmental Protection Agency, The Emissions & Generation Resource Integrated Database, Technical Support Document for eGRID with Year 2018 Data, January 2020, https://www.epa.gov/sites/production/files/2020-01/documents/egrid2018_technical_support_document.pdf.

As shown in Figure 6, for a company with an average demand of 1 MW per year,[33] renewable electricity procurement contracts would lead to a reduction in emissions in the range of 3,500 to 8,760 tons of carbon dioxide per year, depending on the location of the generation. Broadly speaking, the company's contracts would have the greatest carbon reduction benefits in Texas (ERCOT) and in the mid-Atlantic (PJM), which rely more heavily on fossil generation than other parts of the country, such as California (CAISO).[34]

Figure 6: Marginal avoided carbon emissions from a 1 MW average load contract



Source: NorthBridge Group analysis based on data from EPA eGRID, "Summary Tables 2016"; ISO-NE, "New Energy and Peak Load"; CAISO, "Imports Assumed to be Gas"; ERCOT, "Demand and Energy 2018"; PJM, "2018 State of the Market"; and MISO, "Historical Generation Fuel Mix 2018."

This result points to a trade-off associated with decisions on how to procure renewable energy supplies in today's markets: Procuring generation close to corporate loads may be well-aligned with goals to drive local decarbonization and in achieving mid-century decarbonization, but procuring that same amount of generation in other regions of the country may have a greater impact on carbon reductions in the near term. These regional variations in generation mix and carbon emissions have significant impacts on the carbon footprints for each customer type and supply portfolio, as shown in Table 2.

Table 2: Reliance on grid power and corresponding carbon footprint for each supply portfolio and customer type by region

New England (ISO-NE): Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
100% Wind	34%	40%	52%	47%	839	968
100% Solar	50%	48%	72%	73%	1,225	1,162
50% Wind and 50% Solar	26%	27%	56%	51%	644	687
100% Wind with 1 MW/8 MWh Battery	25%	28%	34%	33%	602	692
100% Solar with 1 MW/8 MWh Battery	28%	27%	52%	45%	674	648
50% Wind and 50% Solar with 1 MW/8 MWh Battery	14%	17%	28%	27%	340	424
100% Grid	100%	100%	100%	100%	2,444	2,444

Texas (ERCOT): Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
100% Wind	31%	36%	50%	50%	1,373	1,601
100% Solar	46%	43%	66%	67%	2,045	1,921
50% Wind and 50% Solar	20%	24%	51%	47%	906	1,054
100% Wind with 1 MW/8 MWh Battery	19%	21%	28%	29%	834	921
100% Solar with 1 MW/8 MWh Battery	21%	21%	38%	35%	914	915
50% Wind and 50% Solar with 1 MW/8 MWh Battery	10%	13%	23%	24%	448	559
100% Grid	100%	100%	100%	100%	4,419	4,419

California (CAISO): Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
100% Wind	34%	40%	52%	51%	785	918
100% Solar	44%	38%	62%	64%	1,009	869
50% Wind and 50% Solar	20%	23%	48%	52%	466	524
100% Wind with 1 MW/8 MWh Battery	23%	26%	35%	38%	522	592
100% Solar with 1 MW/8 MWh Battery	16%	15%	33%	30%	361	348
50% Wind and 50% Solar with 1 MW/8 MWh Battery	14%	15%	28%	30%	324	358
100% Grid	100%	100%	100%	100%	2,313	2,313

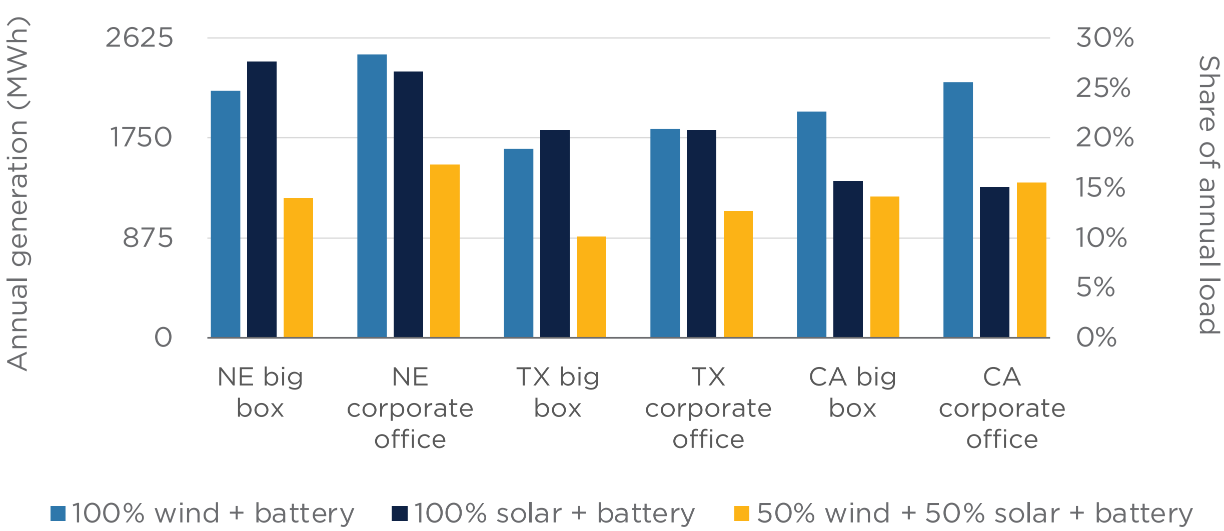
III. CORPORATE RENEWABLE ENERGY PROCUREMENT TO ALIGN WITH EFFORTS TO FULLY DECARBONIZE THE POWER SECTOR

A. Limitations of Relying Exclusively on Variable Renewable Technologies for Full Decarbonization

As of August 2021, at least 19 states had adopted policies to fully decarbonize their electric sectors (some with "net-zero" standards) by mid-century if not earlier, and several legislative proposals have been put forward at the federal level to achieve similar goals nationally.[35] Achieving these goals will require all or nearly all electricity generation to emit little or no carbon into the atmosphere,[36] which means most fossil fuel–fired generation will need to either be replaced with zero-carbon generation or retrofitted with carbon capture and sequestration systems as soon as possible and no later than mid-century.[37]

To provide reliable electricity service to all customers, grid operators have to match both supply and customer load on a near instantaneous basis. Relying exclusively on variable renewable energy resources to achieve decarbonization goals results in a mismatch between supply and demand profiles. In turn, additional resources are needed to maintain balance in the power grid while fully decarbonizing the system. As shown in Figure 7, even if a company used both wind and solar power coupled with battery storage, the company would have to shift or eliminate between 10 percent and 28 percent of their annual demand, depending on their region. The magnitude and widespread nature of these deficits suggest that demand response measures, while valuable in many instances, are unlikely to fully resolve this problem.

Figure 7: Annual deficits by supply portfolio and customer type by region



Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

In addition to this deficit challenge, several other concerns point to the limitations in current procurement practices in achieving full decarbonization of a company's electricity supplies. The first concern is that relying on any single technology pathway to achieve mid-century climate goals, regardless of its primary generating technologies, can reasonably be considered riskier than one that relies on a diversified portfolio.[38] The second concern is the total system cost of providing electric service. Previous deep decarbonization analyses have concluded that 100 percent variable renewable energy scenarios are likely to be materially more costly than diversified portfolios that include firm low-carbon generation as well as variable renewable generation.[39]

Research has shown that the economics of building new solar and wind capacity face two opposing drivers. On the one hand, there are cost reductions due to technology advancements and learning by doing, while on the other hand, market prices and generation revenues are declining faster than cost declines. The combined effects of these two drivers highlight the need for other technologies, including firm dispatchable power, transmission and distribution, and energy storage technologies.[40] For these reasons and others (e.g., the challenges of siting and permitting wind, solar, and transmission at the scale and speed needed to rely on them exclusively to decarbonize the electricity sector), the 100 percent variable renewable energy pathway to full decarbonization of the electric sector is problematic.

B. Alternative Pathways for Full Decarbonization: Overbuilding Battery Storage and/or Buying Excess Renewable Generation

There are several pathways that could address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system. These generally fall into two broad groups.

1. Overbuild and Procure Excess VRE Supplies: Overbuilding battery storage capacity to levels several times higher than examined previously in this paper and/or procuring variable renewable energy supplies that materially exceed 100 percent of annual customer consumption.

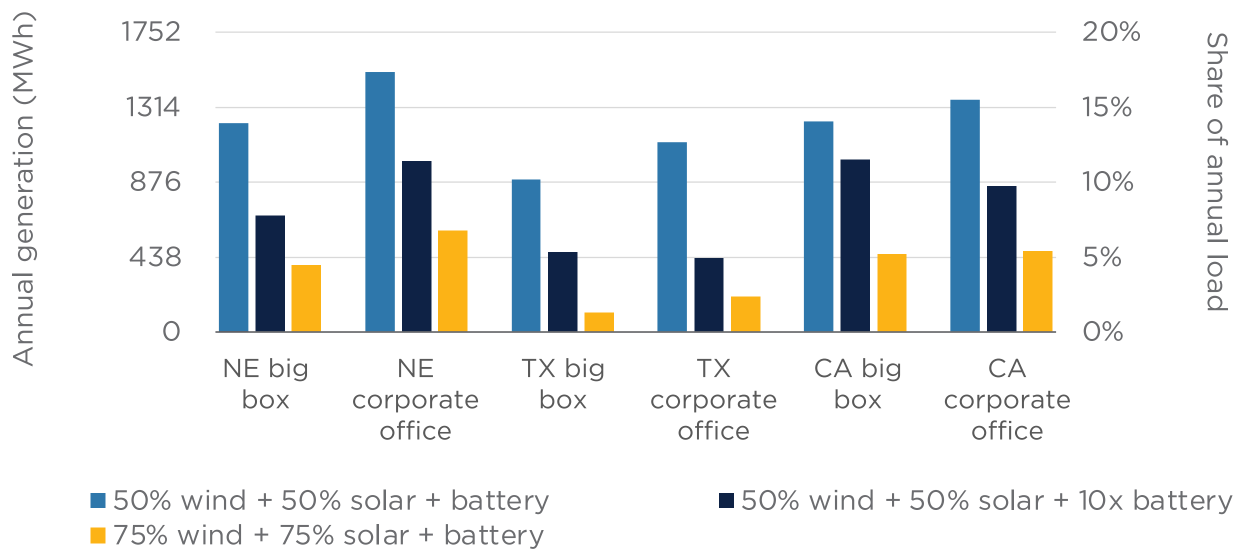
2. Include Firm Low-Carbon Generation and Long-Duration Storage in the Supply Mix: Firm low-carbon generation technologies such as nuclear, fossil with carbon capture and sequestration systems, hydroelectric or advanced geothermal power, and long-duration energy storage technologies such as thermal energy storage or zero-carbon liquid fuels, which can be used later to generate electricity in combustion turbines.

The first group of pathways represent scenarios that should be technically feasible, at least in concept,[41] adding sufficient additional battery storage capacity and new variable renewable energy supplies to meet all customer loads in every hour of the year.

But achieving this outcome would require a truly substantial expansion of battery capacity and/or variable renewable energy supplies, which would reasonably be expected to result in additional costs. This is illustrated in Figure 8, which presents matching analysis results for two scenarios. The first scenario assumes the corporate buyer builds or procures battery capacity that is 10 times that assumed in the previous battery cases (i.e., 10 MW/80 MWh instead of 1

MW/8 MWh), along with a renewable supply mix of 50 percent wind and 50 percent solar. The second scenario assumes the corporate buyer builds or procures variable renewable energy supplies equal to 150 percent of the customer's annual load from renewables (as opposed to the 100 percent levels assumed in the earlier cases), along with the smaller 1 MW/8 MWh of battery capacity. In this second scenario, the customer is assumed to procure half the renewable supplies from wind and half from solar (so that the amount of wind equals 75 percent of total customer load, and the amount of solar equals 75 percent of total customer load). As a consequence, 50 percent of all the energy procured is assumed to be curtailed or wasted. The matching results for these two cases, along with the previous 50 percent wind-50 percent solar-1 MW/8 MWh battery case, are shown in Figure 8.

Figure 8: Annual electricity deficits—battery overbuild and excess renewable procurement scenarios



Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

The results show that overbuilding the battery reduces annual deficits compared with the 1 MW/8 MWh battery scenarios but, in most scenarios, 5 percent to 12 percent of annual customer load would still need to be met with electricity from the power grid. The results for the 150 percent scenario are somewhat better but still fall short of fully resolving the mismatch problem and eliminating deficits.

The challenge of overcoming this mismatch problem with batteries alone is made more difficult by the long duration of some of the deficit periods. Looking across the six scenarios in the three regions and two customer types, the longest period of deficit for the supply portfolio with 50 percent wind, 50 percent solar, and a 1 MW/8 MWh battery (which corresponds to the navy blue bars in Figure 8) ranges between 45 hours and 209 hours or roughly two days to nine days. Increasing the battery capacity tenfold, from 1 MW/8 MWh to 10 MW/80 MWh, allows 1 MW of stored electricity to be discharged each hour over an 80-hour period, 10 times the eight-hour period with the 1 MW/8 MWh battery. However, even this 80-hour period of discharge only covers some of the long duration deficit periods, which, as just described, range up to 209 hours or about nine days in length. This outcome is the result of the limited storage capacity of battery systems, the much longer expected periods of supply deficits, and the fact that, once fully discharged at the beginning of a long deficit period, there is no surplus energy available to recharge the battery to further reduce the period of deficit.

Building yet more battery capacity and procuring yet more renewable supplies than is assumed in these scenarios could at some level fully eliminate the deficits, but the two scenarios shown here suggest the amount of additional build-out and procurement needed to fully eliminate the deficits would be quite substantial.

Ultimately, this becomes a question of economics rather than technical potential or load-matching. As more battery capacity is built and variable renewable energy oversupplies are procured, the total cost of these supplies will increase. But as more variable renewable energy and batteries are procured, curtailments will also rise, and the utilization of these resources will decline. And as this happens, the marginal cost of renewable supplies per unit consumed (i.e., not curtailed) will rise, likely making this pathway to full decarbonization more costly than other pathways, which include a mix of variable renewable and firm low-carbon technologies. Research has highlighted the need for these other technologies, including firm dispatchable power, transmission and distribution, and energy storage technologies.[42]

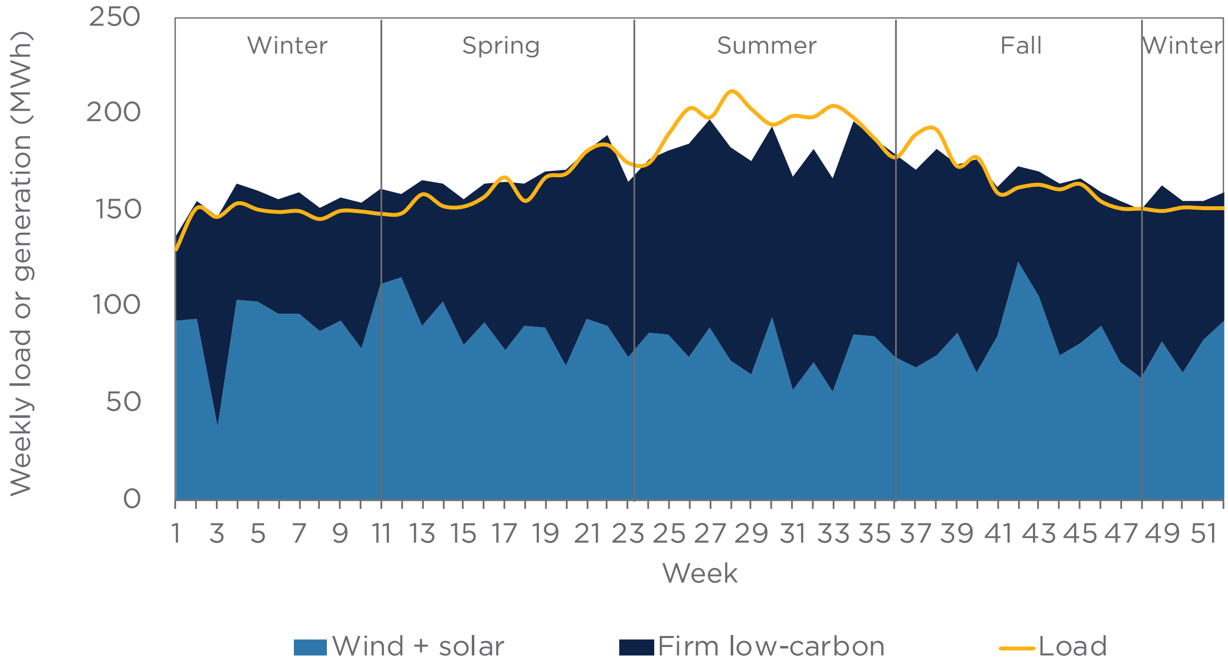
C. Alternative Pathways for Full Decarbonization: The Benefits of Firm Low-Carbon Generation and Long-Duration Energy Storage

Firm low-carbon generation, especially if dispatchable, can complement variable renewable energy by providing energy and capacity when variable renewable supplies are not available. Both thermal energy storage and zero-carbon liquid fuels transform surplus variable renewable electricity for use later to provide firm generation during times when VRE production is insufficient to meet electricity demand.[43]

In the near term, this approach would avoid the frequent extended periods when customers contracting for variable renewable generation are in effect being supplied with generation from the regional grid that includes carbon-emitting fossil generation.

For example, for the previously discussed case of a big box store in ISO New England’s service territory, the use of a 100 percent variable renewable electricity supply mix leads to significant periods of both deficit and surplus. However, a supply mix that includes 50 percent firm dispatchable low-carbon generation along with 25 percent wind, 25 percent solar, and a 1 MW battery can largely eliminate mismatches on an hourly basis between supply and demand over the course of a year.[44] Figures 9 and 10 compare the weekly load and generation profiles for a New England big box store with and without firm dispatchable low-carbon generation. Figure 9 shows a supply mix that includes 50 percent of annual supply from a firm low-carbon generation resource. The availability of firm low-carbon generation in this example allows total generation to closely match customer loads regardless of the amount of variable renewable energy generation produced in any given week. Figure 10 shows the same variable renewable energy and battery portfolio without any firm low-carbon generation in the supply portfolio. Comparing the two figures, the substantial reduction and virtual elimination of shortages in Figure 9 means that the customer's reliance on supply from the grid (or load management) has been substantially reduced compared with the alternative supply portfolio in Figure 10 composed only of variable renewable energy supplies and a battery.

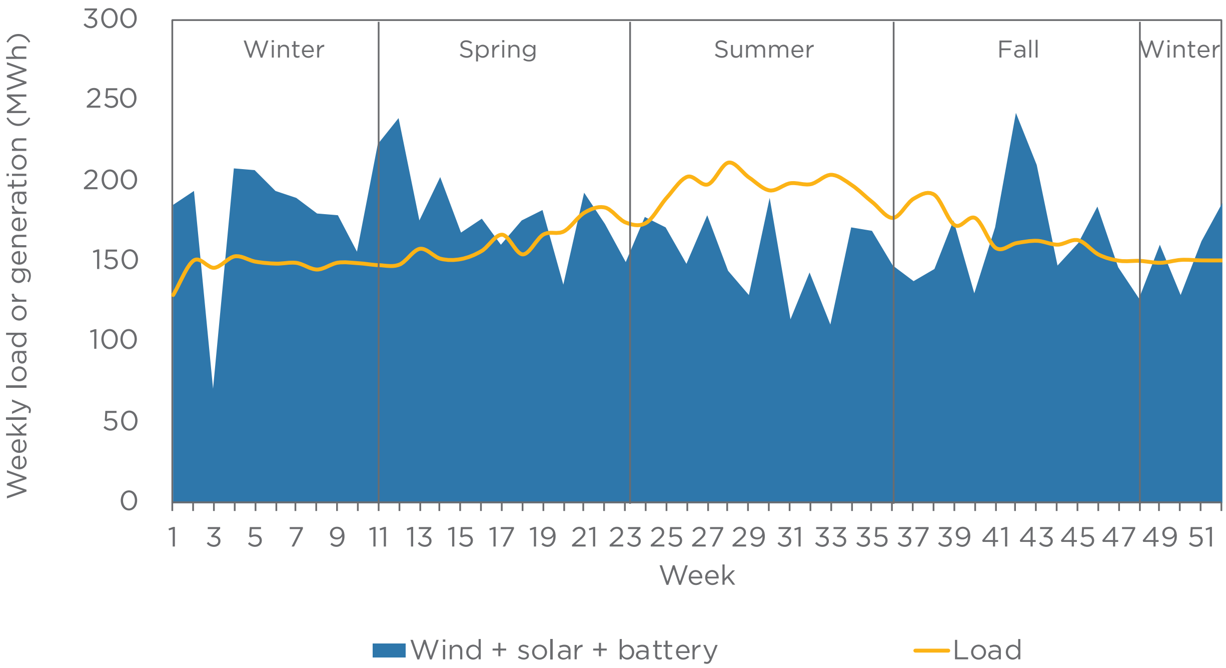
Figure 9: A big box store in New England supplied with 50 percent firm, dispatchable, low-carbon generation, 25 percent wind, and 25 percent solar and a 1 MW/8 MWh battery



Note: Average annual load is 1 MW; annual load = 50 percent low-carbon + 25 percent wind + 25 percent solar; 3 percent of load is served by the grid.

Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

Figure 10: A big box store in New England supplied with 50 percent wind and 50 percent solar and a 1 MW/8 MWh battery (no firm, dispatchable, low-carbon generation)



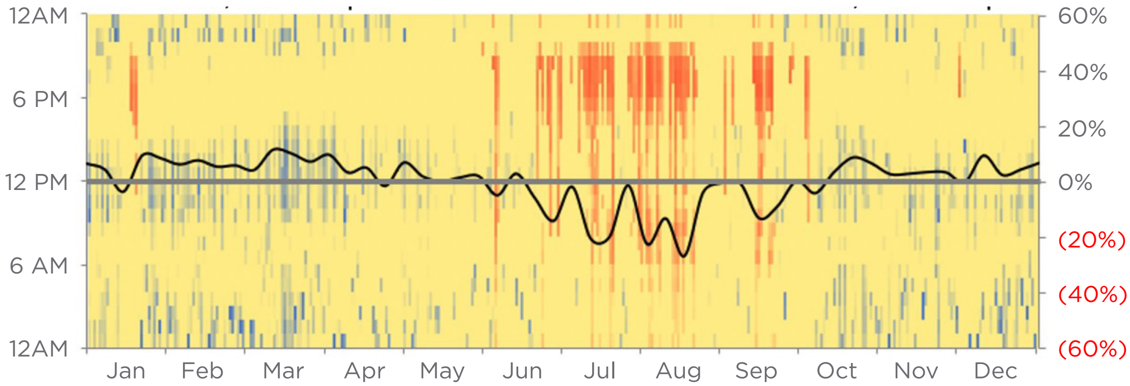
Note: Average annual load is 1 MW; annual load = annual VRE; 14 percent of load is served by the grid.
Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

Further shifting the supply mix toward firm low-carbon generation or energy storage would allow the periods of deficit/curtailment to be fully eliminated.

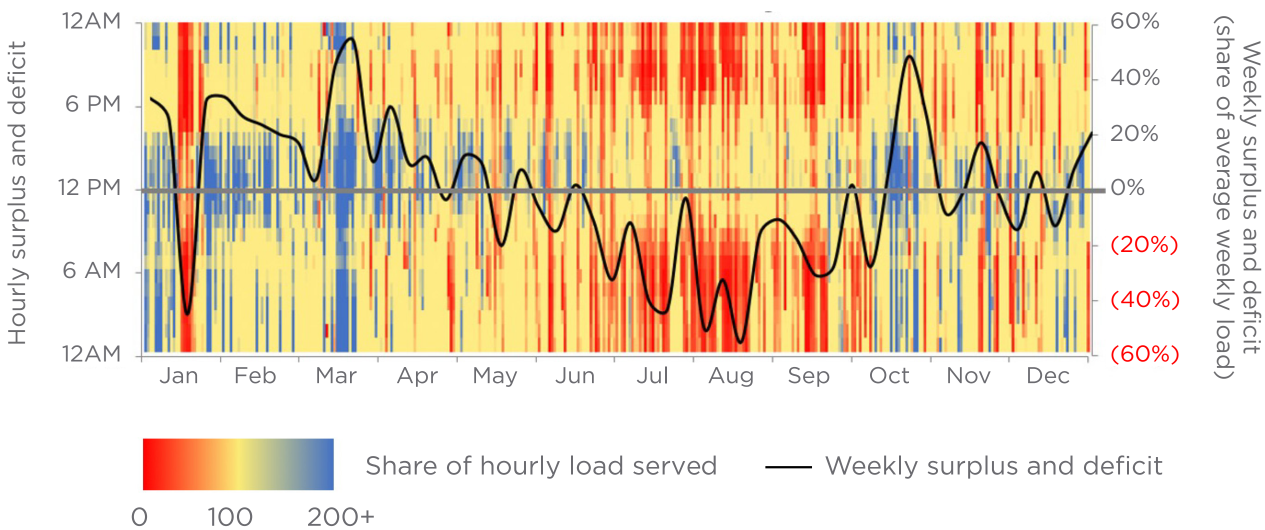
Figures 11 shows the improvement in matching because of the addition of the low-carbon generation to the supply portfolio but on an hourly basis across the year.

Figure 11: Heat maps of a big box store in New England

Mix of VRE, battery, and low-carbon



VRE and battery only

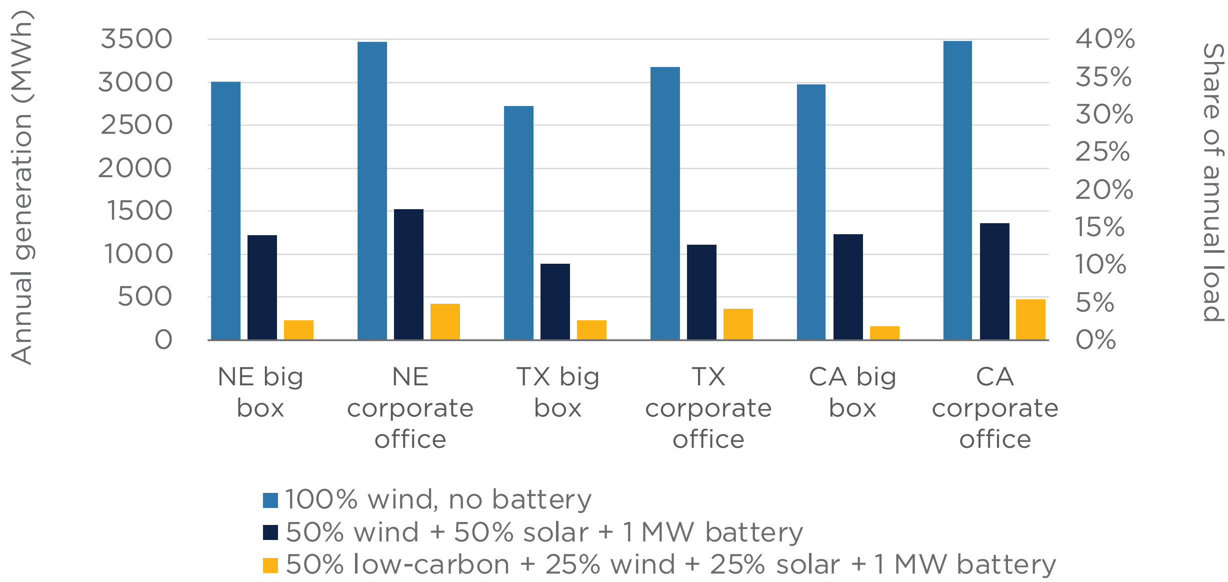


Note: Left axis: red = deficit, blue = surplus; right axis: <0 percent = deficit, >0 percent = surplus; top figure assumes 50 percent firm, dispatchable low-carbon, 25 percent wind, and 25 percent solar generation and a 1 MW/8 MWh battery; bottom figure assumes 50 percent wind and 50 percent solar generation and a 1 MW/8 MWh battery.

Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

This result is not isolated to the ISO New England region or big box store customer type. Rather, a supply mix that includes firm low-carbon generation and variable renewable energy substantially reduced the timing mismatch in all three regions and two customer types examined in this analysis. As shown in Figure 12, a generation portfolio with 50 percent firm low-carbon generation reduced annual deficits by 65 percent to more than 90 percent, depending on the variable renewable energy supply portfolio that it is compared with. These results indicate that, in the near term, deploying a mix of firm low-carbon generation and variable renewable energy could eliminate the times when customers are supplied with carbon-intensive fossil fuel generation and, with full decarbonization, help prevent requirements for frequent and extended demand response.[45]

Figure 12: Annual deficits for generation portfolios with and without firm dispatchable low-carbon resources



Source: Based on analysis by the NorthBridge Group and detailed in the Appendix.

The reliance on grid power and carbon footprints for these three alternative pathway scenarios—overbuilding battery storage, procuring variable renewable energy supplies materially exceeding annual customer consumption, and incorporating firm dispatchable zero-carbon generation—are shown in Table 3, for all three regions and two customer types.

Table 3: Reliance on grid power and corresponding carbon footprint for each supply portfolio and customer type by region—alternative pathways for full decarbonization

New England (ISO-NE): Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
50% Wind + 50% Solar + 10 MW/80 MWh Battery	34%	40%	52%	47%	839	968
75% Wind + 75% Solar + 1 MW/8 MWh Battery	50%	48%	72%	73%	1,225	1,162
25% Wind + 25% Solar + 50% Dispatchable Zero Carbon + 1 MW/8 MWh Battery	26%	27%	56%	51%	644	687

Texas (ERCOT): Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
50% Wind + 50% Solar + 10 MW/80 MWh Battery	5%	5%	12%	12%	234	218
75% Wind + 75% Solar + 1 MW/8 MWh Battery	1%	2%	4%	7%	57	105
25% Wind + 25% Solar + 50% Dispatchable Zero Carbon + 1 MW/8 MWh Battery	1%	3%	11%	22%	57	146

California (CAISO): Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
50% Wind + 50% Solar + 10 MW/80 MWh Battery	11%	10%	23%	20%	266	225
75% Wind + 75% Solar + 1 MW/8 MWh Battery	5%	5%	12%	12%	121	124
25% Wind + 25% Solar + 50% Dispatchable Zero Carbon + 1 MW/8 MWh Battery	1%	4%	5%	18%	17	81

D. Procurement of Firm Low-Carbon Generation

While some advanced low-carbon generation and long-duration storage technologies are years from being fully demonstrated and commercialized, others could provide incremental generation for corporate procurement contracts on an earlier time frame (i.e., soon enough that forward-looking corporate buyers could begin planning for them now). Several near-term examples include the following:

- Hydropower
  - Turbine upgrades at existing hydropower plants
  - New and increased plant capacity, including imports from Canada and dam retrofits
- Nuclear power[46]
  - Life extensions and plant improvements to increase the capacity rating at existing nuclear plants
  - Next generation small modular reactors
- Fossil fuel power plants with carbon emission capture and storage technologies
  - Carbon capture retrofits at existing plants with storage of carbon dioxide
  - Next generation oxy-combustion technology with storage of carbon dioxide

Furthermore, recent market activity suggests there are likely to be opportunities to secure generation from some of these resources on commercially acceptable terms in the near term. For example:

- several states have recently agreed to support the continued operation of existing nuclear plants that might otherwise be shut down for economic reasons by providing financial incentives.[47] New buyer demand for the electrons and environmental attributes of such resources can help extend their life span and avoid the increased carbon emissions that could result from their retirement.[48]
- Massachusetts has contracted for long-term supplies of new hydropower reservoirs in Canada at a levelized delivered cost (including transmission) of less than $60/MWh.[49]
- with the recently issued guidance from the IRS on treatment of the federal 45Q tax credit, several carbon capture and sequestration projects could break ground in the near term.[50]
- NET Power, a joint venture of energy company 8 Rivers and several others, has developed a new Allam Cycle power plant technology, recently proposed for commercial development at two sites in the United States, that is designed to produce pipeline-ready carbon dioxide for sequestration and electricity that is cost-competitive with conventional natural gas combined cycle power plants.[51]
- NuScale Power based in Portland, Oregon, is developing a new modular light water nuclear reactor and working with the Utah Associated Municipal Power Systems toward the development of a first project.[52]

CONCLUSIONS AND RECOMMENDATIONS

Actions by companies to pursue decarbonization goals can help accelerate the transition to a decarbonized electric grid. However, the gap between supply profiles for variable renewable generation and demand profiles for these companies leads to significant risks for organizations pursuing these types of goals. In turn, there is an opportunity for companies to align their goals with pathways to achieve deep decarbonization of the power sector.[53] In addition to moving toward closer geographic matching between contracted electricity supplies and demand, the analysis in this report reveals two high-level takeaways that should be considered in next generation procurement strategies.

1. **More Closely Match When Contracted Electricity Is Produced with When It Is Consumed**

In a fully decarbonized electric system, all or nearly all electric generation will need to be carbon-free and that generation will need to match total electric system load on a near instantaneous basis. In turn, hourly time matching of electricity supplies and customer load is a logical next step in corporate procurement efforts. If hourly matching is not possible because of data or other practical limitations, an initial step toward this goal and improvement over the current practice of procuring supplies to match corporate load on an annual basis (though not analyzed in this report) is that corporate buyers could seek to procure a mix of low-carbon energy supplies that match their loads on a seasonal or monthly basis.

2. **Procure a Portfolio of Low-Carbon Electricity, Including Variable Renewables, Firm Low-Carbon Resources, and Energy Storage**

Wind and solar energy are valuable tools in achieving decarbonization targets. But adopting procurement practices that have the effect of diversifying supply portfolios to include a mix of firm low-carbon generation as well as variable renewable energy generation and energy storage provides numerous advantages.[54] Companies could directly procure a portfolio of low-carbon electricity—including variable renewables, firm low-carbon resources, and energy storage—by assembling a portfolio of resources on its own or, alternatively, contracting with a third-party supplier (e.g., competitive supplier or regulated utility) to offer a product that better matches zero-carbon supply with a customer's consumption pattern throughout the year.

Advancements in corporate target setting and procurement methods that reflect these approaches could send stronger price signals to drive commercial investment in zero-carbon generation technologies that generate output that better coincides with the timing of customer loads, accelerate carbon emission reductions in the near term, and, over time, accelerate the innovation and commercialization of advanced technologies that are needed to achieve the goal of full decarbonization in a practical and affordable manner. They are also reasonably well-aligned with the Biden administration's January 27, 2021 "Executive Order on Tackling the Climate Crisis at Home and Abroad," which, among other initiatives, directs the development of a federal clean electricity procurement strategy consistent with achieving a carbon-free electricity sector by no later than 2035[55].

These advancements could reasonably be expected to provide the following advantages to companies:

1. **Lower Risk**

Moving away from a 100 percent renewables to a zero-carbon focus can prepare companies for changes in federal, state, and local policies (e.g., RECs and net metering). Furthermore, this diversified approach can reasonably be expected to shield companies from technology limitations, such as the inability to meet hourly customer demand in real time using variable renewable generation during certain parts of the year. While a zero-carbon target might be met with 100 percent renewables (e.g., as may be the case if a region has significant geothermal and/or large hydropower resources), a ZC100 focus ensures that companies achieve their emission reduction objectives if variable renewables are unable to meet their needs in each hour throughout the year.

2. **Avoid Accusations of Greenwashing**

By transitioning from 100 percent renewable strategies to targets that align with deep decarbonization efforts, companies can avoid accusations of greenwashing. By matching when and where companies use electricity with zero-carbon sources, compared with when and where contracted variable renewable electricity is produced, they can avoid criticisms related to false accounting and unverifiable offsets. Furthermore, as state and local governments move toward ZC100 as the preferred standard (several states have adopted policies to fully decarbonize their electric sectors by mid-century, if not earlier, and several legislative proposals have been put forward at the federal level to achieve similar goals nationally), companies that transition to procurement goals focused on ZC100 will benefit from best-in-class ESG stewardships and a preemptive stance against shareholder pushback.

3. **Foster Positive Local Community Engagement**

State and local jurisdictions that may be wary of 100 percent renewable targets might be amenable to improved partnerships for companies that adopt zero-carbon targets that lead to local gains. For example, in congested regions, offtake agreements with companies could reduce curtailment of both renewables and other zero-carbon supplies. These agreements could benefit both companies (that could potentially receive cheap electricity) and local jurisdictions by improving return on investment for zero-carbon supplies. This approach could also attract positive attention and responses from green groups.

4. **Upgrade Brand**

By aligning corporate targets with new and emerging state and national policies around the United States and globally—for example, ambitious clean energy standards rather than 100 percent renewable standards—leading companies can potentially attract new customers and gain market share. Their proactive action could also be used to attract new spokespeople and investors (e.g., socially responsible investment groups). By having documented verifiable reductions in their carbon footprint, companies can build their brand and support ESG efforts.

5. **Socialize Best Corporate Practices and Policy Models to Speed up Decarbonization**

Early corporate adopters of ZC100 targets can establish new guidelines and market standards for company procurement practices that align with broader deep decarbonization efforts. By establishing clear and transparent clean energy procurement practices and facilitating availability of underlying emission data and emission accounting infrastructure systems, leading companies can demystify how to meet company goals related to reducing their carbon footprint for other corporations to follow and adopt. Furthermore, a public focus on technologically diverse pathways to complete decarbonization can send a reinforcing signal to states and the federal government that decarbonization policies are better structured in this way than through restrictive policies solely centered on variable renewables. These forms of business and policy socialization will lever corporate leadership efforts and likely speed up the decarbonization of the US electricity sector, consistent with corporate policy.

APPENDICES

A. Study Methodology

Goals

The primary goals of the analysis are threefold. The first is analytical in nature—to understand how corporate purchases of variable renewable energy that equal, over the course of a full year, the total amount of electric load of a corporate facility impact today's power markets in terms of reduced carbon emissions and align with longer term deep decarbonization objectives, as well as how corporate procurement practices of this type might be improved going forward. The second goal is to develop this understanding for diverse regions, various types of corporate customers, and different variable renewable energy portfolios to provide insight into the extent to which the results are broadly applicable to corporate purchasing practices in the United States. The third is to produce simple and transparent materials illustrating why and how changes in corporate procurement practices[56] could improve the ability of companies to achieve their emission reduction goals while also supporting the wider decarbonization of the power grid in the United States.[57]

More specifically, the analytic goals include estimating the extent to which this procurement practice.

- Results in wind and solar energy supplies, with or without battery capacity, that match corporate electric loads on an hourly, weekly, seasonal, and annual basis, and to the extent they do not fully match, better understand the total amount of deficit and surplus energy during these periods over the course of the year
- In today's electric markets, how these deficits might lead to continued reliance on power supplies from the local regional electric grid, unabated fossil generation, and continued emissions of GHGs (despite a corporate buyer contracting with a renewable energy supplier for 100 percent its total annual consumption)
- In future electric markets that are fully decarbonized, how this would require corporate customer loads to be curtailed to match supply and load and maintain system reliability
- The value of complementing wind and solar supplies with other low-carbon generation and long-duration energy storage resources, including firm dispatchable low-carbon technologies, to achieve a fully decarbonized electric grid without the need to curtail customer loads

Approach and Scope

At its core, this analysis involved a series of comparisons of hourly chronological deterministic electric load profiles to hourly chronological deterministic generation from portfolios of variable energy resources over the course of a full year (i.e., over 8,760 hours). By comparing these consumption and production profiles on an hourly basis, the authors quantified and considered the extent of any energy mismatch on an hourly, weekly, seasonal, and annual basis.

To understand the extent to which the results are widely applicable, the authors performed this analysis for three regions of the country—New England, Texas, and California[58]—and two representative types of corporate customers—a "big box store" and a corporate "Office Building." The combinations of these regions and customer types produced six distinct region/customer combinations. For each of these, the authors examined nine supply portfolios, including wind, solar, and batteries as follows[59]:

Nine Supply Portfolios Analyzed

1. One hundred percent wind—meaning the total amount of wind energy procured over the course of the year, 8,760 MWh, equaled the total amount of customer electricity consumption over the year, 8,760 MWh
2. One hundred percent solar
3. Fifty percent wind and 50 percent solar
4. One hundred percent wind with 1 MW/8 MWh battery capacity capable of storing 8 MWhs of usable electricity and discharging that over an eight-hour period at a rate of 1 MW per hour, which is equal to the average hourly customer load over the year
5. One hundred percent solar with 1 MW/8 MWh battery capacity
6. Fifty percent wind and 50 percent solar with 1 MW/8 MWh battery capacity
7. Fifty percent wind and 50 percent solar with 10 MW/80 MWh battery capacity (10 times the storage and discharge capability of the 1 MW/8 MWh battery)
8. Seventy-five percent wind and 75 percent solar with 1 MW/8 MWh battery capacity—meaning the customer chose to contract for variable renewable energy supplies equal to 150 percent of customer electric loads, in effect over procuring supply in an effort to reduce the periods when renewable supply is not available
9. Twenty-five percent wind, 25 percent solar, 50 percent firm dispatchable zero-carbon generation with 1 MW/8 MWh battery capacity[60]

The six region/customer combinations and nine supply portfolios produced 54 distinct scenarios. As a reference point, the authors also quantified the carbon impact associated with 100 percent reliance on energy from the local regional grid in each of the six region/customer combinations.

Analysis, Calculations, and Outputs

For each of these scenarios, the authors assumed the representative customers had a 1 MW average hourly load over the course of the year and consumed 8,760 MWh of energy over the year, in accordance with the hourly load pattern for that type of customer and region of the country (i.e., in some hours, customer load was higher than 1 MW, and in other hours, it was lower than 1 MW, but over the entire year, it averaged 1 MW). Similarly, the authors assumed that the contracted wind and/or solar resources generated 8,760 MWh of renewable supply on an annual basis in accordance with the appropriate hourly generating profile for that type of resource in each region of the country.

The data underlying the analysis were drawn from several sources. The customer load profiles are based on hourly DOE representative load profiles for a big box store, represented by a supermarket load profile, and a corporate office building, represented by a large office load profile. The wind generation profiles are based on actual 2018 wind output from the respective RTO normalized for wind capacity between those regions and this analysis. The solar generation profiles are based on expected hourly solar output from the locational hourly solar estimator (PV Watts) from the National Renewable Energy Laboratory (NREL), with the exception of the California solar profile, which uses actual 2018 solar output from CAISO.[61,62] The solar data is also normalized for solar capacity between those regions and this analysis.

The battery technology assumptions used in this analysis were optimistic relative to today's technology and neglect to include expected efficiency losses. An advanced lithium-ion battery with a 1 MW capacity was assumed to discharge 1 MW for eight hours with zero losses. The battery operating logic was such that it would charge in times of excess supply (if it was not already totally full) and discharge in times of load deficits (if it was not totally empty). By way of comparison, today's standard Li-ion battery operating in the wholesale market can typically discharge up to four hours at full discharge capability with 11 percent losses.[63] The assumptions for a generic firm dispatchable zero-carbon technology assumed it could ramp up or down to match renewable generation with load and charge the battery in periods of excess supply.

For each of the 54 scenarios, the authors evaluated the hourly, weekly, seasonal, and annual mismatch between contracted supplies and customer loads; the portion of customer load served by contracted variable renewable energy supplies and the portion of customer load that continues to rely on energy supplied from the local regional grid; the GHG emissions associated with relying on energy from the regional grid; the deficits and likely curtailments that would result in a fully decarbonized electric system; and the improvement in these metrics resulting from a supply portfolio including both variable renewable energy and firm dispatchable zero-carbon generation.

B. Study Results by Region

Within each region, the authors provided information about the supply and customer load profile input characteristics, followed by the results of the authors' analysis, including the percent of annual customer load taken from the electric grid, the percent of hours that the customer relies on the local electric grid, and an estimate of the associated tons of carbon emissions from electric grid power used to serve that customer.

New England (ISO-NE)

Inputs and Summary Results for New England

Supply Profile Inputs

The authors assumed that the contracted wind and/or solar resources generated 8,760 MWh of renewable supply on an annual basis (unless otherwise specified), in accordance with the appropriate hourly generating profile for that type of resource in New England. The data underlying the analysis was drawn from several sources. The wind generation profiles are based on actual 2018 wind output from ISO-NE. The solar generation profiles are based on expected hourly solar output from NREL's locational hourly solar estimator.[64]

Based on current onshore wind technology and wind patterns in New England, a representative onshore wind power facility has a 27 percent annual capacity factor.[65] To generate 8,760 MWh of renewable supply on an annual basis (to satisfy a 100 percent RE target for a representative customers having a 1 MW average hourly load over the year), the contracted peak wind capacity would need to be about 3.7 MW. Wind generation is estimated to be highest during the winter season and lowest during the summer period. By comparison, based on current solar technology and solar patterns in New England, solar power has a 16 percent annual capacity factor. To generate 8,760 MWh of renewable supply on an annual basis (to satisfy a 100 percent RE target for a representative customer having a 1 MW average hourly load over the year), the contracted solar capacity would need to be about 6.4 MW. In contrast to wind generation, solar generation is estimated to be highest during the summer season and lowest during the winter period.

Table A1: Generation capacity factor %

New England (ISO-NE)	Annual	Winter	Spring	Summer	Fall
Onshore Wind[66]	26.9%	33.0%	28.6%	18.6%	27.7%
Solar[67]	15.6%	12.7%	17.1%	17.8%	14.6%
Firm Dispatchable Zero Carbon[68]	69.7%	55.3%	61.3%	90.8%	71.0%

Given that both the wind and/or solar capacity required to meet a 100 percent RE target greatly exceeds the average hourly demand of the customer, it is reasonable to expect that in hours when these facilities are generating energy at or near their capacity, significant surpluses of energy will occur, and in hours when these intermittent resources do not generate electricity, significant deficits will be likely.

All nine of the supply portfolios listed above include onshore wind and/or solar energy. In one of the nine supply portfolios, the authors added generic firm dispatchable zero-carbon technology and assumed it could ramp up or down to match renewable generation with load and charge the battery in periods of excess supply. The capacity factors for this resource are much higher than those for the wind and solar resources and are a function of both the renewable generation output and customer load. The capacity factor for this resource is higher in the summer when wind generation is relatively low and customer load is high.

Customer Load Profile Inputs

For each scenario, the authors assumed the representative customers had a 1 MW average hourly load over the year and so consumed 8,760 MWh of energy over the year, in accordance with the hourly load pattern for that type of customer in New England. The customer load profiles are based on hourly DOE representative load profiles for a big box store, represented by a supermarket load profile, and a corporate office building, represented by a large office load profile.

Based on customer characteristics and weather patterns in New England, a representative big box store customer has a 51 percent annual load factor.[69] To consume 8,760 MWh on an annual basis (i.e., a representative customers having a 1 MW average hourly load over the year), the big box store would have a peak demand of approximately 2.0 MW. By comparison, a representative office building customer has a 41 percent annual load factor. To consume 8,760 MWh on an annual basis, the office building would have a peak demand of approximately 2.4 MW. Both the representative big box store customer and the office building customer are expected to consume more electricity during the summer period than in the other seasons because of air conditioning load.

Table A2: Customer load factor %

New England (ISO-NE)	Annual	Winter	Spring	Summer	Fall
Big Box Store	50.7%	45.1%	48.2%	58.8%	50.5%
Office Building	41.2%	36.7%	39.2%	47.8%	41.1%

It is noticeable that the customer load factors are higher than the capacity factors of the renewable energy generation. These differences in supply and load profiles (i.e., patterns in generation and consumption) contribute to the timing mismatches described in this report. Some commercial and industrial customers may have higher load factors than the representative corporate customers selected for this analysis (e.g., a data center or an around-the-clock manufacturing plant). A customer with a high load factor consumption pattern (normalized to consume 8,760 MWh in a year like the other representative customers) would imply a lower customer peak demand and a flatter consumption pattern than analyzed in this study.[70] Therefore, in some hours, deficits could be larger while, in others, smaller than that shown in the summary of results below, but the overall findings would be unchanged.[71]

Summary of Results

Table A3 summarizes for each supply portfolio and customer type the results of the authors' analysis for the New England region in terms of the percent of annual customer load taken from the local electric grid, the percent of hours that the customer relies on the local electric grid, and an estimate of the associated tons of carbon emissions from electric grid power used to serve that customer.

Table A3: Summary of results—New England (ISO-NE)

Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power[72] (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
1. 100% Wind	34%	40%	52%	47%	839	968
2. 100% Solar	50%	48%	72%	73%	1,225	1,162
3. 50% Wind and 50% Solar	26%	27%	56%	51%	644	687
4. 100% Wind with 1 MW/8 MWh Battery	25%	28%	34%	33%	602	692
5. 100% Solar with 1 MW/8 MWh Battery	28%	27%	52%	45%	674	648
6. 50% Wind and 50% Solar with 1 MW/8 MWh Battery	14%	17%	28%	27%	340	424
7. 50% Wind and 50% Solar with 10 MW/80 MWh Battery	8%	11%	14%	17%	190	279
8. 75% Wind and 75% Solar with 1 MW/8 MWh Battery	4%	7%	10%	12%	108	166
9. 25% Wind, 25% Solar, and 50% Firm Dispatchable Zero-Carbon Generation with 1 MW/8 MWh Battery	3%	5%	12%	16%	63	117
10. 100% Grid	100%	100%	100%	100%	2,444	2,444

Analysis of the two representative companies operating in New England (i.e., in the ISO-NE RTO) indicated that there are likely to be significant periods of "deficit" (i.e., when the company's electricity demand exceeds available supply from the renewable electricity supply) and "surplus" (i.e., when available supply exceeds the buyer's consumption). These mismatches occurred across both customer types (i.e., the "big box store and corporate office building) for all three supply mixes (i.e., 100 percent wind, 100 percent solar, and 50/50 wind and solar). While the introduction of on-site energy storage systems reduced these deficits and surpluses, they were unable to eliminate the gap between demand and supply in any of the scenarios examined. A more detailed matching analysis for each supply portfolio is shown in the pages that follow—first, for a "big box store and second, a corporate office building. For the initial supply portfolios analyzed—100 percent wind power or 100 percent solar power—to serve a big box store in New England, the authors provided figures showing (a) hourly deficits and surpluses, (b) weekly deficits and surpluses, and (c) hours in a representative week with a deficit or surplus. These figures illustrate the analysis conducted for all 54 scenarios. While the results for all scenarios are summarized in a table for each region, for purposes of brevity, the authors included in this Appendix a figure of just the weekly deficits and surpluses for a selected subset of the remaining scenarios.

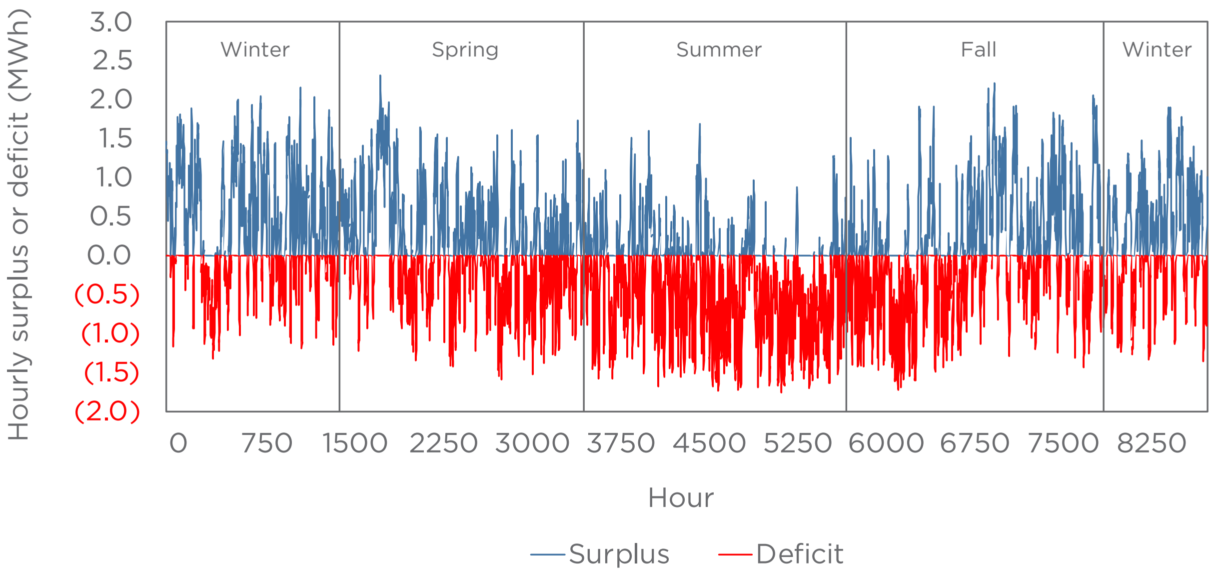
Analysis of Supply Portfolio Scenarios for a Big Box Store in New England

Scenario 1: 100 Percent Wind Power

For the representative big box store (e.g., Target or Walmart), Figure A1 shows the deficits and surpluses for the case of a big box store that procures 100 percent onshore wind generation resources to meet its RE100 target. While surpluses were largely observed in the winter and the deficits were generally seen in the summer, mismatches occurred throughout the entire year. Overall, the big box store relied on the local power grid to meet its consumption in 52 percent of the hours in the year, representing 34 percent of the customer's total annual consumption (2,978 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its carbon dioxide emissions associated with its electricity supply by an estimated 66 percent (1,605 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 839 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

The authors compared customer consumption and generation production profiles on an hourly basis to quantify and evaluate the extent of any energy mismatch over different periods (e.g., hourly, daily, weekly, seasonal, and annual basis). Figure A1 below shows the hourly deficits and surpluses for a big box store with a 100 percent onshore wind supply contract in New England.

Figure A1: A big box store in New England supplied with 100 percent onshore wind power: hourly deficits and surpluses

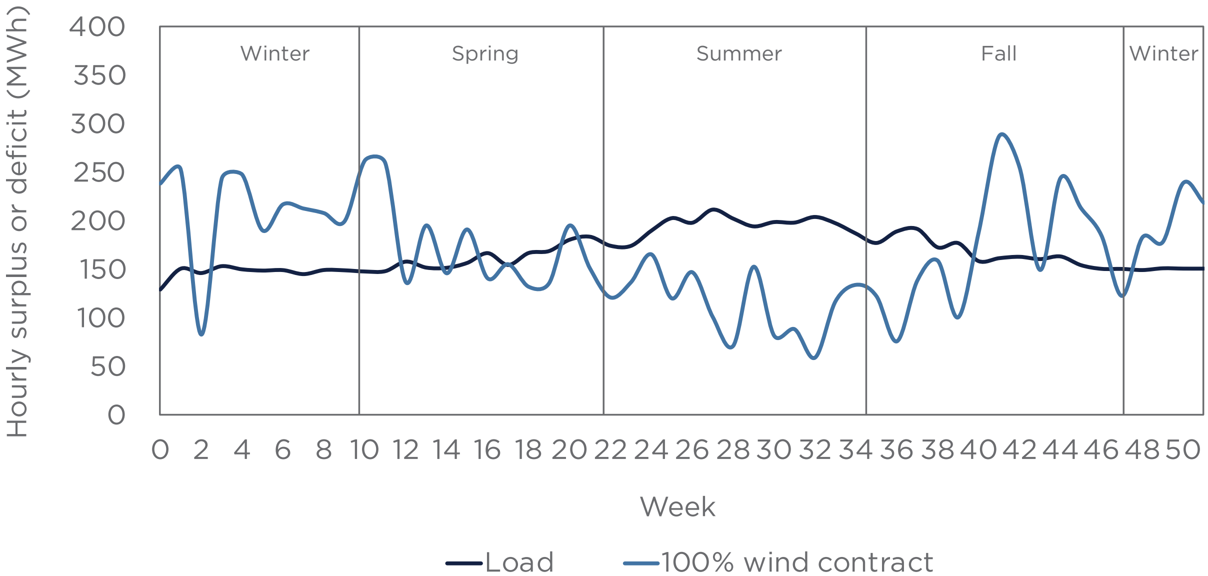


Note: Average annual load is 1 MW; annual load = annual VRE; 34 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; ISO-NE wind generation capacity, ABB/Energy Velocity generating unit capacity database.

When shown on a weekly basis, the seasonal mismatch between the company's consumption and the supply from the onshore wind power that they procured was more evident as shown in Figure A2. In aggregate, approximately 34 percent of the big box store's annual consumption was supplied by the regional grid.

Figure A2: A big box store in New England supplied with 100 percent onshore wind power: weekly deficits and surpluses



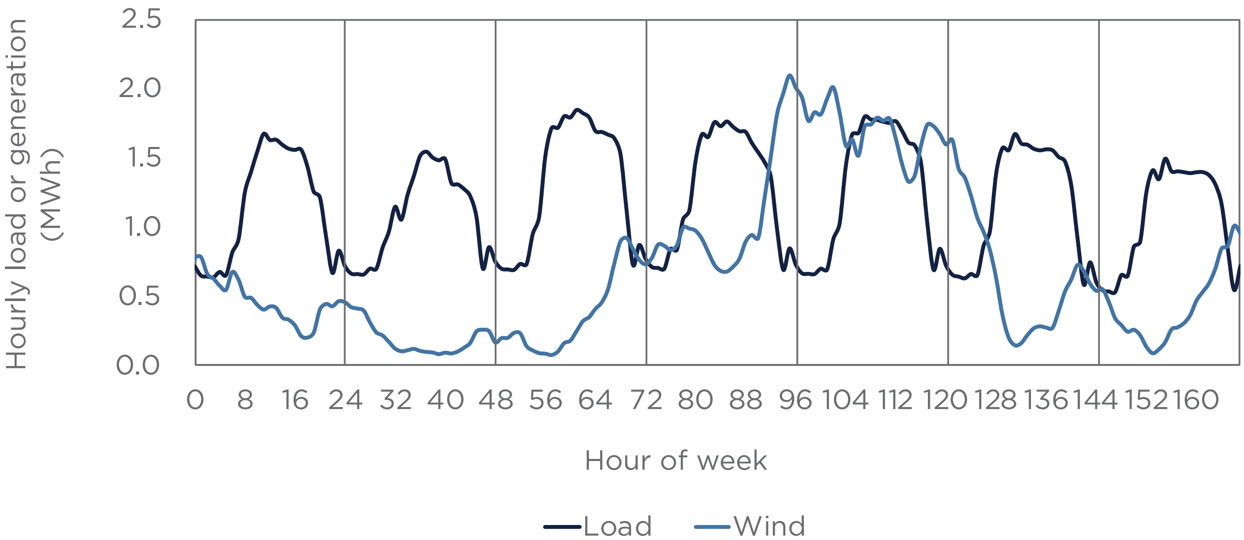
Note: Average annual load is 1 MW; annual load = annual VRE; 34 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; ISO-NE wind generation capacity, ABB/Energy Velocity generating unit capacity database.

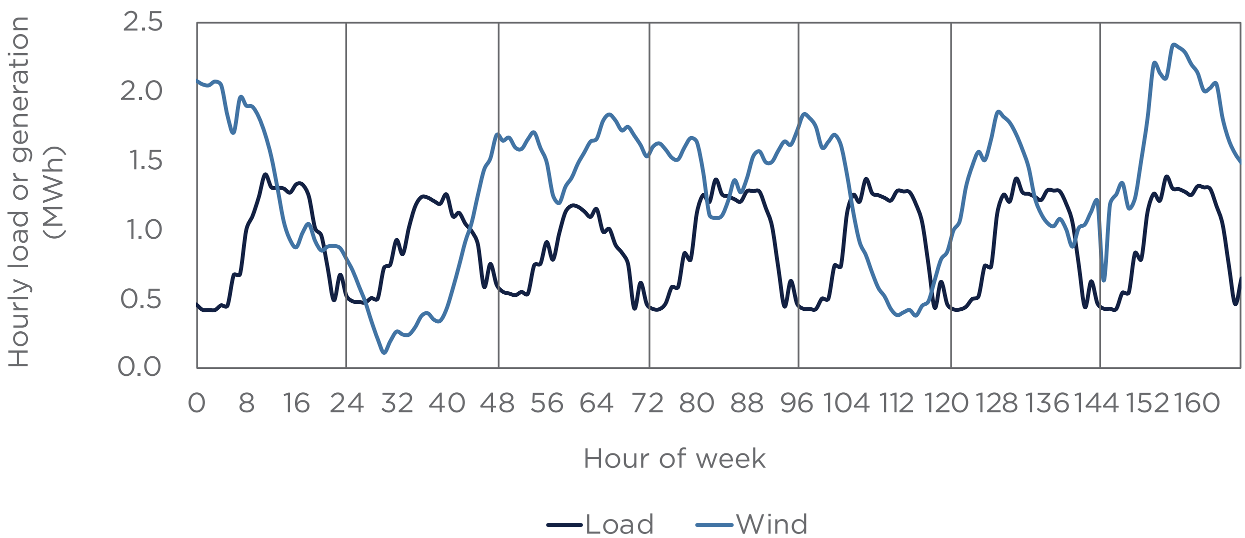
Taking a look at hours during a representative week in August with a net deficit, the customer is reliant on the grid for 61 percent of its weekly consumption in this scenario. However, the big box store is a net supplier to the grid for a day-and-a-half in the middle of that same deficit week. During a representative week in December with a net surplus, the company is most often supplying wind power to the grid. However, even in this scenario, the company relies on the grid to meet 13 percent of its weekly electricity demand.

Figure A3: A big box store in New England supplied with 100 percent onshore wind power: hours in a representative week with deficit or surplus[73]

Week 34: Aug. 19 through Aug. 25 (typical week with net deficit)



Week 52: Dec. 23 through Dec. 29 (typical week with net surplus)



Note: Average annual load is 1 MW; annual load = annual VRE; 61 percent of load is served by the grid (top); 13 percent of load is served by the grid (bottom).

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; ISO-NE wind generation capacity, ABB/Energy Velocity generating unit capacity database.

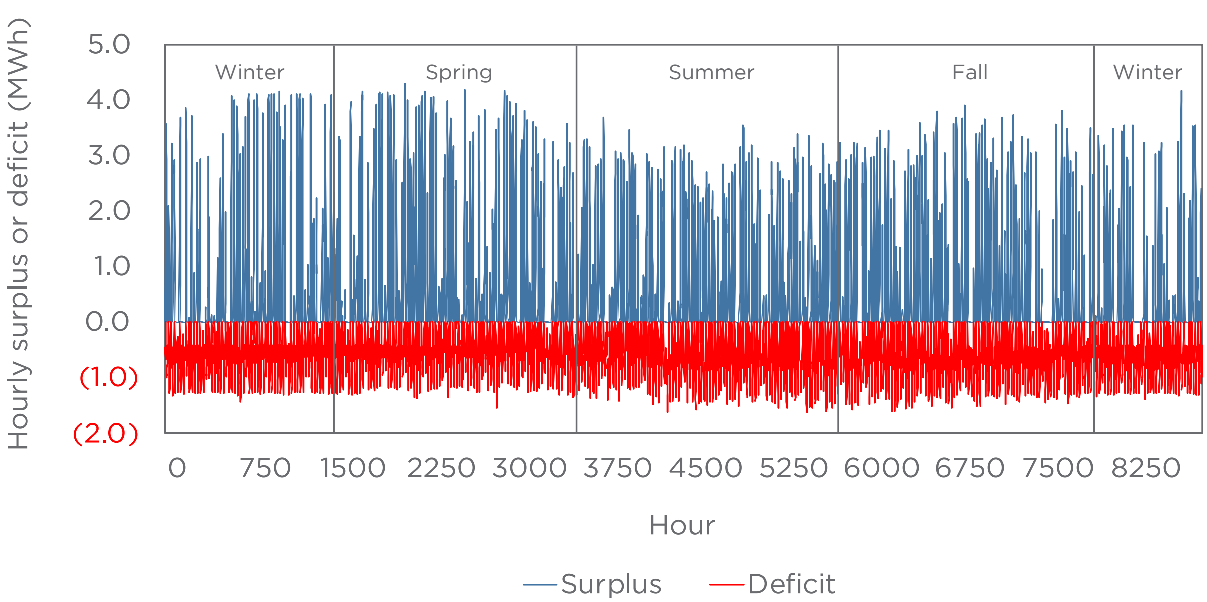
Understanding the duration of these deficits and surpluses is important when evaluating the value of storage solutions.

Scenario 2: 100 Percent Solar Power

The mismatch between supply and demand is even larger in the scenario where the big box store procures 100 percent solar power. When the sun is shining during the middle of the day, the customer is generally supplying surplus generation to the grid, and conversely at night, the customer is usually taking supply from the regional grid. The largest mismatches are seen in the late fall and winter seasons. Overall, the big box store relied on the local power grid to meet its consumption in 72 percent of the hours in the year, representing 50 percent of the customer's total annual consumption (4,380 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 50 percent (1,219 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 1,225 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A4 below shows the hourly deficits and surpluses for a big box store with a 100 percent onshore wind supply contract in New England.

Figure A4: A big box store in New England supplied with 100 percent solar power: hourly deficits and surpluses

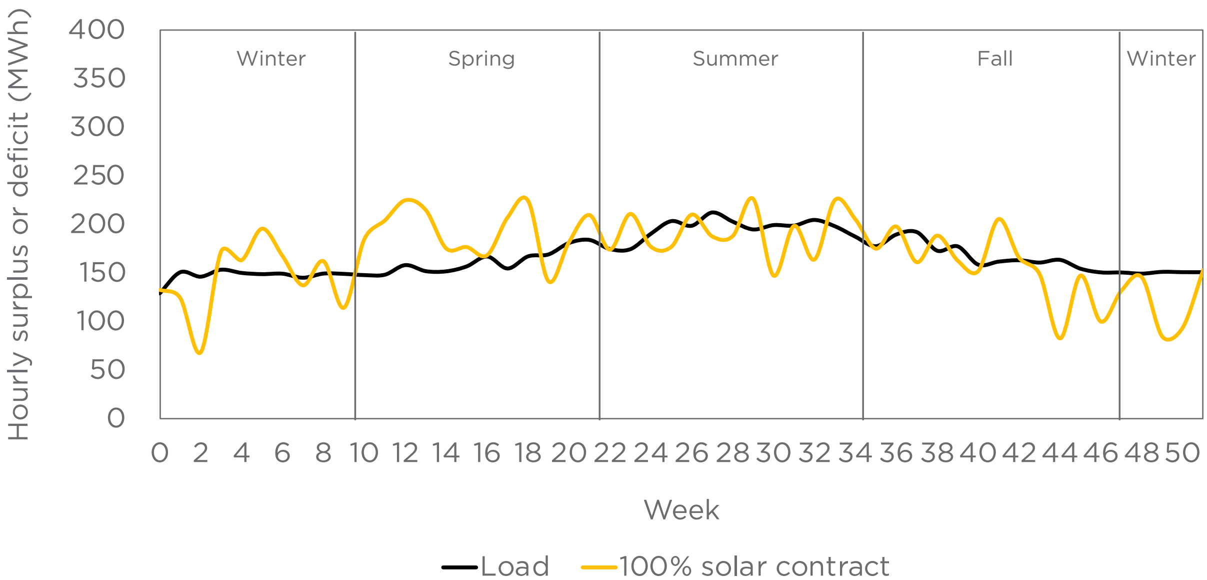


Note: Average annual load is 1 MW; annual load = annual VRE; 50 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE solar generation capacity, ABB/Energy Velocity generating unit capacity database.

When shown on a weekly basis, the seasonal mismatch between the company's consumption and the supply from the solar power that they procured was more evident as shown in Figure A5. In aggregate, approximately 50 percent of the big box store's annual consumption was supplied by the regional grid.

Figure A5: A big box store in New England supplied with 100 percent solar power: weekly deficits and surpluses



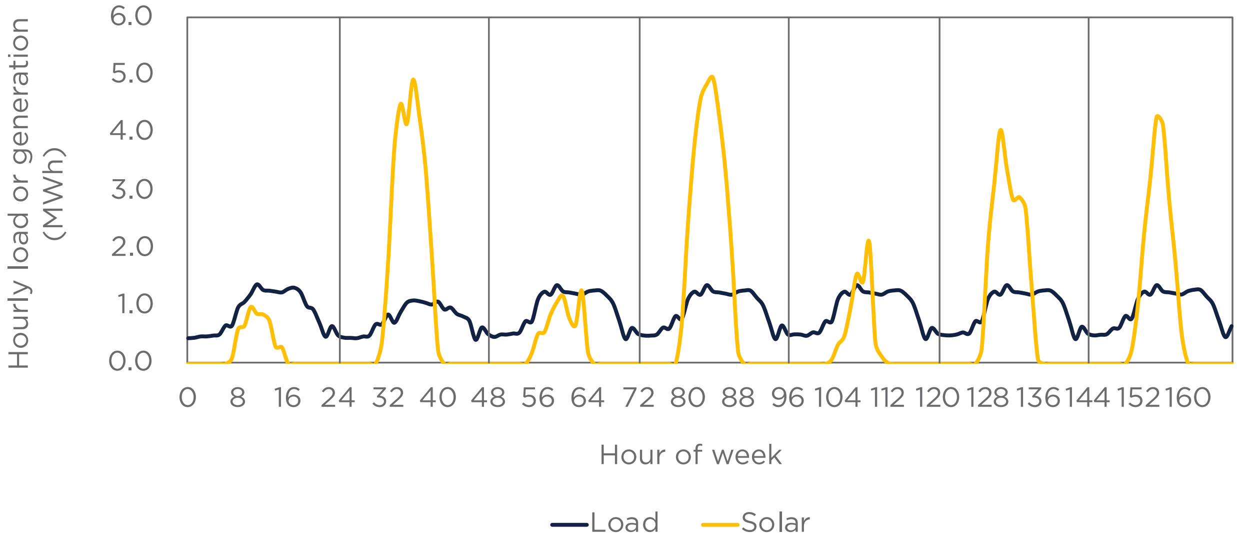
Note: Average annual load is 1 MW; annual load = annual VRE; 50 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, [http://pvwatts.nrel.gov/pvwatts.php; ISO-NE solar generation capacity](http://pvwatts.nrel.gov/pvwatts.php), ABB/Energy Velocity generating unit capacity database.

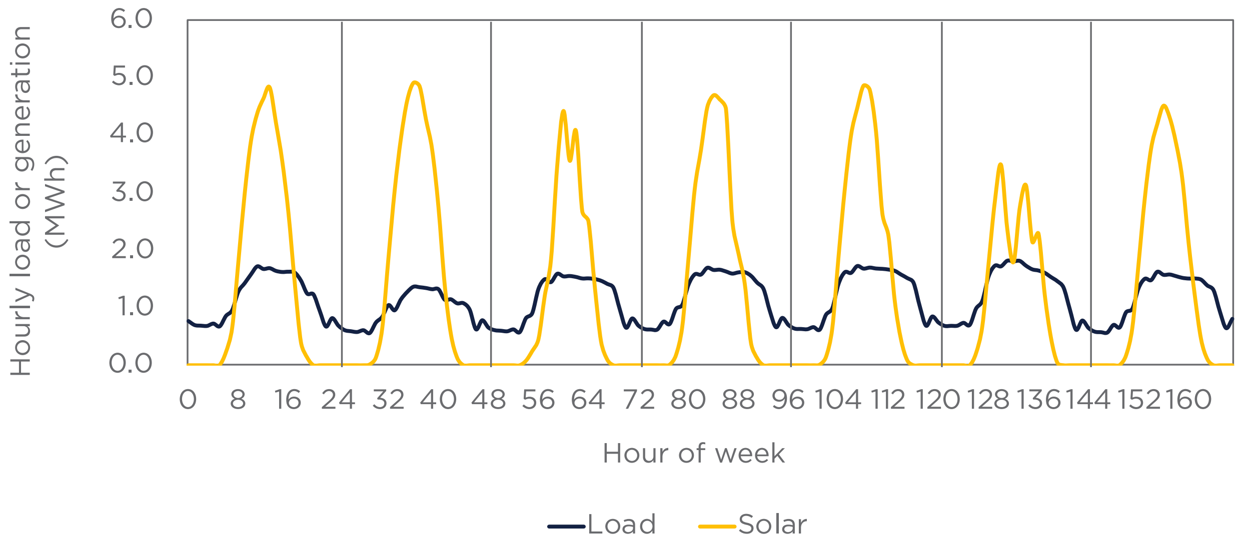
Figure A6 below shows the deficits and surpluses in hours during a representative week in January with a net deficit and during a representative week in July with a net surplus.

Figure A6: A big box store in New England supplied with 100 percent solar power: hours in a representative week with deficit or surplus

Week 2: Jan. 7 through Jan. 13 (typical week with net deficit)



Week 30: July 22 through July 28 (typical week with net surplus)



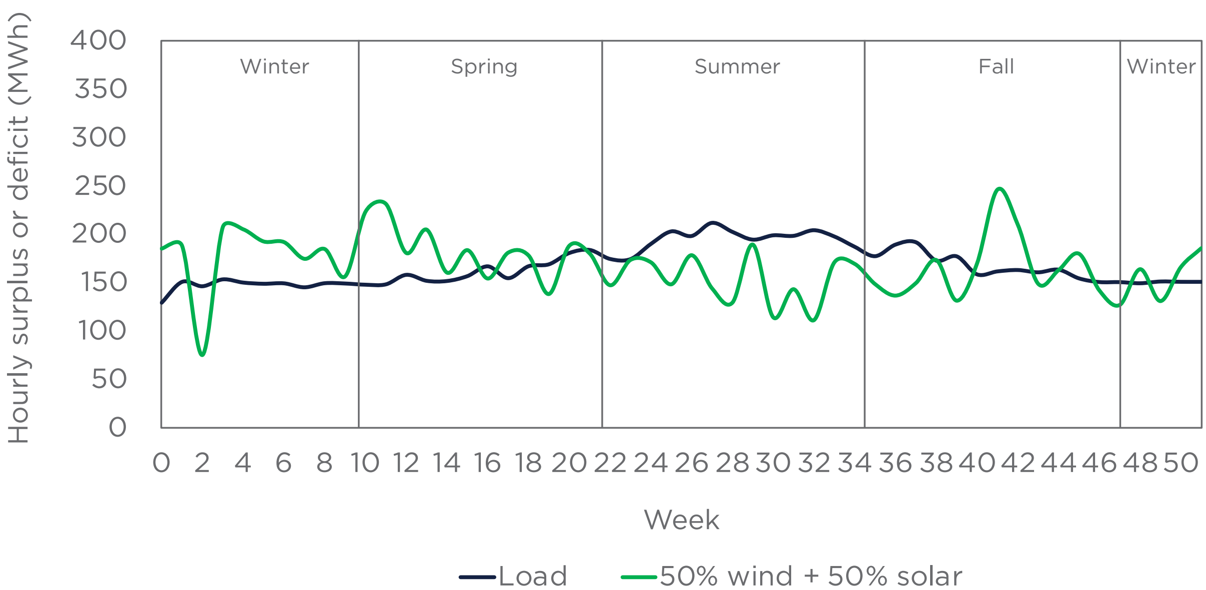
Note: Average annual load is 1 MW; annual load = annual VRE; 56 percent of load is served by the grid (top); 48 percent of load is served by the grid (bottom).

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 3: 50 Percent Wind and 50 Percent Solar Power

Given the broadly complimentary nature of wind and solar power in the electricity supply, this scenario explored the impacts of procuring a mixed portfolio with 50 percent wind energy and 50 percent solar energy instead of wholly one or the other. As shown in Figure A7, this mix of supply resources led to a minor improvement with regard to the supply and demand mismatch challenge relative to the 100 percent wind scenario and a substantial improvement to the 100 percent solar scenario. However, even with this mixed portfolio, the big box store relied on the local power grid to meet its consumption in 56 percent of the hours in the year, representing 26 percent of the customer's total annual consumption (2,278 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 74 percent (1,800 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 644 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A7: A big box store in New England supplied with 50 percent wind power and 50 percent solar power: weekly deficits and surpluses



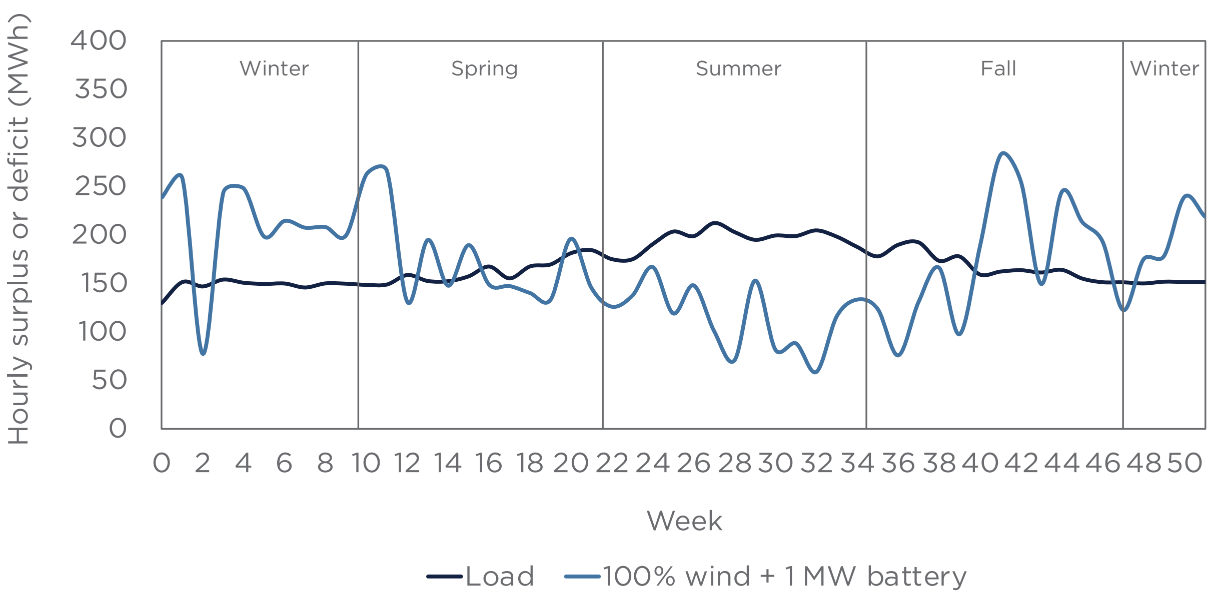
Note: Average annual load is 1 MW; annual load = annual VRE; 26 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; ISO-NE solar and wind generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 4: 100 Percent Wind Power with 1 MW/8 MWh Battery

The following big box store scenarios added battery storage to the supply portfolio scenarios described above to help alleviate the timing mismatch between renewable energy supply and customer load. Initially, to the 100 percent wind power case, the authors included a battery with 1 MW output capacity equivalent to the company's average hourly load with 8 hours of discharge capability. Adding the battery improved intraday (e.g., daytime versus nighttime) matching. However, timing mismatches still existed, leading to reliance on grid-supplied electricity. Overall, the big box store relied on the local power grid to meet its consumption in 34 percent of the hours in the year, representing 25 percent of the customer's total annual consumption (2,190 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 75 percent (1,842 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 602 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A8: A big box store in New England supplied with 100 percent wind power with 1 MW battery: weekly deficits and surpluses



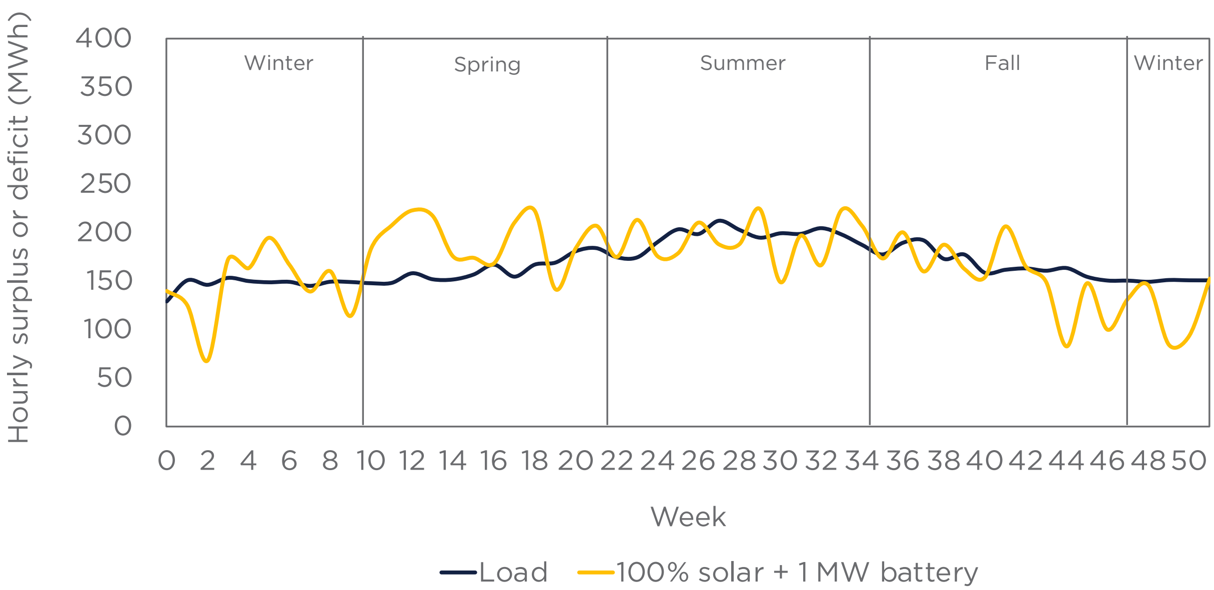
Note: Average annual load is 1 MW; annual load = annual VRE; 25 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; ISO-NE wind generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 5: 100 Percent Solar Power with 1 MW/8 MWh Battery

Next, the authors included a battery with 1 MW output capacity to the 100 percent solar power case shown earlier. As before, adding the battery improved intraday (e.g., daytime versus nighttime) matching. However, timing mismatches still existed, leading to reliance on grid-supplied electricity. Overall, the big box store relied on the local power grid to meet its consumption in 52 percent of the hours in the year, representing 28 percent of the customer's total annual consumption (2,453 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 72 percent (1,770 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 674 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A9: A big box store in New England supplied with 100 percent solar power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 28 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses..

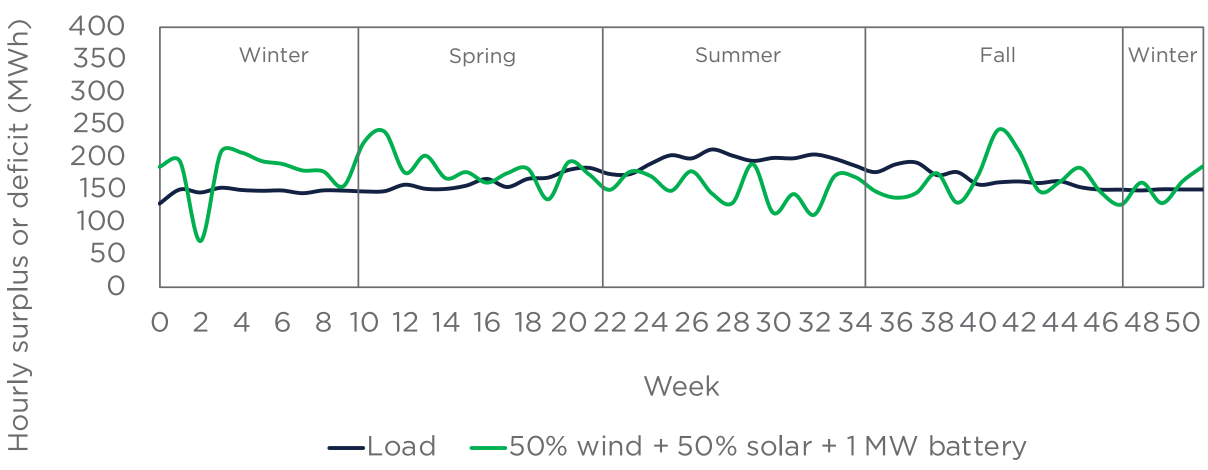
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 6: 50 Percent Wind and 50 Percent Solar Power with 1 MW/8 MWh Battery

Given that a mix of wind and solar power produces a smaller gap between supply and demand than 100 percent of either wind or solar, the next scenario for the ISO NE big box store considered this mixed supply portfolio (i.e., 50 percent wind and 50 percent solar) with a 1 MW battery to improve the effective match between supply and demand resources. Again, adding the battery improved intraday (e.g., daytime versus nighttime) matching. However, timing mismatches still existed, leading to reliance on grid-supplied electricity. Overall, the big box store relied on the local power grid to meet its consumption in 28 percent of the hours in the year, representing 14 percent of the customer's total annual consumption (1,226 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 86 percent (2,104 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 340 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

At a high level, Figure A10 below shows the weekly deficits and surpluses in this scenario were similar as those shown previously in Figure A7 for the equivalent 50 percent wind/50 percent solar scenario without a battery. This highlights that the battery is not large enough to bridge gaps that extend over longer periods. For example, even in seasons of general excess supply (i.e., the winter), there are still individual weeks with significant deficit. In turn, the customer remained reliant on the grid for electricity supply despite having a battery with eight hours of discharge capability.

Figure A10: A big box store in New England supplied with 50 percent wind power and 50 percent solar power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 14 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses..

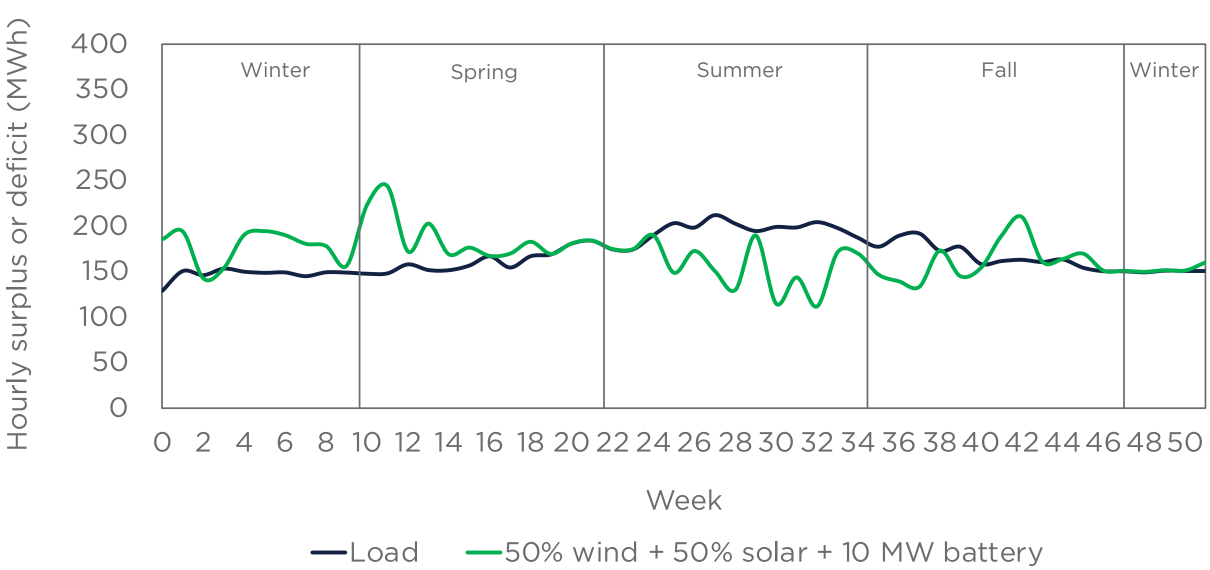
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Thus, while wind and/or solar generation when combined with batteries at an amount equivalent to average hourly customer load can help improve the hourly mismatch, the battery does little to meaningfully improve the long-duration mismatch, causing customers to continue to rely on the regional grid, including carbon-emitting fossil generation.

Scenario 7: 50 Percent Wind and 50 Percent Solar Power with 10 MW/80 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered a scenario where the corporate buyer builds or procures battery capacity ten times that assumed in the previous battery cases (10 MW/80MWh rather than 1 MW/8 MWh), along with a renewable supply mix of 50 percent wind and 50 percent solar. Overall, the big box store relied on the local power grid to meet its consumption in 14 percent of the hours in the year, representing 8 percent of the customer's total annual consumption (701 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 92 percent (2,254 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 190 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A11: A big box store in New England supplied with 50 percent wind power and 50 percent solar power with 10 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 8 percent of load is served by the grid; battery is assumed to discharge 10 MW for each of 8 hours (80 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

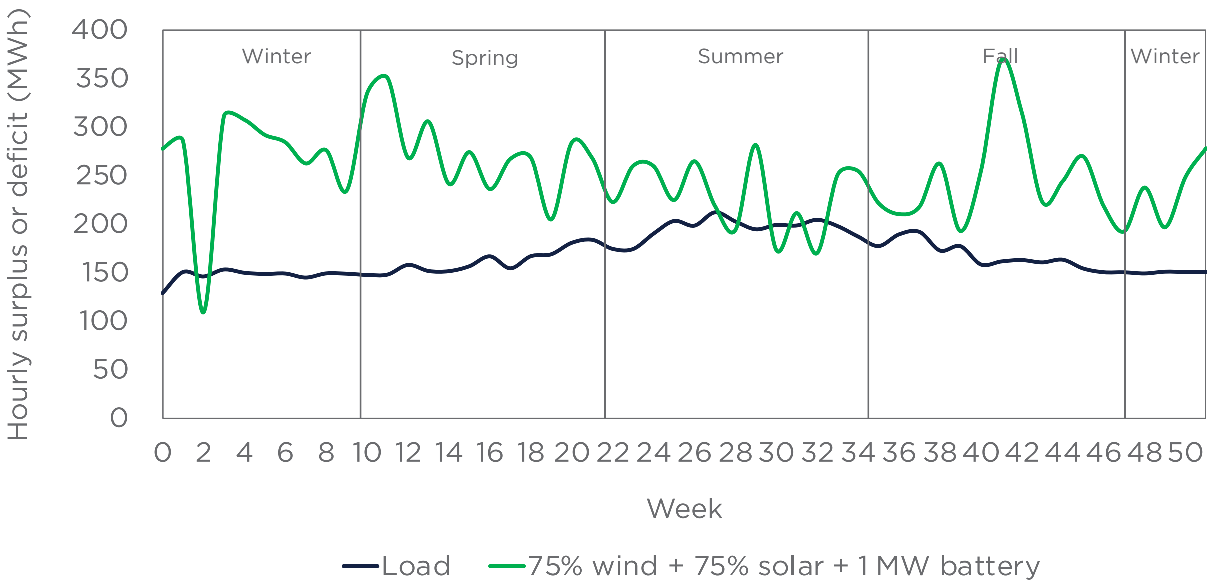
The results show that overbuilding the battery to 10 times that assumed in the previous battery case (10 MW/80 MWh) reduces annual deficits compared with the 1 MW/8 MWh battery scenarios, but that 8 percent of annual customer load would still need to be curtailed to achieve full decarbonization. This remaining deficit occurs because, despite its much larger capacity, this battery cannot supply all remaining customer needs during the long duration deficits in the summer and early fall as shown in Figure A11.

Scenario 8: 75 Percent Wind and 75 Percent Solar Power with 1 MW/8 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered over procuring variable renewable energy supplies that materially exceed 100 percent of annual customer consumption. This scenario assumes the corporate buyer builds or procures variable renewable energy supplies equal to 150 percent of the customer's annual load from renewables (as opposed to the 100 percent levels assumed in the earlier cases), along with 1 MW of battery capacity. In this scenario, the customer is further assumed to procure half the renewable supplies from wind and half from solar (so that the amount of wind equals 75 percent of total customer load, and the amount of solar equals 75 percent of total customer load). As a consequence, 50 percent of the all the energy procured is assumed to be curtailed or wasted.

Overall, in this scenario, the big box store relied on the local power grid to meet its consumption in 10 percent of the hours in the year, representing 4 percent of the customer's total annual consumption (350 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 96 percent (2,336 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 108 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A12: A big box store in New England supplied with 75 percent wind power and 75 percent solar power with 1 MW battery: weekly deficits and surpluses



*Note: Average annual load is 1 MW; 150 percent * annual load = annual VRE; 4 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses; customer builds or procures 150 percent of annual load.*

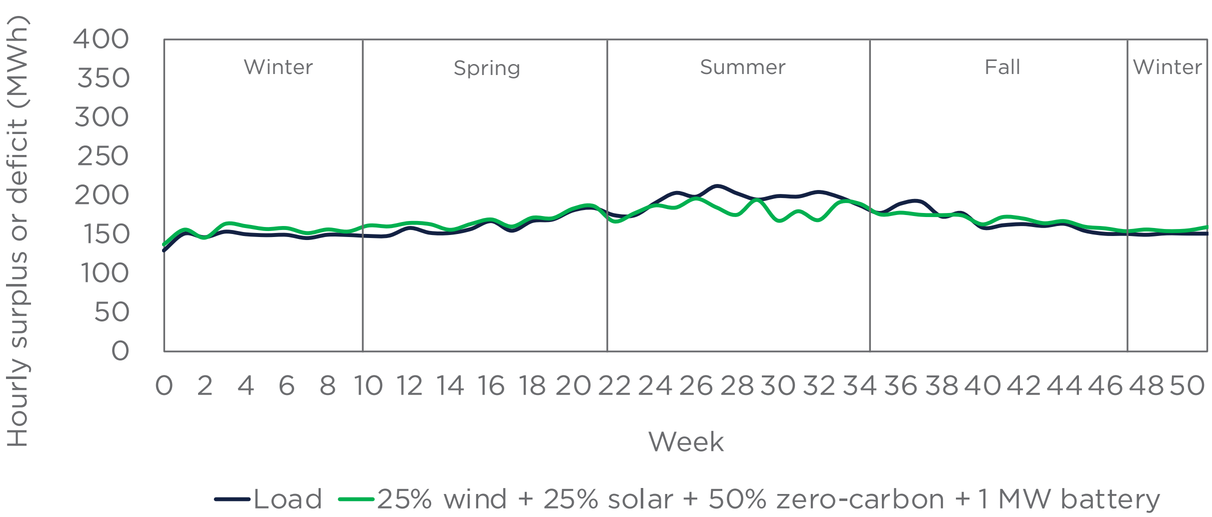
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE wind and solar generation capacity, ABB/ Energy Velocity generating unit capacity database.

Scenario 9: 25 Percent Wind, 25 Percent Solar, and 50 Percent Firm Dispatchable Zero-Carbon Power with 1 MW/8 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered the inclusion of firm dispatchable zero-carbon generation technologies such as nuclear, fossil with carbon capture and sequestration systems, hydroelectric or advanced geothermal power, and long-duration energy storage technologies such as thermal energy storage or zero-carbon liquid fuels, which can be used later to generate electricity in combustion turbines. For example, a supply mix that includes 50 percent firm dispatchable zero-carbon generation along with 25 percent wind, 25 percent solar and a 1 MW battery can largely eliminate mismatches on an hourly basis between supply and demand over the course of a year.

Overall, the big box store relied on the local power grid to meet its consumption in 12 percent of the hours in the year, representing 3 percent of the customer's total annual consumption (263 out of 8,760 MWh). In this scenario, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 97 percent (2,381 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, the customer is still responsible for 63 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A13: A big box store in New England supplied with 25 percent wind power, 25 percent solar power, and 50 percent firm dispatchable zero-carbon power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 3 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

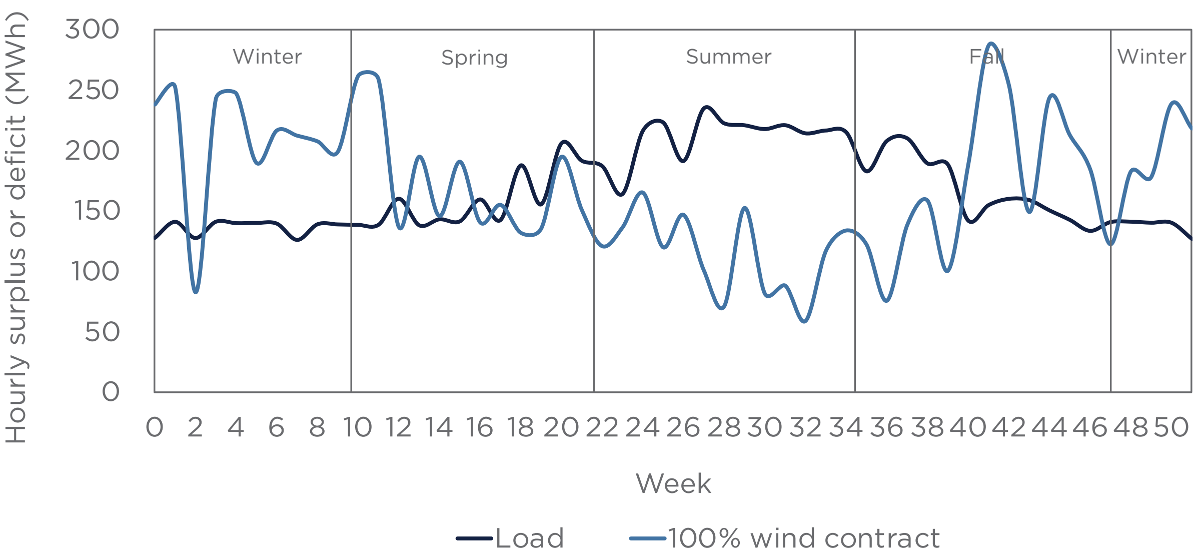
The availability of firm dispatchable zero-carbon generation in this example allows total generation to closely match customer loads regardless of the amount of variable renewable energy generation produced in any given week. Further shifting the supply mix toward firm dispatchable low-carbon generation or energy storage would allow the periods of deficit/curtailment to be fully eliminated.

Analysis of Selected Supply Portfolio Scenarios (1, 2, 6, and 9) for an Office Building in New England

Scenario 1: 100 Percent Wind Power

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures 100 percent onshore wind generation resources to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 47 percent of the hours in the year, representing 40 percent of the customer's total annual consumption (3,469 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 60 percent (1,476 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 968 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A14: An office building in New England supplied with 100 percent onshore wind power: weekly deficits and surpluses



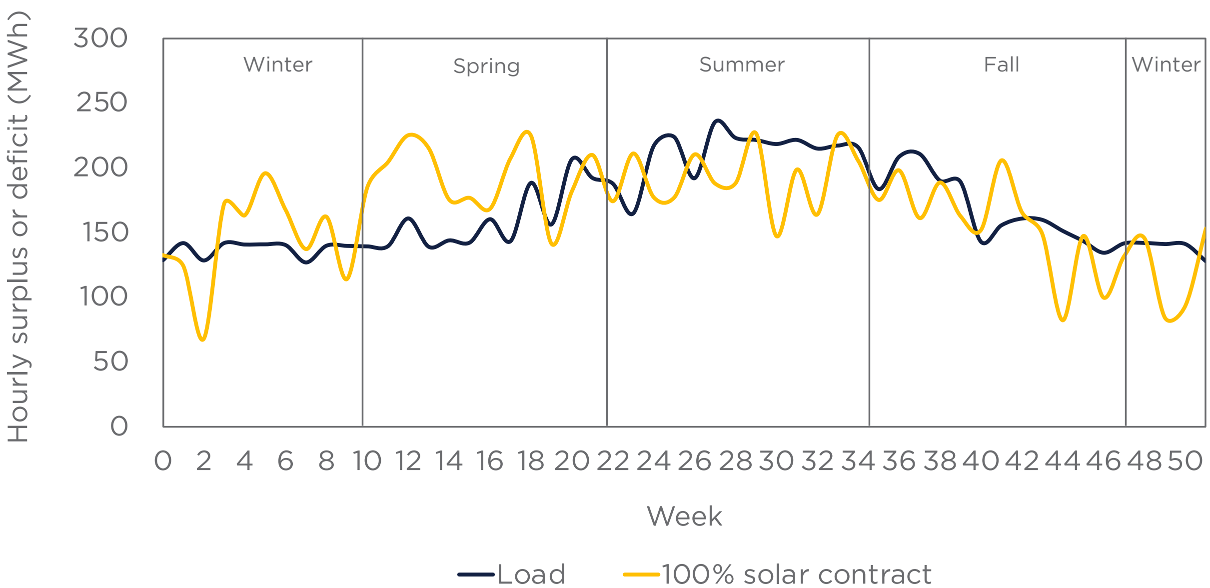
Note: Average annual load is 1 MW; annual load = annual VRE; 40 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; ISO-NE wind generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 2: 100 Percent Solar Power

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures 100 percent solar generation resources to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 73 percent of the hours in the year, representing 48 percent of the customer's total annual consumption (4,163 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 52 percent (1,282 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 1,162 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A15: An office building in New England supplied with 100 percent solar power: weekly deficits and surpluses



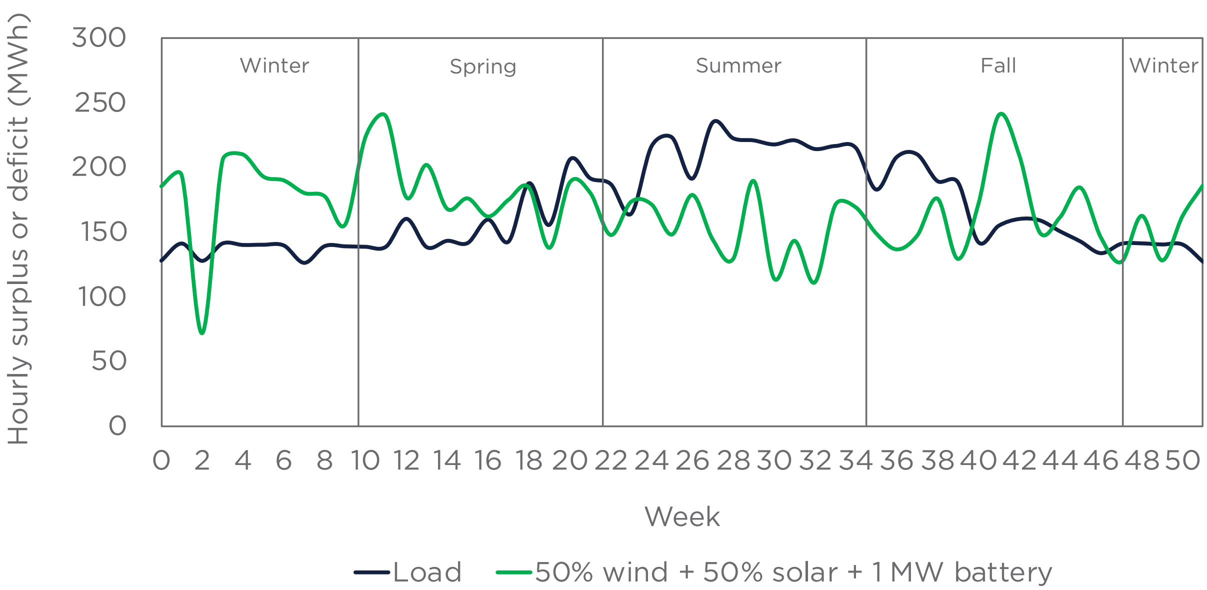
Note: Average annual load is 1 MW; annual load = annual VRE; 48 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 6: 50 Percent Wind and 50 Percent Solar Power with 1 MW/8 MWh Battery

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures a mixed supply portfolio (i.e., 50 percent wind and 50 percent solar) with a 1 MW battery to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 27 percent of the hours in the year, representing 17 percent of the customer's total annual consumption (1,520 out of 8,760 MWh). Due to the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 83 percent (2,020 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 424 tons of CO_2 emissions due to its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A16: An office building in New England supplied with 50 percent wind power and 50 percent solar power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 17 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

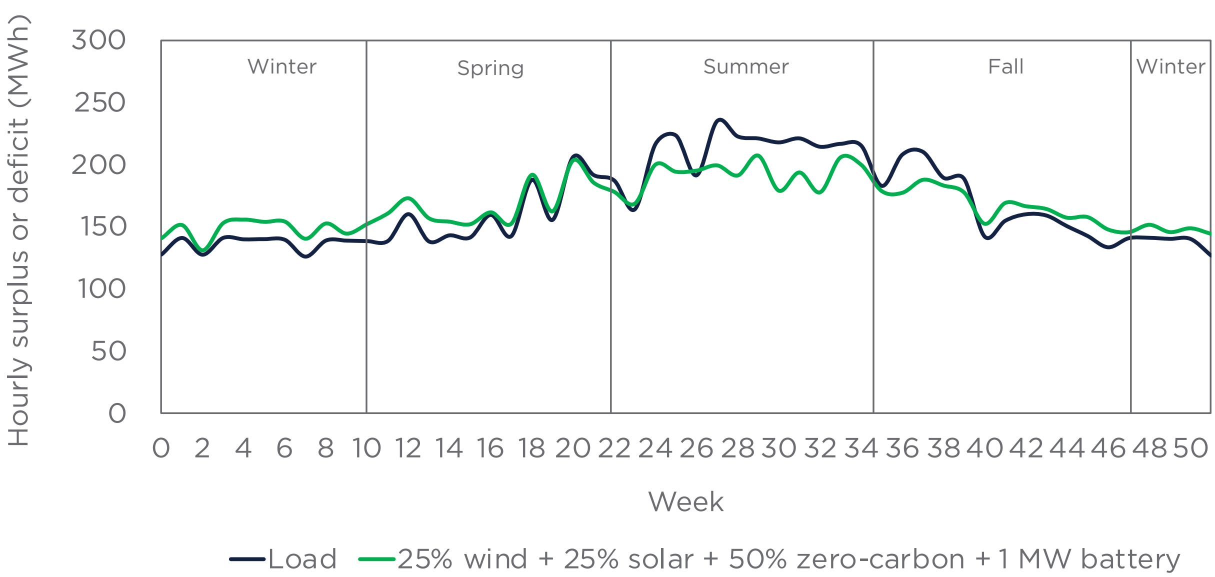
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 9: 25 Percent Wind, 25 Percent Solar, and 50 Percent Firm Dispatchable Zero-Carbon Power with 1 MW/8 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered the inclusion of firm dispatchable zero-carbon generation technologies. For example, a supply mix that includes 50 percent firm dispatchable zero-carbon generation along with 25 percent wind, 25 percent solar, and a 1 MW battery can largely eliminate mismatches on an hourly basis between supply and demand over the course of a year.

Overall, the Office Building relied on the local power grid to meet its consumption in 16 percent of the hours in the year, representing 5 percent of the customer's total annual consumption (420 out of 8,760 MWh). In this scenario, the Office Building reduced its CO_2 emissions associated with its electricity supply by an estimated 95 percent (2,327 tons) relative to the 2,444 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, the customer is still responsible for 117 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A17: An office building in New England supplied with 25 percent wind power, 25 percent solar power, and 50 percent firm dispatchable zero-carbon power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 5 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ISO-NE 2018 hourly wind output, https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ISO-NE wind and solar generation capacity, ABB/ Energy Velocity generating unit capacity database.

The availability of firm dispatchable zero-carbon generation in this example allows total generation to closely match customer loads regardless of the amount of variable renewable energy generation produced in any given week. Further shifting the supply mix toward firm dispatchable low-carbon generation or energy storage would allow the periods of deficit/curtailment to be fully eliminated.

Texas (ERCOT)

Inputs and Summary Results for Texas

Supply Profile Inputs

The authors assumed that the contracted wind and/or solar resources generated 8,760 MWh of renewable supply on an annual basis (unless otherwise specified), in accordance with the appropriate hourly generating profile for that type of resource in Texas. The data underlying the analysis was drawn from several sources. The wind generation profiles are based on actual hourly 2018 wind output from ERCOT. The solar generation profiles are based on expected hourly solar output from NREL's locational hourly solar estimator.[74]

Based on current onshore wind technology and wind patterns in Texas, a representative onshore wind power facility has a 37 percent annual capacity factor. To generate 8,760 MWh of renewable supply on an annual basis (to satisfy a 100 percent RE target for a representative customer having a 1 MW average hourly load over the year), the contracted peak wind capacity would need to be about 2.7 MW. By comparison, based on current solar technology and solar patterns in Texas, solar power has a 19 percent annual capacity factor. To generate 8,760 MWh of renewable supply on an annual basis (to satisfy a 100 percent RE target for a representative customer having a 1 MW average hourly load over the year), the contracted solar capacity would need to be about 5.2 MW.

Table A4: Generation capacity factor %

Texas (ERCOT)	Annual	Winter	Spring	Summer	Fall
Onshore Wind[75]	36.7%	38.0%	43.0%	35.3%	30.3%
Solar	19.1%	13.1%	21.5%	23.6%	18.0%
Firm Dispatchable Zero Carbon[76]	77.9%	69.6%	69.4%	87.5%	84.9%

Given that both the wind and/or solar capacity required to meet a 100 percent RE target greatly exceeds the average hourly demand of the customer, it is reasonable to expect that in hours when these facilities are generating energy at or near their capacity, significant surpluses of energy will occur, and in hours when these intermittent resources do not generate electricity, significant deficits will be likely.

Customer Load Profile Inputs

For each scenario, the authors assumed the representative customers had a 1 MW average hourly load over the year and so consumed 8,760 MWh of energy over the year, in accordance with the hourly load pattern for that type of customer in Texas. The customer load profiles are based on hourly DOE representative load profiles for a big box store, represented by a supermarket load profile, and a corporate Office Building, represented by a large office load profile.

Based on customer characteristics and weather patterns in Texas, a representative big box store customer has a 55 percent annual load factor. To consume 8,760 MWh on an annual basis (i.e., a representative customer having a 1 MW average hourly load over the year), the big box store would have a peak demand of approximately 1.8 MW. By comparison, a representative Office Building customer has a 51 percent annual load factor. To consume 8,760 MWh on an annual basis, the Office Building would have a peak demand of approximately 2.0 MW.

Table A5: Customer load factor %

Texas (ERCOT)	Annual	Winter	Spring	Summer	Fall
Big Box Store	54.7%	46.2%	53.8%	63.6%	55.1%
Office Building	50.5%	43.6%	50.8%	56.7%	50.6%

Summary of Results

Table A6 summarizes for each supply portfolio and customer type the results of the authors' analysis for the Texas region in terms of the percent of annual customer load taken from the local electric grid, the percent of hours that the customer relies on the local electric grid, and an estimate of the associated tons of carbon emissions from electric grid power used to serve that customer.

Table A6: Summary of results—Texas (ERCOT)

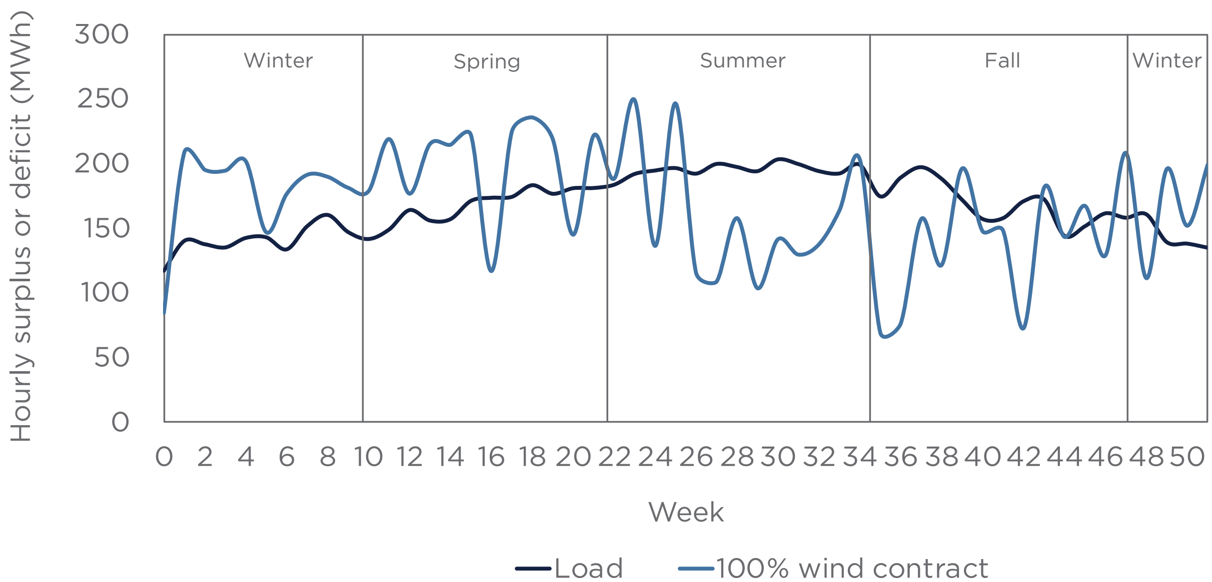
Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power[77] (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
1. 100% Wind	31%	36%	50%	50%	1,373	1,601
2. 100% Solar	46%	43%	66%	67%	2,045	1,921
3. 50% Wind and 50% Solar	20%	24%	51%	47%	906	1,054
4. 100% Wind with 1 MW/8 MWh Battery	19%	21%	28%	29%	834	921
5. 100% Solar with 1 MW/8 MWh Battery	21%	21%	38%	35%	914	915
6. 50% Wind and 50% Solar with 1 MW/8 MWh Battery	10%	13%	23%	24%	448	559
7. 50% Wind and 50% Solar with 10 MW/80 MWh Battery	5%	5%	12%	12%	234	218
8. 75% Wind and 75% Solar with 1 MW/8 MWh Battery	1%	2%	4%	7%	57	105
9. 25% Wind, 25% Solar, and 50% Firm Dispatchable Zero-Carbon Generation with 1 MW/8 MWh Battery	1%	3%	9%	16%	57	146
10. 100% Grid	100%	100%	100%	100%	4,419	4,419

Analysis of Selected Supply Portfolio Scenarios (1, 2, 6, and 9) for a Big Box Store in Texas

Scenario 1: 100 Percent Wind Power

The figure below shows the weekly deficits and surpluses for the case of a big box store that procures 100 percent onshore wind generation resources to meet its RE100 target. Overall, the big box store relied on the local power grid to meet its consumption in 50 percent of the hours in the year, representing 31 percent of the customer's total annual consumption (2,721 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its carbon dioxide emissions associated with its electricity supply by an estimated 69 percent (3,046 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 1,373 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A18: A big box store in Texas supplied with 100 percent onshore wind power: weekly deficits and surpluses



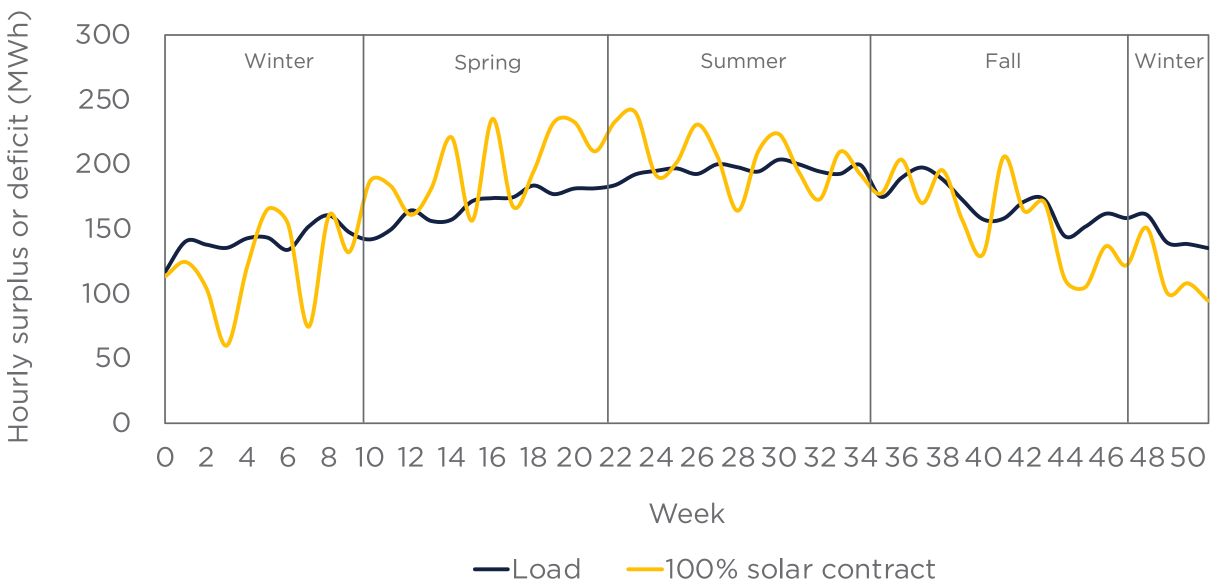
Note: Average annual load is 1 MW; annual load = annual VRE; 31 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ERCOT 2018 hourly wind output, http://www.ercot.com/gridinfo/generation; ERCOT wind generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 2: 100 Percent Solar Power

The figure below shows the weekly deficits and surpluses for the case of a commercial big box store that procures 100 percent solar generation resources to meet its RE100 target. Overall, the big box store relied on the local power grid to meet its consumption in 66 percent of the hours in the year, representing 46 percent of the customer's total annual consumption (4,054 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its carbon dioxide emissions associated with its electricity supply by an estimated 54 percent (2,374 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 2,045 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A19: A big box store in Texas supplied with 100 percent solar power: weekly deficits and surpluses



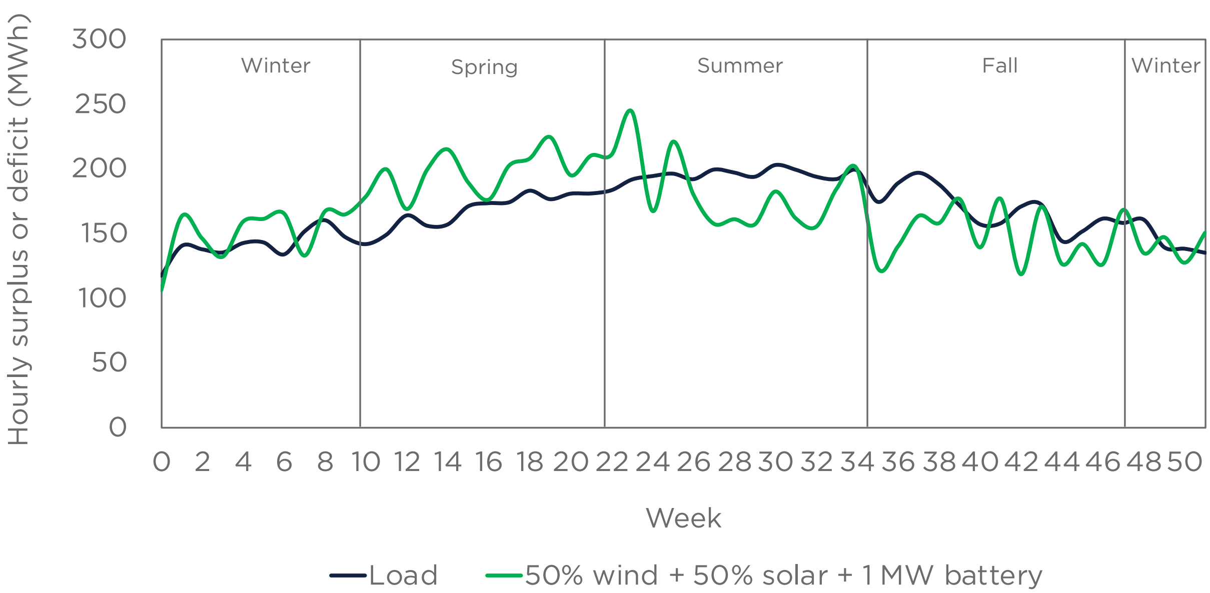
Note: Average annual load is 1 MW; annual load = annual VRE; 46 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ERCOT solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 6: 50 Percent Wind and 50 Percent Solar Power with 1 MW/8 MWh Battery

The figure below shows the weekly deficits and surpluses for the case of a big box store that procures a mixed supply portfolio (i.e., 50 percent wind and 50 percent solar) with a 1 MW battery to meet its RE100 target. Overall, the big box store relied on the local power grid to meet its consumption in 23 percent of the hours in the year, representing 10 percent of the customer's total annual consumption (888 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its carbon dioxide emissions associated with its electricity supply by an estimated 90 percent (3,971 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 448 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A20: A big box store in Texas supplied with 50 percent wind power and 50 percent solar power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 10 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

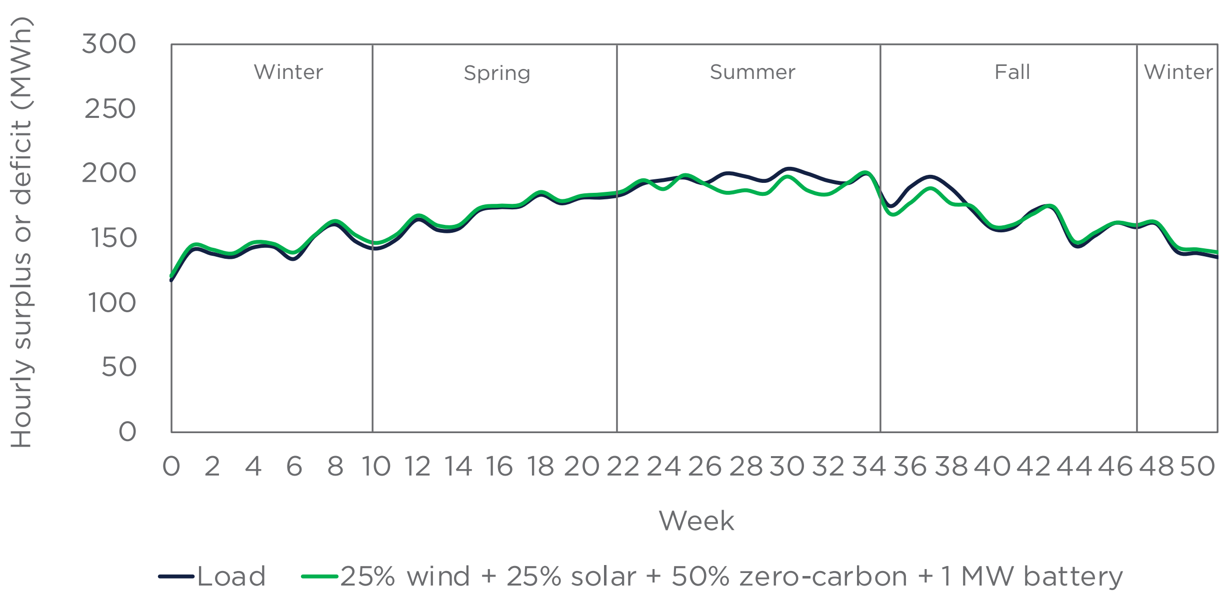
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ERCOT 2018 hourly wind output, http://www.ercot.com/gridinfo/generation; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ERCOT wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 9: 25 Percent Wind, 25 Percent Solar, and 50 Percent Firm Dispatchable Zero-Carbon Power with 1 MW/8 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered the inclusion of firm dispatchable zero-carbon generation technologies. For example, a supply mix that includes 50 percent firm dispatchable zero-carbon generation along with 25 percent wind, 25 percent solar, and a 1 MW battery can largely eliminate mismatches on an hourly basis between supply and demand over the course of a year.

Overall, the big box store relied on the local power grid to meet its consumption in 9 percent of the hours in the year, representing 1 percent of the customer's total annual consumption (112 out of 8,760 MWh). In this scenario, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 99 percent (4,362 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, the customer is still responsible for 57 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A21: A big box store in Texas supplied with 25 percent wind power, 25 percent solar power, and 50 percent firm dispatchable zero-carbon power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 1 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ERCOT 2018 hourly wind output, http://www.ercot.com/gridinfo/generation; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ERCOT wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

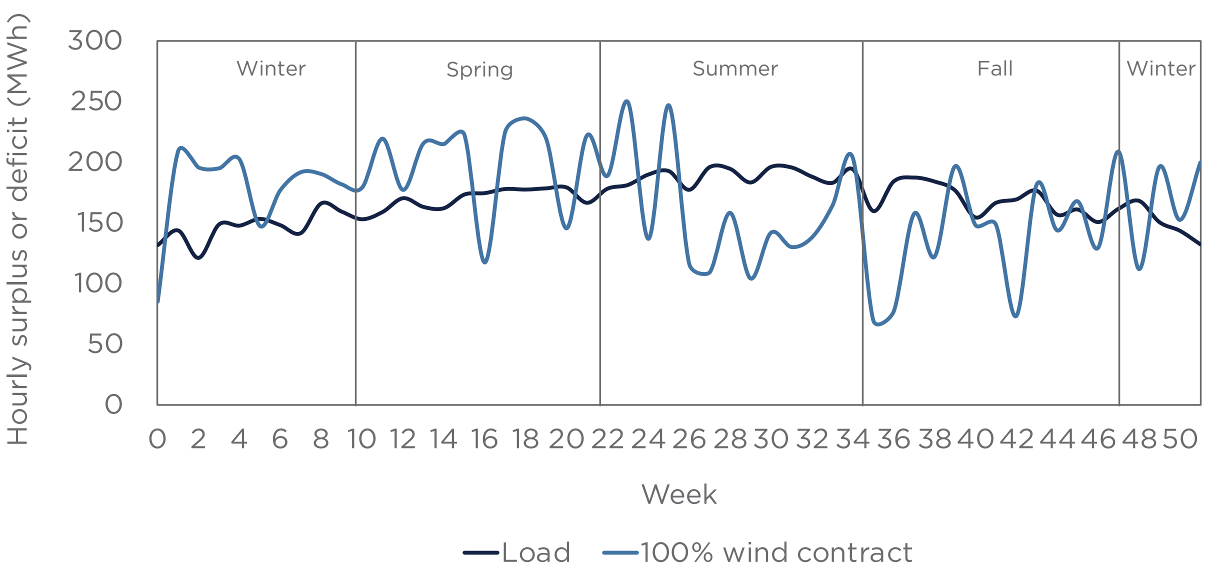
The availability of firm dispatchable zero-carbon generation in this example allows total generation to closely match customer loads regardless of the amount of variable renewable energy generation produced in any given week. Further shifting the supply mix toward firm dispatchable low-carbon generation or energy storage would allow the periods of deficit/ curtailment to be fully eliminated.

Analysis of Selected Supply Portfolio Scenarios (1, 2, 6, and 9) for an Office Building in Texas

Scenario 1: 100 Percent Wind Power

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures 100 percent onshore wind generation resources to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 50 percent of the hours in the year, representing 36 percent of the customer's total annual consumption (3,174 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 64 percent (2,818 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 1,601 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A22: An office building in Texas supplied with 100 percent onshore wind power: weekly deficits and surpluses



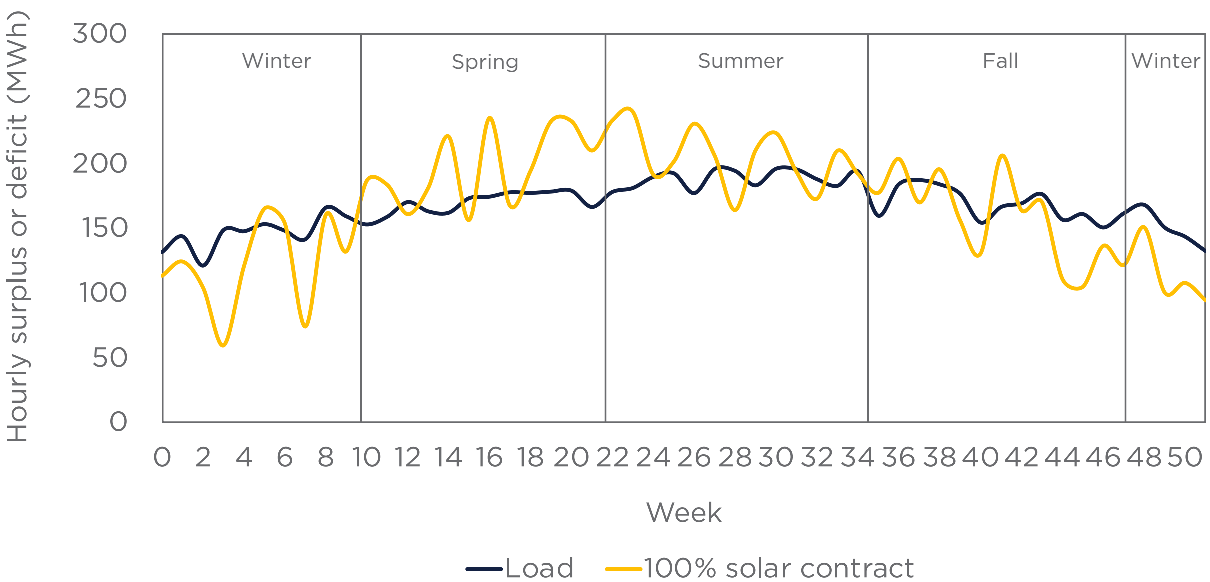
Note: Average annual load is 1 MW; annual load = annual VRE; 36 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ERCOT 2018 hourly wind output, http://www.ercot.com/gridinfo/generation; ERCOT wind generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 2: 100 Percent Solar Power

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures 100 percent solar generation resources to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 67 percent of the hours in the year, representing 43 percent of the customer's total annual consumption (3,808 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 57 percent (2,498 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 1,921 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A23: An office building in Texas supplied with 100 percent solar power: weekly deficits and surpluses



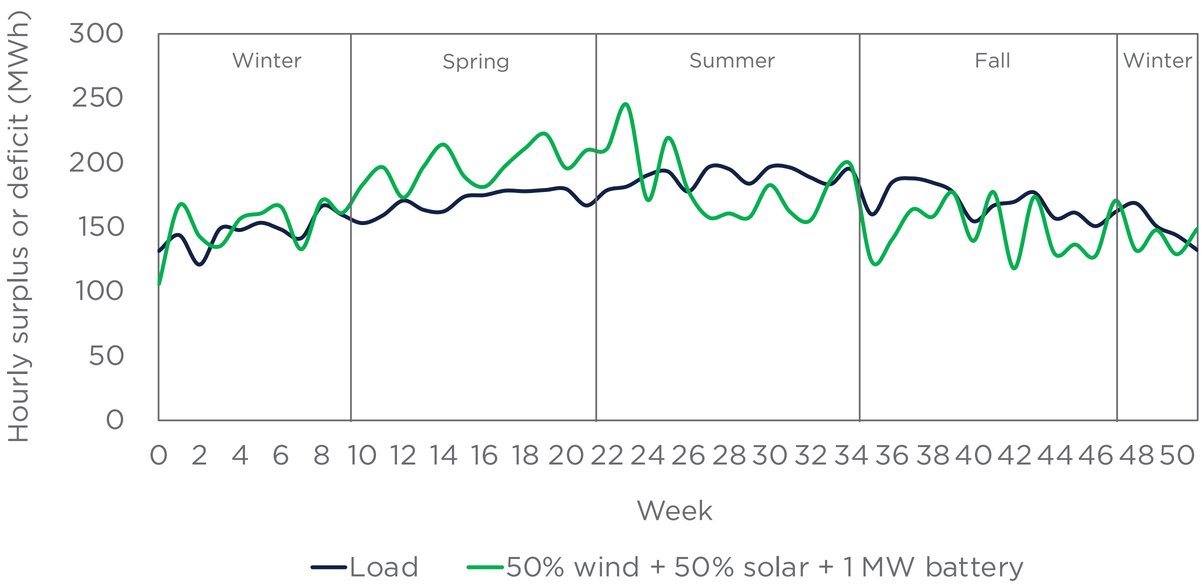
Note: Average annual load is 1 MW; annual load = annual VRE; 43 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ERCOT solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 6: 50 Percent Wind and 50 Percent Solar Power with 1 MW/8 MWh Battery

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures a mixed supply portfolio (i.e., 50 percent wind and 50 percent solar) with a 1 MW battery to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 24 percent of the hours in the year, representing 13 percent of the customer's total annual consumption (1,109 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 87 percent (3,860 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 559 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A24: An office building in Texas supplied with 50 percent wind power and 50 percent solar power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 13 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

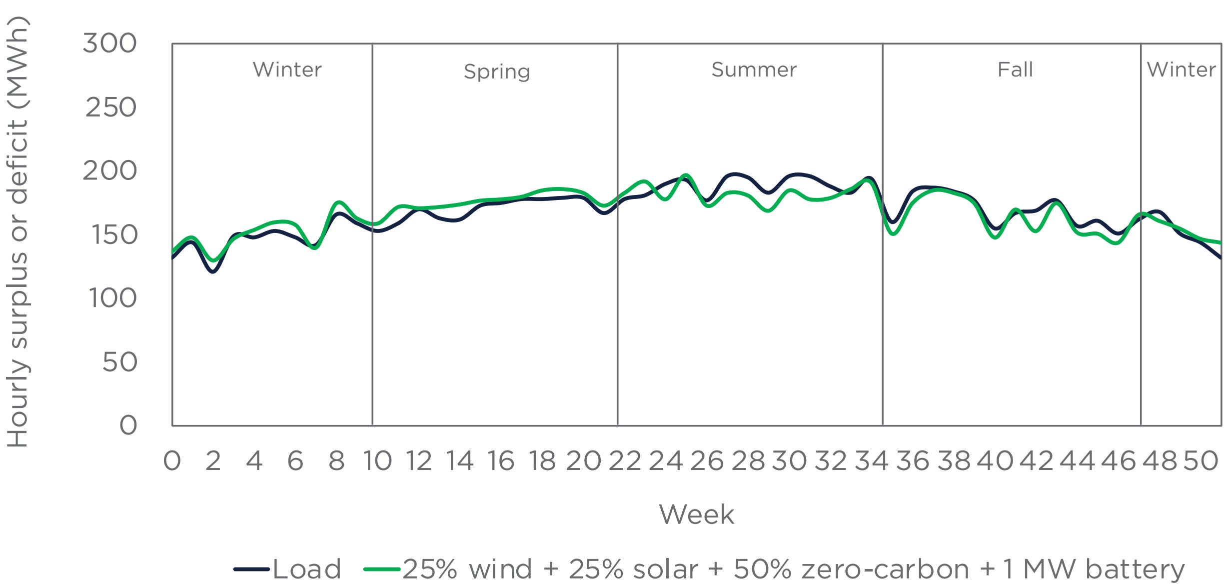
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ERCOT 2018 hourly wind output, http://www.ercot.com/gridinfo/generation; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ERCOT wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 9: 25 Percent Wind, 25 Percent Solar, and 50 Percent Firm Dispatchable Zero-Carbon Power with 1 MW/8 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered the inclusion of firm dispatchable zero-carbon generation technologies. For example, a supply mix that includes 50 percent firm dispatchable zero-carbon generation along with 25 percent wind, 25 percent solar, and a 1 MW battery can largely eliminate mismatches on an hourly basis between supply and demand over the course of a year.

Overall, the office building relied on the local power grid to meet its consumption in 16 percent of the hours in the year, representing 3 percent of the customer's total annual consumption (290 out of 8,760 MWh). In this scenario, the Office Building reduced its CO_2 emissions associated with its electricity supply by an estimated 97 percent (4,273 tons) relative to the 4,419 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, the customer is still responsible for 146 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A25: An office building in Texas supplied with 25 percent wind power, 25 percent solar power, and 50 percent firm dispatchable zero-carbon power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 3 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; ERCOT 2018 hourly wind output, http://www.ercot.com/gridinfo/generation; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; ERCOT wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

The availability of firm dispatchable zero-carbon generation in this example allows total generation to closely match customer loads regardless of the amount of variable renewable energy generation produced in any given week. Further shifting the supply mix toward firm dispatchable low-carbon generation or energy storage would allow the periods of deficit/curtailment to be fully eliminated.

California (CAISO)

Inputs and Summary Results for California

Supply Profile Inputs

The authors assumed that the contracted wind and/or solar resources generated 8,760 MWh of renewable supply on an annual basis (unless otherwise specified), in accordance with the appropriate hourly generating profile for that type of resource in California. The wind and solar generation profiles for California are based on actual 2018 output data from CAISO.[78]

Based on current onshore wind technology and wind patterns in California, a representative onshore wind power facility has a 29 percent annual capacity factor. To generate 8,760 MWh of renewable supply on an annual basis (to satisfy a 100 percent RE target for a representative customers having a 1 MW average hourly load over the year), the contracted peak wind capacity would need to be about 3.4 MW. By comparison, based on current solar technology and solar patterns in California, solar power has a 26 percent annual capacity factor. To generate 8,760 MWh of renewable supply on an annual basis (to satisfy a 100 percent RE target for a representative customer having a 1 MW average hourly load over the year), the contracted solar capacity would need to be about 3.8 MW.

Table A7: Generation capacity factor %

California (CAISO)	Annual[79]	Winter	Spring	Summer	Fall
Onshore Wind	29.1%	18.5%	36.2%	38.6%	22.7%
Solar	25.9%	17.4%	28.7%	33.4%	24.0%
Firm Dispatchable Zero Carbon[80]	74.2%	83.7%	64.8%	64.0%	84.6%

Given that both the wind and/or solar capacity required to meet a 100 percent RE target greatly exceeds the average hourly demand of the customer, it is reasonable to expect that in hours when these facilities are generating energy at or near their capacity, significant surpluses of energy will occur, and in hours when these intermittent resources do not generate electricity, significant deficits will be likely.

Customer Load Profile Inputs

For each scenario, the authors assumed the representative customers had a 1 MW average hourly load over the year and so consumed 8,760 MWh of energy over the year, in accordance with the hourly load pattern for that type of customer in California. The customer load profiles are based on hourly DOE representative load profiles for a big box store, represented by a supermarket load profile, and a corporate Office Building, represented by a large office load profile.

Based on customer characteristics and weather patterns in California, a representative big box store customer has a 60 percent annual load factor. To consume 8,760 MWh on an annual basis (i.e., a representative customer having a 1 MW average hourly load over the year), the big box store would have a peak demand of approximately 1.7 MW. By comparison, a representative Office Building customer has a 45 percent annual load factor. To consume 8,760 MWh on an annual basis, the Office Building would have a peak demand of approximately 2.2 MW.

Table A8: Customer load factor %

California (CAISO)	Annual	Winter	Spring	Summer	Fall
Big Box Store	54.7%	46.2%	53.8%	63.6%	55.1%
Office Building	50.5%	43.6%	50.8%	56.7%	50.6%

Summary of Results

Table A9 summarizes for each supply portfolio and customer type the results of the authors' analysis for the California region in terms of the percent of annual customer load taken from the local electric grid, the percent of hours that the customer relies on the local electric grid, and an estimate of the associated tons of carbon emissions from electric grid power used to serve that customer.

Table A9: Summary of results—California (CAISO)

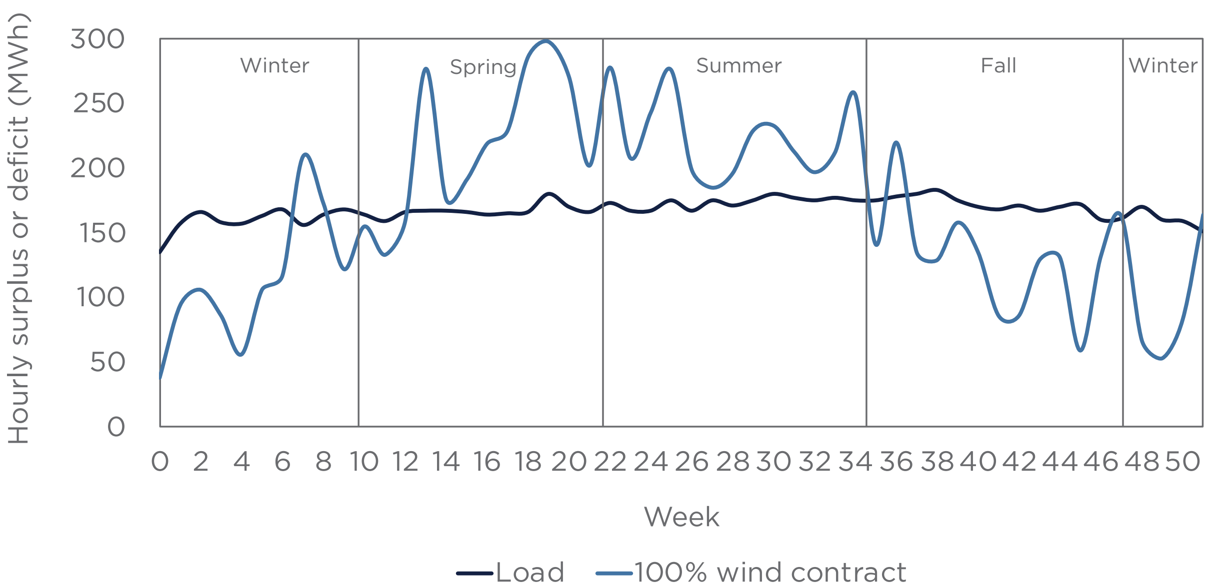
Supply Portfolio	% of Annual Customer Load Taken from the Electric Grid		% of Hours That Customer Relies on the Electric Grid		Carbon Emissions from Electric Grid Power[81] (tons of CO_2/year)	
	Big Box Store	Office Building	Big Box Store	Office Building	Big Box Store	Office Building
1. 100% Wind	34%	40%	52%	51%	785	918
2. 100% Solar	44%	38%	62%	64%	1,009	869
3. 50% Wind and 50% Solar	20%	23%	48%	52%	466	524
4. 100% Wind with 1 MW/8 MWh Battery	23%	26%	35%	38%	522	592
5. 100% Solar with 1 MW/8 MWh Battery	16%	15%	33%	30%	361	348
6. 50% Wind and 50% Solar with 1 MW/8 MWh Battery	14%	15%	28%	30%	324	358
7. 50% Wind and 50% Solar with 10 MW/80 MWh Battery	11%	10%	23%	20%	266	225
8. 75% Wind and 75% Solar with 1 MW/8 MWh Battery	5%	5%	12%	12%	121	124
9. 25% Wind, 25% Solar, and 50% Firm Dispatchable Zero-Carbon Generation with 1 MW/8 MWh Battery	1%	4%	6%	18%	17	81
10. 100% Grid	100%	100%	100%	100%	2,313	2,313

Analysis of Selected Supply Portfolio Scenarios (1, 2, 6, and 9) for a Big Box Store in California

Scenario 1: 100 Percent Wind Power

The figure below shows the weekly deficits and surpluses for the case of a big box store that procures 100 percent onshore wind generation resources to meet its RE100 target. Overall, the big box store relied on the local power grid to meet its consumption in 52 percent of the hours in the year, representing 34 percent of the customer's total annual consumption (2,973 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its carbon dioxide emissions associated with its electricity supply by an estimated 66 percent (1,528 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 785 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A26: A big box store in California supplied with 100 percent onshore wind power: weekly deficits and surpluses



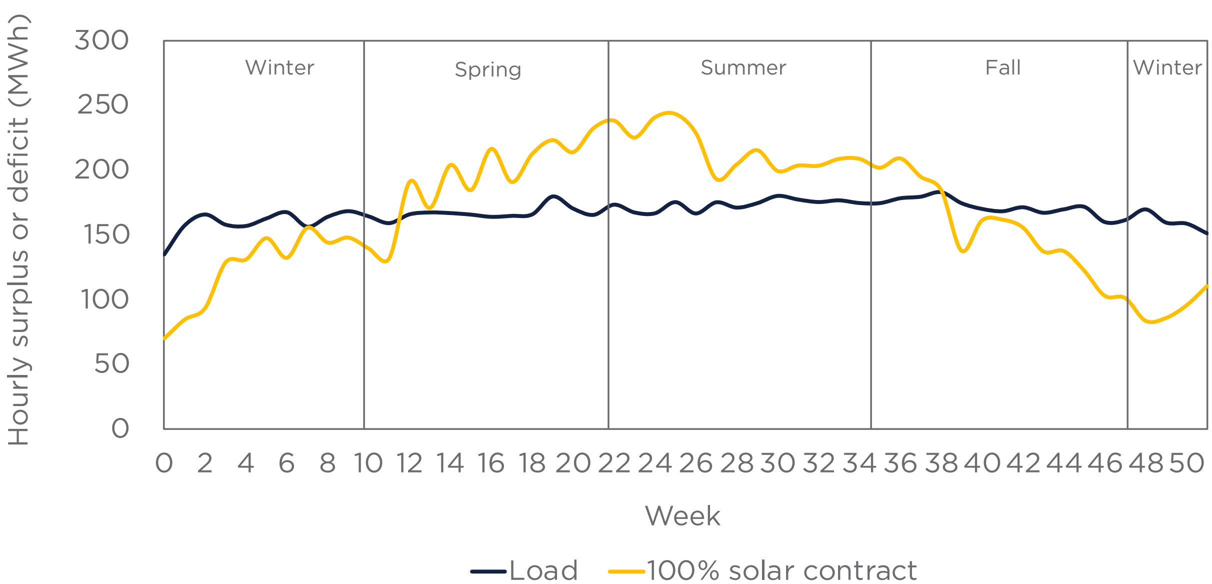
Note: Average annual load is 1 MW; annual load = annual VRE; 34 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; CAISO wind generation, ABB/Energy Velocity renewable generation by fuel type; CAISO wind generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 2: 100 Percent Solar Power

The figure below shows the weekly deficits and surpluses for the case of a commercial big box store that procures 100 percent solar generation resources to meet its RE100 target. Overall, the big box store relied on the local power grid to meet its consumption in 62 percent of the hours in the year, representing 44 percent of the customer's total annual consumption (3,822 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its carbon dioxide emissions associated with its electricity supply by an estimated 56 percent (1,304 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 1,009 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A27: A big box store in California supplied with 100 percent solar power: weekly deficits and surpluses



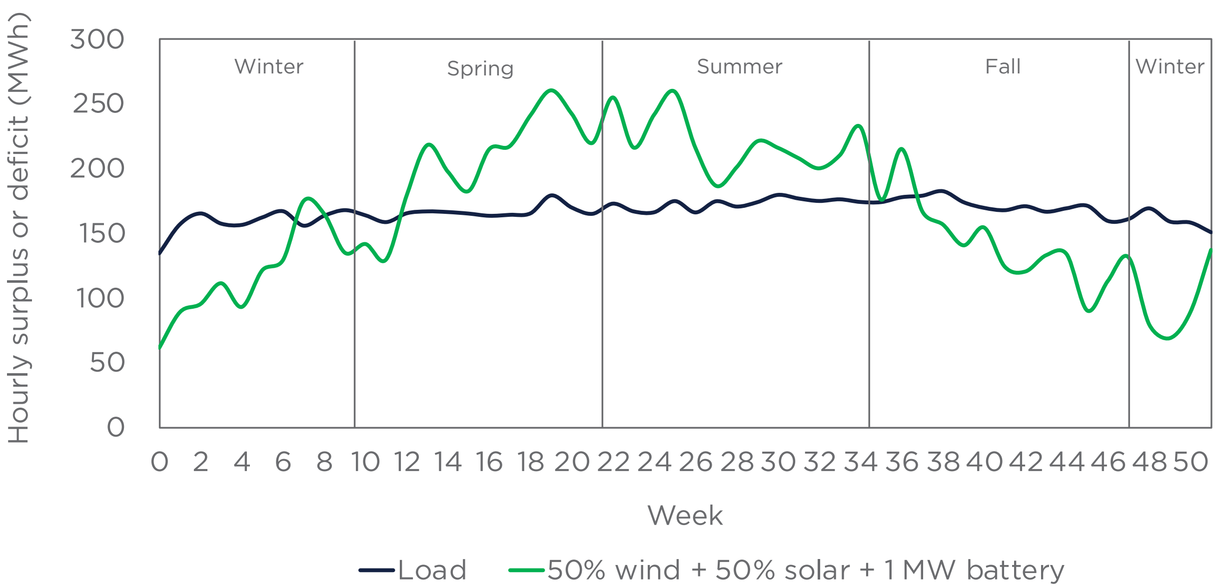
Note: Average annual load is 1 MW; annual load = annual VRE; 44 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; CAISO solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 6: 50 Percent Wind and 50 Percent Solar Power with 1 MW/8 MWh Battery

The figure below shows the weekly deficits and surpluses for the case of a big box store that procures a mixed supply portfolio (i.e., 50 percent wind and 50 percent solar) with a 1 MW battery to meet its RE100 target. Overall, the big box store relied on the local power grid to meet its consumption in 28 percent of the hours in the year, representing 14 percent of the customer's total annual consumption (1,228 out of 8,760 MWh). Because of the customer's RE100 procurement, the big box store reduced its carbon dioxide emissions associated with its electricity supply by an estimated 86 percent (1,989 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 324 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A28: A big box store in California supplied with 50 percent wind power and 50 percent solar power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 14 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

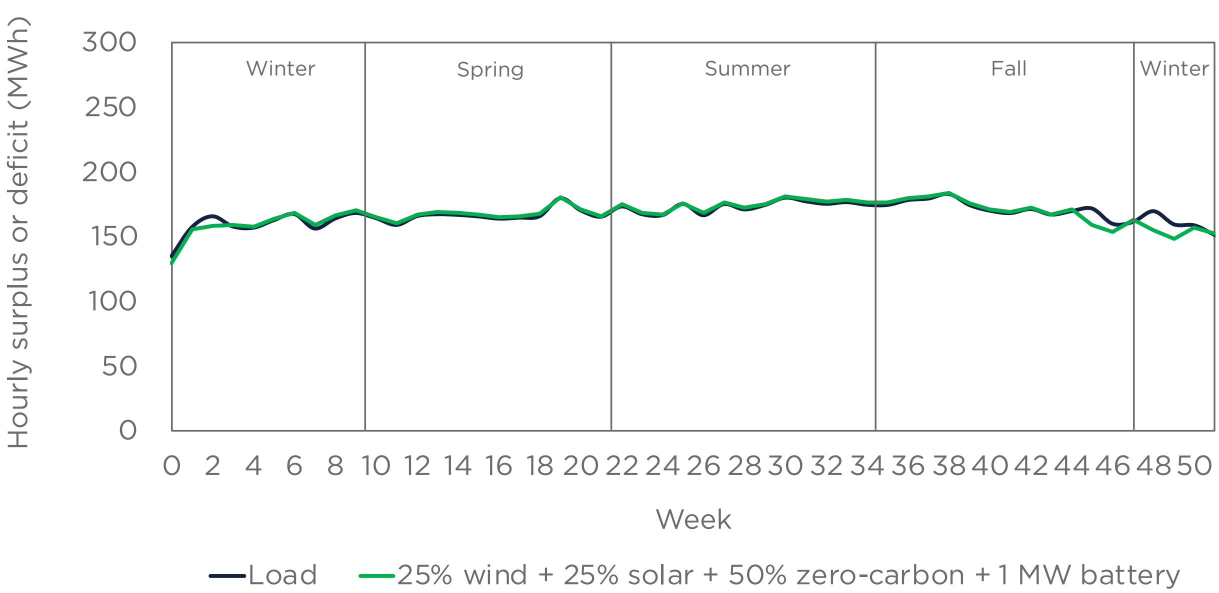
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; CAISO wind generation, ABB/Energy Velocity renewable generation by fuel type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; CAISO wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 9: 25 Percent Wind, 25 Percent Solar, and 50 Percent Firm Dispatchable Zero-Carbon Power with 1 MW/8 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered the inclusion of firm dispatchable zero-carbon generation technologies. For example, a supply mix that includes 50 percent firm dispatchable zero-carbon generation along with 25 percent wind, 25 percent solar, and a 1 MW battery can largely eliminate mismatches on an hourly basis between supply and demand over the course of a year.

Overall, the big box store relied on the local power grid to meet its consumption in 6 percent of the hours in the year, representing 1 percent of the customer's total annual consumption (63 out of 8,760 MWh). In this scenario, the big box store reduced its CO_2 emissions associated with its electricity supply by an estimated 99 percent (2,296 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, the customer is still responsible for 17 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A29: A big box store in California supplied with 25 percent wind power, 25 percent solar power, and 50 percent firm dispatchable zero-carbon power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 1 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; CAISO wind generation, ABB/Energy Velocity renewable generation by fuel type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; CAISO wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

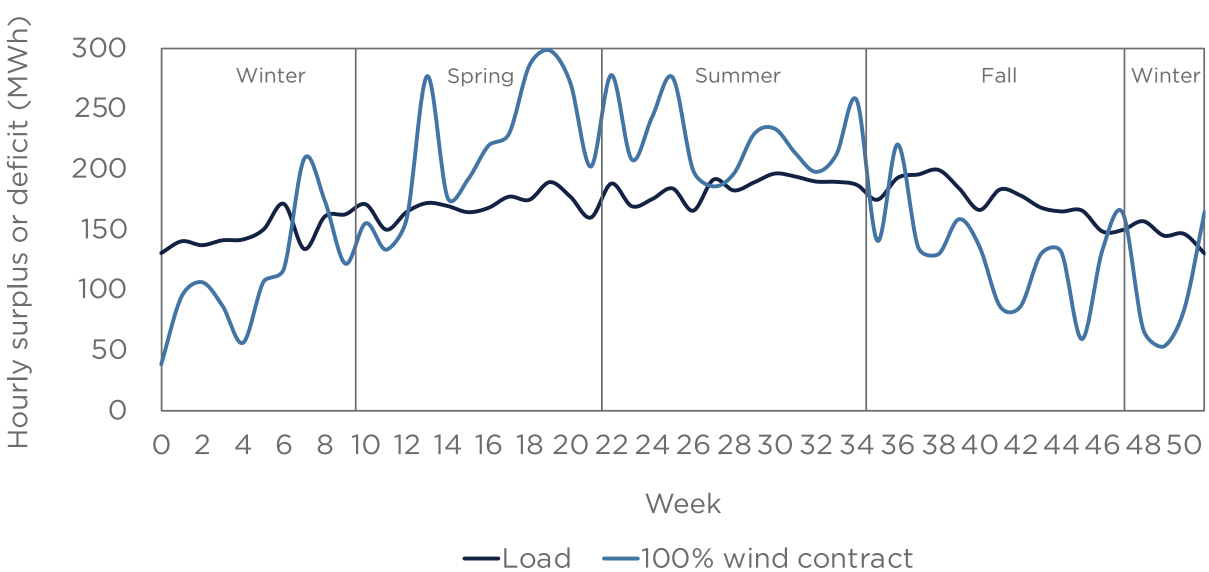
The availability of firm dispatchable zero-carbon generation in this example allows total generation to closely match customer loads regardless of the amount of variable renewable energy generation produced in any given week. Further shifting the supply mix toward firm dispatchable low-carbon generation or energy storage would allow the periods of deficit/curtailment to be fully eliminated.

Analysis of Selected Supply Portfolio Scenarios (1, 2, 6, and 9) for an Office Building in California

Scenario 1: 100 Percent Wind Power

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures 100 percent onshore wind generation resources to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 51 percent of the hours in the year, representing 40 percent of the customer's total annual consumption (3,479 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 60 percent (1,395 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 918 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A30: An office building in California supplied with 100 percent onshore wind power: weekly deficits and surpluses



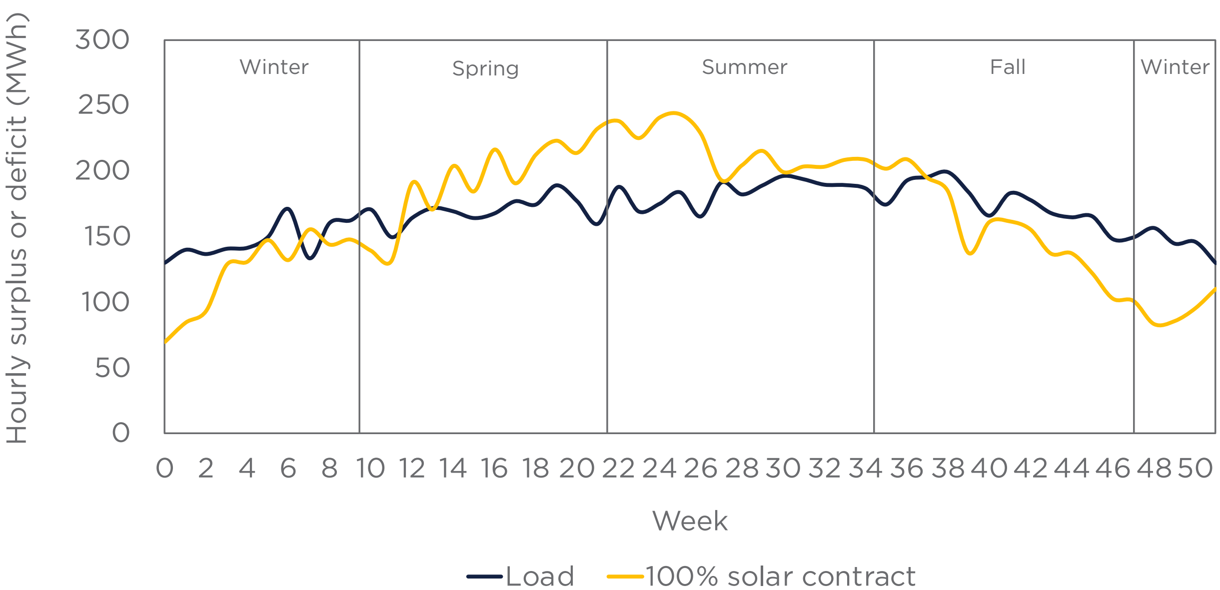
Note: Average annual load is 1 MW; annual load = annual VRE; 40 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; CAISO wind generation, ABB/Energy Velocity renewable generation by fuel type; CAISO wind generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 2: 100 Percent Solar Power

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures 100 percent solar generation resources to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 64 percent of the hours in the year, representing 38 percent of the customer's total annual consumption (3,292 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 62 percent (1,444 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 869 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A31: An office building in California supplied with 100 percent solar power: weekly deficits and surpluses



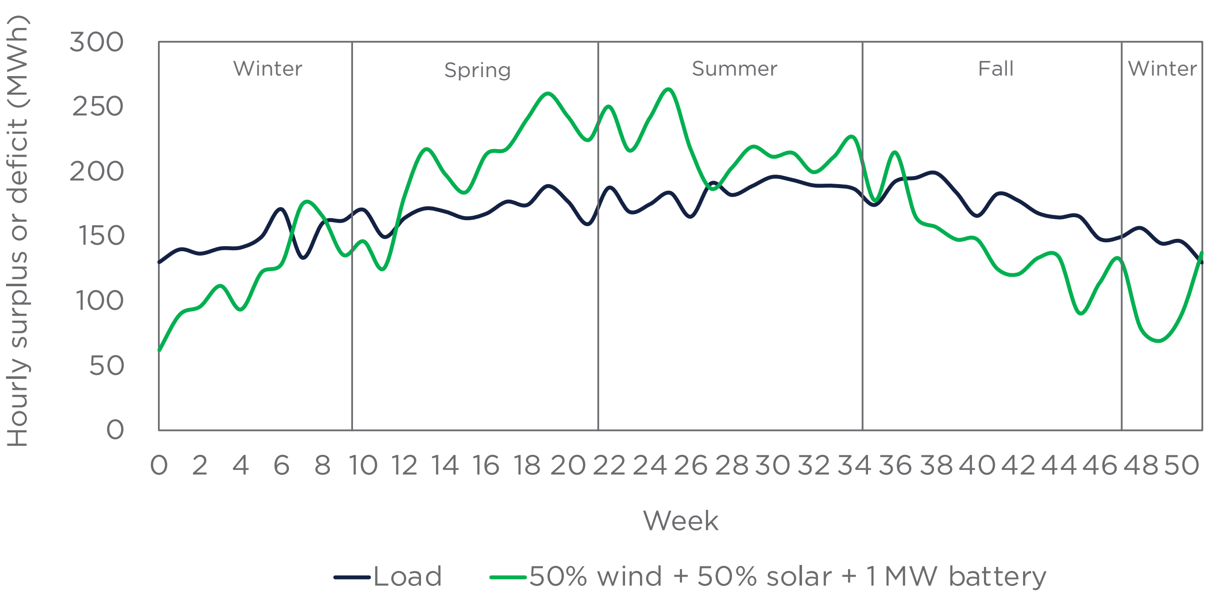
Note: Average annual load is 1 MW; annual load = annual VRE; 38 percent of load is served by the grid.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; CAISO solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 6: 50 Percent Wind and 50 Percent Solar Power with 1 MW/8 MWh Battery

The figure below shows the weekly deficits and surpluses for the case of a commercial Office Building that procures a mixed supply portfolio (i.e., 50 percent wind and 50 percent solar) with a 1 MW battery to meet its RE100 target. Overall, the Office Building relied on the local power grid to meet its consumption in 30 percent of the hours in the year, representing 15 percent of the customer's total annual consumption (1,357 out of 8,760 MWh). Because of the customer's RE100 procurement, the Office Building reduced its carbon dioxide emissions associated with its electricity supply by an estimated 85 percent (1,955 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, despite achieving the RE100 target, the customer is still responsible for 358 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A32: An office building in California supplied with 50 percent wind power and 50 percent solar power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 15 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

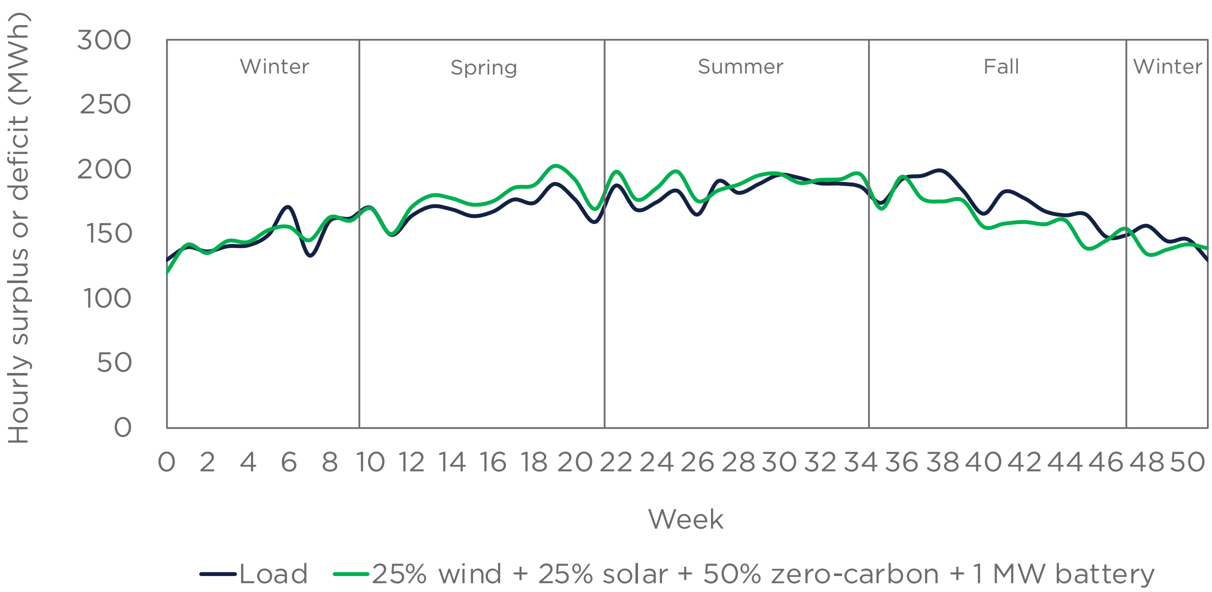
Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; CAISO wind generation, ABB/Energy Velocity renewable generation by fuel type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; CAISO wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

Scenario 9: 25 Percent Wind, 25 Percent Solar, and 50 Percent Firm Dispatchable Zero-Carbon Power with 1 MW/8 MWh Battery

To further address the mismatch between renewable energy supply and customer demand profiles to fully decarbonize the electric system, the authors considered the inclusion of firm dispatchable zero-carbon generation technologies. For example, a supply mix that includes 50 percent firm dispatchable zero-carbon generation along with 25 percent wind, 25 percent solar, and a 1 MW battery can largely eliminate mismatches on an hourly basis between supply and demand over the course of a year.

Overall, the Office Building relied on the local power grid to meet its consumption in 18 percent of the hours in the year, representing 4 percent of the customer's total annual consumption (308 out of 8,760 MWh). In this scenario, the Office Building reduced its CO_2 emissions associated with its electricity supply by an estimated 96 percent (2,232 tons) relative to the 2,313 tons of emissions that would have occurred if it relied on the local power grid for 100 percent of its electricity supply. However, the customer is still responsible for 81 tons of CO_2 emissions because of its continued reliance on energy from the local regional grid when grid power fills in during periods of renewable energy deficit.

Figure A33: An office building in California supplied with 25 percent wind power, 25 percent solar power, and 50 percent firm dispatchable zero-carbon power with 1 MW battery: weekly deficits and surpluses



Note: Average annual load is 1 MW; annual load = annual VRE; 3 percent of load is served by the grid; battery is assumed to discharge 1 MW for each of 8 hours (8 MWh) with zero losses.

Source: DOE load profiles, https://openei.org/datasets/files/961/pub/; CAISO wind generation, ABB/Energy Velocity renewable generation by fuel type; NREL PV Watts solar generation, http://pvwatts.nrel.gov/pvwatts.php; CAISO wind and solar generation capacity, ABB/Energy Velocity generating unit capacity database.

The availability of firm dispatchable zero-carbon generation in this example allows total generation to closely match customer loads regardless of the amount of variable renewable energy generation produced in any given week. Further shifting the supply mix toward firm dispatchable low-carbon generation or energy storage would allow the periods of deficit/curtailment to be fully eliminated.

NOTES

1. "RE100 Members," https://www.there100.org/re100-members.
2. For cases where companies procure the combinations of wind and solar power that are outlined in Table 2.
3. In its core scenarios, this analysis includes an advanced battery that is capable of storing 8 megawatt-hours (MWhs) of usable electricity and discharging it at a rate of 1 megawatt (MW) per hour, which is the average hourly demand assumed for customers in this analysis.
4. Additional details can be found in Table 2 and Figure 7.
5. James Kobus, Ali Nasrallah, and Jim Guidera, "The Role of Corporate Renewable Power Purchase Agreements in Supporting US Wind and Solar Deployment," Center on Global Energy Policy, Columbia University SIPA, March 24, 2021, https://www.energypolicy.columbia.edu/research/report/role-corporate-renewable-power-purchase-agreements-supporting-us-wind-and-solar-deployment.
6. State RPS programs vary widely in terms of program structure, enforcement mechanisms, size, and application.
7. James Kobus, Ali Nasrallah, and Jim Guidera, "The Role of Corporate Renewable Power Purchase Agreements in Supporting US Wind and Solar Deployment," Center on Global Energy Policy, Columbia University SIPA, March 24, 2021, https://www.energypolicy.columbia.edu/research/report/role-corporate-renewable-power-purchase-agreements-supporting-us-wind-and-solar-deployment.
8. "Achieving Our 100% Renewable Energy Purchasing Goal and Going Beyond," Google, December 2016, https://static.googleusercontent.com/media/www.google.com/en//green/pdf/achieving-100-renewable-energy-purchasing-goal.pdf.
9. James Kobus, Ali Nasrallah, and Jim Guidera, "The Role of Corporate Renewable Power Purchase Agreements in Supporting US Wind and Solar Deployment," Center on Global Energy Policy, Columbia University SIPA, March 24, 2021, https://www.energypolicy.columbia.edu/research/report/role-corporate-renewable-power-purchase-agreements-supporting-us-wind-and-solar-deployment.
10. "E&C Leaders Release Framework of the Clean Future Act, A Bold New Plan to Achieve a 100 Percent Clean Economy by 2050," House Committee on Energy and Commerce, January 8, 2020, https://energycommerce.house.gov/newsroom/press-releases/ec-leaders-release-framework-of-the-clean-future-act-a-bold-new-plan-to.
11. Scope 2 emissions are defined as the indirect emissions from the generation of purchased energy.

12. Saptarshi Das, Eric Hittinger, and Eric Williams, "Learning Is Not Enough: Diminishing Marginal Revenues and Increasing Abatement Costs of Wind and Solar," *Renewable Energy* 156 (August 2020): 634–644, https://doi.org/10.1016/j.renene.2020.03.082.

13. James Kobus, Ali Nasrallah, and Jim Guidera, "The Role of Corporate Renewable Power Purchase Agreements in Supporting US Wind and Solar Deployment," Center on Global Energy Policy, Columbia University SIPA, March 24, 2021, https://www.energypolicy.columbia.edu/research/report/role-corporate-renewable-power-purchase-agreements-supporting-us-wind-and-solar-deployment.

14. That is, where a utility acts as an intermediary on behalf of a buyer in a PPA deal, handling the transfer of both money and energy from the renewables project.

15. Under prevailing reporting regimes, claims of renewable electricity use are mostly demonstrated through RECs either owned by the buyer or retired on its behalf. A buyer can apply RECs (which are measured in MWh) against its actual electricity consumption (also measured in MWh) within a given year. Since a REC is considered to represent an "emissions factor" of zero carbon per MWh, the owner of that REC can treat a corresponding MWh of its consumption (regardless of the actual emissions factor of the electricity consumed) as zero. If an owner's total number of MWh represented by RECs equals the total MWh of its load, it can claim to be using "100% renewable electricity."

16. Virtual PPAs (VPPAs) currently represent the vast majority of PPAs between corporations and renewable generation projects. In contrast to physical PPAs, virtual PPAs don't require the physical delivery of the electricity produced by the renewable generator to the corporate buyer. Rather, a VPPA is a financial transaction, where the buyer agrees to virtually purchase electricity that is generated by the renewables project at a fixed or other contractual price. Reference: James Kobus, Ali Nasrallah, and Jim Guidera, "The Role of Corporate Renewable Power Purchase Agreements in Supporting US Wind and Solar Deployment," Center on Global Energy Policy, Columbia University SIPA, March 24, 2021, https://www.energypolicy.columbia.edu/research/report/role-corporate-renewable-power-purchase-agreements-supporting-us-wind-and-solar-deployment.

17. "Corporate Statements about the Use of Renewable Energy: What Does 100% Renewable Really Mean?" Environmental Law Institute, 2019, https://www.eli.org/sites/default/files/eli-pubs/corporate-renewables.pdf.

18. "Achieving Our 100% Renewable Energy Purchasing Goal and Going Beyond," Google, December 2016, https://static.googleusercontent.com/media/www.google.com/en//green/pdf/achieving-100-renewable-energy-purchasing-goal.pdf.

19. "REBA Deal Tracker," Renewable Energy Buyers Alliance, https://rebuyers.org/deal-tracker/. Capacity installations compiled from EIA data. For years 2014 through 2017, Electric Power Annual Table 4.6, https://www.eia.gov/electricity/annual/backissues.php. For 2018, capacity estimate from EIA Today in Energy "More than 60% of electric generating capacity installed in 2018 was fueled by natural gas," https://www.eia.gov/todayinenergy/detail.php?id=38632.

20. Unless located at the customer site, the electrons generated by the contracted wind or solar facility are not actually flowing to the customer but rather to the local electric grid, where they are comingled with the electrons from other generators.

21. This data was sourced from DOEE Representative Load Profiles https://openei.org/datasets/files/961/pub/.

22. More specifically, the NE-ISO, the CAISO and ERCOT.

23. See footnote 13: This data was sourced from DOEE Representative Load Profiles https://openei.org/datasets/files/961/pub/.

24. Representative deterministic hourly customer load and generation supply profiles were used specific to the region of the country, type of customer, and type of supply resource. Actual customer loads and generation supply patterns may vary from expected levels due to a variety of factors (e.g., weather conditions, power plant operations and customer operations, etc.).

25. This analysis assumes an advanced lithium-ion battery with a 1 MW capacity (equal to the assumed average hourly customer load) that can discharge 1 MW for each of eight hours (i.e., 8 MWh). The battery logic was such that it would charge in times of excess supply (if it was not already totally full) and discharge in times of load deficits (if it was not totally empty). By way of comparison, today's standard battery typically discharges over about four hours at full discharge capability.

26. While in today's power markets, surplus renewable energy may displace unabated fossil generation, in a fully decarbonized power market, surplus renewable generation not needed to serve load will be unused. This is reasonably expected to lower the effective utilization of renewable energy investments and, in turn, raise system costs without producing emission benefits.

27. Coal plants may have lower marginal costs than natural gas plants depending on the region and the characteristics of the plant.

28. Marginal costs in the supply curve refer to the short-run variable costs to operate an existing generating resource. These costs differ from the capital costs to build and develop a new plant and a plant's fixed operating costs that are not tied to small changes in generation. Peaking oil and gas plants typically have lower total capital costs to develop but are more expensive to operate on a marginal cost basis. Therefore, peaking units tend to be used less frequently than other types of resources. Natural gas and coal plants operate as baseload or intermediate plants with the ability to ramp up or down. Nuclear and hydroelectric plants typically have higher capital costs to develop but relatively low fuel costs on a per unit basis and therefore tend to operate more frequently as baseload units.

29. In 2019, about 63 percent of total US electricity generated at utility-scale facilities came from fossil fuels—coal, natural gas, petroleum, and other gases. About 20 percent was from nuclear energy, 7 percent was from hydroelectric energy, and 9 percent was from renewable wind and solar energy sources. (https://www.eia.gov/tools/faqs/faq.

php?id=427&t=3).

30. See the following sources from the DOE-EIA and Lazard for estimates of the Levelized Cost of Energy: https://www.lazard.com/perspective/lcoe2019, and https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

31. "Energy Transition Fact Sheet: Pathways to 100% Clean Electricity," Columbia University's Center on Global Energy Policy, February 11, 2021, https://www.energypolicy.columbia.edu/research/article/energy-transition-fact-sheet-pathways-100-clean-electricity.

32. Power plant emission rates also vary by a variety of factors specific to an individual generating unit.

33. As with the other analysis presented in this report, illustrative example includes a large company with an average demand of 1 MW over a year with 8,760 hours would consume 8,760 MWH of electricity and, in this example, purchases 8,760 MWH of "green" wind or solar energy (and RECs).

34. While the Midwest (MISO) and mid-Atlantic (PJM) regions of the country were not fully analyzed in this study, they are included here to further demonstrate the point that the emission impacts of new renewables development will vary by region of the country.

35. "100% Clean Energy Collaborative—Table of 100% Clean Energy States," Clean Energy States Alliance, accessed June 2021, https://www.cesa.org/projects/100-clean-energy-collaborative/table-of-100-clean-energy-states/.

36. "Energy Transition Fact Sheet: Pathways to 100% Clean Electricity," Columbia University's Center on Global Energy Policy, February 11, 2021, https://www.energypolicy.columbia.edu/research/article/energy-transition-fact-sheet-pathways-100-clean-electricity.

37. In 2019, about 63 percent of US electricity generated at utility-scale facilities came from fossil fuels—coal, natural gas, petroleum, and other gases. (https://www.eia.gov/tools/faqs/faq.php?id=427&t=3). In addition, most analysts believe the electric sector will need to be substantially expanded to supply the carbon-free electricity needed to decarbonize other sectors of the economy, including transportation, space heating, and some industrial applications.

38. "Energy Transition Fact Sheet: Pathways to 100% Clean Electricity," Columbia University's Center on Global Energy Policy, February 11, 2021, https://www.energypolicy.columbia.edu/research/article/energy-transition-fact-sheet-pathways-100-clean-electricity; Sepulveda, Joule, 2018, https://doi.org/10.1016/j.joule.2018.08.006; U.S. Mid-Century Strategy for Deep Decarbonization, 2016; "Deeper Decarbonization Pathways to 350 ppm," Evolved Energy Research, May 8, 2019, https://resources.unsdsn.org/350-ppm-pathways-for-the-united-states; "Deep Decarbonization in the Northeastern U.S. and Expanded Coordination with Hydro-Québec," Evolved Energy Research, April 2018, https://resources.unsdsn.org/deep-decarbonization-in-the-northeast-united-states-and-expanded-coordination-with-hydro-quebec; "Pathways to a Clean Energy Future in the Northwest: An Economy Wide Deep Decarbonization Pathways Study," Evolved Energy Research and the Clean

Energy Transitions Institute, June 2019, https://www.cleanenergytransition.org/meeting-the-challenge; Emil Dimanchev, Joshua Hodge, and John Parsons, "Two-Way Trade in Green Electrons: Deep Decarbonization of the Northeastern U.S. and the Role of Canadian Hydropower," MIT CEEPR Research Brief, 2020, http://ceepr.mit.edu/files/papers/2020-003-Brief.pdf.

39. "Energy Transition Fact Sheet: Pathways to 100% Clean Electricity," Columbia University's Center on Global Energy Policy, February 11, 2021, https://www.energypolicy.columbia.edu/research/article/energy-transition-fact-sheet-pathways-100-clean-electricity.

40. "Energy Transition Fact Sheet: Pathways to 100% Clean Electricity," Columbia University's Center on Global Energy Policy, February 11, 2021, https://www.energypolicy.columbia.edu/research/article/energy-transition-fact-sheet-pathways-100-clean-electricity.

41. Setting aside other likely constraints including the siting and permitting of energy generation and transmission infrastructure.

42. "Energy Transition Fact Sheet: Pathways to 100% Clean Electricity," Columbia University's Center on Global Energy Policy, February 11, 2021, https://www.energypolicy.columbia.edu/research/article/energy-transition-fact-sheet-pathways-100-clean-electricity; S. Das, E. Hittinger, and E. Williams. "Learning Is Not Enough: Diminishing Marginal Revenues and Increasing Abatement Costs of Wind and Solar," Renewable Energy 156 (2020): 634–644, https://doi.org/10.1016/j.renene.2020.03.082; N. Sepulveda, J. D. Jenkins, R. Lester, and F. de Sisternes, "The role of firm low-carbon electricity resources in deep decarbonization of electric power generation," *Joule* 2, no. 11 (2018): 2403–2420, https://doi.org/10.1016/j.joule.2018.08.006.

43. New regional transmission and customer demand management programs are other complementary means that could help balance renewable supplies and customer loads.

44. In this analysis, the firm resource modeled was assumed to be dispatchable.

45. Long-duration energy storage technologies such as thermal energy storage have not been analyzed in this study but could have a similar impact as shown and described for firm low-carbon generation.

46. In 2019, about 20 percent of US electricity generated at utility-scale facilities came from nuclear generation. Reference: "What is U.S. electricity generation by energy source?" US Energy Information Administration, February 2021, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

47. "Five states have implemented programs to assist nuclear power plants," US Energy Information Administration, October 7, 2019, https://www.eia.gov/todayinenergy/detail.php?id=41534#:~:text=In%20late%20July%202019%2C%20Ohio,nuclear%20power%20plants%20since%202017.

48. In several US regions, the retirement of nuclear generators could set back progress on grid decarbonization. In a 2018 report, the Union of Concerned Scientists estimated that "losing

the at-risk plants early could result in a cumulative 4 to 6 percent increase in US power sector carbon emissions by 2035 (0.7 billion to 1.25 billion metric tons) from burning more natural gas and coal. This pathway would make it more difficult for the United States to achieve deep cuts in carbon emissions." (https://www.ucsusa.org/sites/default/files/attach/2018/11/Nuclear-Power-Dilemma-executive-summary.pdf).

49. Massachusetts Department of Energy Resources letter to the Massachusetts Department of Public Utilities, July 23, 2018, re: Petitions for Approval of Proposed Long-Term Contracts for Renewable Resources Pursuant to Section 83D of Chapter 188 of the Acts of 2016, DPU 18–64, 18–65, 18–66.

50. "Credit for Carbon Oxide Sequestration: A Rule by the Internal Revenue Service on 01/15/2021," Federal Register, https://www.federalregister.gov/documents/2021/01/15/2021-00302/credit-for-carbon-oxide-sequestration.

51. Akshat Rathi, "U.S. Startup Plans to Build First Zero-Emission Gas Power Plants," Bloomberg, April 15, 2021, https://www.bloomberg.com/news/articles/2021-04-15/u-s-startup-plans-to-build-first-zero-emission-gas-power-plants.

52. "The Carbon Free Power Project," NuScale, https://www.nuscalepower.com/projects/carbon-free-power-project.

53. Roger Ballentine, "The Role of Corporate Energy Procurement in Grid Decarbonization: Defining Next Generation Procurement Goals and Strategies," Green Strategies White Paper, February 2020, http://www.greenstrategies.com/report-the-role-of-corporate-energy-procurement-in-grid-decarbonization/.

54. See also "Energy Transition Fact Sheet: Pathways to 100% Clean Electricity," Columbia University's Center on Global Energy Policy, February 11, 2021, https://www.energypolicy.columbia.edu/research/article/energy-transition-fact-sheet-pathways-100-clean-electricity.

55. The White House, "Executive Order on Tackling the Climate Crisis at Home and Abroad," January 27, 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/.

56. For example: (1) shifting from a goal of "100 percent renewables" to "100 percent zero-carbon" to allow for the use of a diverse set technologies that include firm dispatchable power generation options, (2) to match the power supplies that the company procures to their demand on an hourly basis, preferably by location, and (3) to develop new emissions data tracking and accounting systems consistent with that kind of procurement system.

57. This support could also lead to additional innovation and commercialization of advanced zero-carbon generation technologies that require additional demonstration and deployment to improve their performance and reduce costs. Of note is a related publication from the Center on Global Energy Policy that explores the potential benefits of "Demand-Pull" innovation policies (Sivaram et. al., "To Bring Emissions-Slashing Technologies to Market, the United States Needs Targeted Demand-Pull Innovation Policies," Center on Global Energy Policy, January 20, 2021, https://www.energypolicy.

columbia.edu/research/commentary/bring-emissions-slashing-technologies-market-united-states-needs-targeted-demand-pull-innovation).

58. Specifically, the ISO-NE (in New England), ERCOT (in Texas), and CAISO (in California) regional transmission organizations.

59. The analysis assumed that customers could not or would not materially alter the level or pattern of their electric demands to more closely match the time pattern of their variable renewable energy supply.

60. Annual energy supply on a MWh basis is 25 percent wind, 25 percent solar, and 50 percent firm dispatchable zero-carbon power. The capacity of the firm, zero-carbon power has the same rating through the year (the authors did not distinguish between summer and winter ratings or take into account scheduled maintenance outages, etc.). It was also assumed to be dispatchable. In other words, the authors assumed a fixed amount of firm dispatchable capacity that, given the wind and solar output and the customer's load pattern across the year, supplied 50 percent of the customer's annual energy requirements.

61. DOE Load Profiles can be found here: https://openei.org/datasets/files/961/pub/. For an explanation of the load profiles, see: Eric Wilson, "Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States," Open Energy Data Initiative, National Renewable Energy Laboratory, November 2014, https://data.openei.org/submissions/153, and for the map of climate regions, see Deru et al. US Department of Energy Commercial Reference Building Models of National Building Stock. National Renewable Energy Laboratory, February 2011, p. 16, https://www.nrel.gov/docs/fy11osti/46861.pdf.

62. "PVWatts Calculator," National Renewable Energy Laboratory, https://pvwatts.nrel.gov/pvwatts.php.

63. Lazard, "Lazard Levelized Cost of Storage Version 5.0," November 2019, https://www.lazard.com/media/451087/lazards-levelized-cost-of-storage-version-50-vf.pdf.

64. For ISO-NE, the NREL PV Watts location was the Boston Logan Airport.

65. The capacity factor is calculated as the number of MWh generated during the period divided by the product of the peak capacity in MW and the number of hours during the period.

66. Wind data is based on actual installed capacity operating performance in the region. New wind and solar facilities may exhibit somewhat higher capacity factors, but the overall findings of the study would be unchanged.

67. Solar capacity factors are calculated on an alternating current basis.

68. Since this resource is dispatchable, generation varies to better match load. Figures represent the average of Big-Box Store and Office Building cases.

69. The customer load factor is calculated as the number of MWh consumed during the period divided by the product of the peak demand in MW and the number of hours during the period.

70. At the extreme, a 100 percent load factor customer would have a demand of 1 MW in each and every hour of the year.

71. As noted in the body of this paper, Google did a detailed analysis of its electricity consumption and supply at its data centers around the world and found similar results as this study with respect to Google's reliance on energy supply from the local grid.

72. This customer's average annual load is 1 MW (i.e., on average, the customer uses 1 MW every hour of the year). Thus, a large corporate customer in New England with an average annual load of 10 MW could roughly be expected to emit 10 times the amount of carbon shown in the table, depending on the contract structure.

73. Of the 52 weeks in the year, some weeks exhibit extreme deficits or surpluses. The authors chose this representative week to illustrate a typical week with a net deficit or net surplus to highlight the hourly pattern and duration of shortages and surpluses during that week.

74. For ERCOT, the NREL PV Watts location for downtown Houston, Texas (National Solar Radiation Database [NSRDB] data), was used.

75. Wind data is based on actual installed capacity operating performance in the region. New wind and solar facilities may exhibit somewhat higher capacity factors, but the overall findings of the study would be unchanged.

76. Since this resource is dispatchable, generation varies to better match load. Figures represent the average of Big-Box Store and Office Building cases.

77. This customer's average annual load is 1 MW (i.e., on average, the customer uses 1 MW every hour of the year). Thus, a large corporate customer in New England with an average annual load of 10 MW could roughly be expected to emit 10 times the amount of carbon shown in the table, depending on the contract structure.

78. Notably, the solar capacity factors are much higher in California than other areas of the authors' study, which used NREL irradiance data. The higher capacity factor in California is likely due in large part to (1) higher irradiance in that region of the country and (2) data differences such as a greater bent toward utility-scale installations in CAISO.

79. Wind and solar data is based on actual installed capacity operating performance in the region. New wind and solar facilities may exhibit somewhat higher capacity factors, but the overall findings of the study would be unchanged.

80. Since this resource is dispatchable, generation varies to better match load. Figures represent the average of Big-Box Store and Office Building cases.

81. This customer's average annual load is 1 MW (i.e., on average, the customer uses 1 MW every hour of the year). Thus, a large corporate customer in New England with an average annual load of 10 MW could roughly be expected to emit 10 times the amount of carbon dioxide shown in the table, depending on the contract structure.

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