CLIMATE READi
RESILIENCE AND ADAPTATION INITIATIVE

EPRI

TECHNICAL REPORT

CLIMATE VULNERABILITY CONSIDERATIONS FOR THE POWER SECTOR

End-Use Assets and Distributed Energy Resources

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EXECUTIVE SUMMARY

EPRI's Climate REsilience and ADaptation initiative (READi) [1] is dedicated to developing a comprehensive and consistent approach to assessing physical climate risk to power industry assets and systems and identifying a framework to address those risks and enhance resiliency of the systems. The objective of this effort is to develop a common approach to risk identification, adaptation, and planning for the impacts of climate change to energy grid assets and the integrated power system. The initiative includes three workstreams: physical climate data and guidance, asset vulnerability and adaptation, and system planning and prioritization. This report documents a literature review to characterize asset vulnerability to climate change for distributed energy resources and key end use products whose failure or inefficient operation may have an impact on the grid. This study documents the current state of knowledge on these topics and identifies research gaps. This report serves as one volume in a series of related literature reviews that address climate impacts for different asset types in the electric power sector. Other volumes include:

1. Non-nuclear generation [2]
2. Transmission and distribution [3]
3. Nuclear generation [4]
4. Cross-cutting topics (i.e., worker health and safety, environmental justice, and shifts in ecological patterns) [5]

Development of a common approach to assess vulnerability includes the following components:

- Determining how to effectively apply climate trends and projections when selecting, specifying, designing, and installing new assets, as well as when refurbishing existing assets.
- Establishing methods to understand the ability of existing assets to withstand future climate conditions.
- Identifying and assessing potential adaptation strategies' effects on climate risk.
- Providing a consistent approach to energy system and asset vulnerability assessment to inform investment decision makers.

The literature review is focused on key sources addressing **what and how current and changing climate can impact key end-use assets and distributed energy resources** (DER), and what the projected climate-related impacts are anticipated to be. For DER this report focused on climate impacts to small-scale solar and batteries, while the end-use sections focused on specific end-use categories whose failures or inefficiencies related to climate may impact the grid and/or power company operations. These include electric vehicles (EVs) and their associated charging infrastructure, data centers, and space conditioning systems including air-source heat pumps.

This report is intended to inform decision-makers about climate change risks and assessment strategies. It is also intended to provide a foundation for the next phase of READi research to advance the development of a framework for climate change vulnerability and adaptation assessment.

KEY TAKEAWAYS

Microgrids, a concept where distributed energy resources (DER) serve power to loads while disconnected from the main grid, provide the largest potential benefit from DER in response to climate change. Electric service disruption, wherein service from the grid is temporarily interrupted to the customer facility, may occur more frequently due to extreme weather events associated with climate change. Research thus far has shown that if disruption occurs, with sufficient planning, DER can enable continuity of electric service to customer loads where needed.

However, research on how climate impacts DER is currently limited due to the relatively lower penetration and more recent emergence of these technologies. Similarly, research is limited for end-use assets, which are also considered emerging technologies with potential to contribute to society’s decarbonization efforts.

DER and end-use products can all be impacted by extreme weather events and other weather trends that occur due to climate change, particularly extreme temperatures. For example, Lithium Ion (Li-Ion) battery energy storage (associated with DER and EVs) is known to have performance issues in both cold and hot temperatures. Rooftop solar panels are often subject to the same climate vulnerabilities as large-scale solar installations, such as loss of efficiency from extreme temperatures and lowered irradiance (e.g., cloud cover, snowfall, icing, etc.) as well as damage from flooding.

Heat pumps for space conditioning also can be impacted by extreme climate conditions, through efficiency loss under extreme temperatures as well as disruption or damage to outdoor compressor units from high humidity or snowfall levels. Flooding, freezing, and extreme hot temperatures have impacted data center operation through cooling efficiency loss as well as data center disruption due to damage caused by frozen pipes bursting and flooding associated with cooling system equipment after a freeze event. Moreover, extreme temperatures and climate conditions can impact EV fleet charging, causing higher power draw than during normal temperature conditions as well as shifts in patterns (e.g., timing and location) of charging. For example, spikes in EV charging can occur as drivers fully charge vehicles in preparation for forecasted weather events (e.g., hurricane or flood) and/or to prepare for evacuation.

1 INTRODUCTION

1.1 EPRI Climate READi and Energy System and Asset Vulnerability Assessment

EPRI's Climate REsilience and ADaptation initiative (READi) is focused on developing a comprehensive and consistent approach to physical climate risk assessment and adaptation planning. The initiative includes three workstreams:

1. Physical climate data and guidance,
2. Asset vulnerability and adaptation, and
3. System planning and prioritization.

This report assimilates salient points from a literature review conducted under the second workstream, assessing vulnerabilities of end-use assets and distributed energy resources (DER). Identifying climate variables and how they can impact DER and/or end-use assets, provides a foundation of understanding that can then be applied to the next task. Namely, READi aims to develop a common approach to risk mitigation considering impacts of climate change to grid assets as well as the integrated power system. Future work includes establishing methods to understand the ability of existing assets to withstand climate events. A READi framework (under development in 2024) can be effectively applied to identify climate trends and projections when selecting, specifying, designing, and installing new assets, as well as when refurbishing existing assets. The goal is to identify and assess potential adaptation and mitigation strategies' impacts on risk. The end result is to inform investment decision makers, by providing a consistent approach to energy system and asset risk assessment from climate hazards.

1.2 Climate and End-Use Assets/DER

Climate and weather stressors impact many aspects of generation, transmission, and distribution systems, and end-use of electricity [6] throughout the world. As the global climate continues to change, these impacts are likely to become more pronounced in the decades to come, particularly as extreme events increase in frequency and intensity [1]. Figure 1 shows observed trends and anticipated future changes for select climate impact stressors in North America. There is strong scientific consensus that warming will continue and that there will be increasing precipitation variability. Warming temperatures do not preclude cold spells from continuing to occur, although they are expected less often. Severe storms like hurricanes and tornadoes are expected to occur more commonly [7]. Extreme temperatures and more frequent severe weather events will continue to be very costly to the economy and the grid, primarily through asset destruction, if adequate preparations are not made.

CLIMATIC IMPACT-DRIVER	OBSERVED TREND	FUTURE CHANGES
Extreme heat	∧ Upward trend	∧ High confidence of increase
Cold spell	∨ Downward trend	∨ High confidence of decrease
Snow and glaciers	∨ Downward trend	∨ High confidence of decrease
Heavy precipitation	∧ Upward trend	∧ High confidence of increase
Drought	— No assessment given	∧ Medium confidence of increase
Fire weather	∧ Upward trend	∧ ∧ High confidence of increase in Western NA, medium confidence of increase in Central and Eastern NA
Coastal and river flooding	∧ Upward trend	∧ High confidence of increase
Tropical cyclone, severe wind	— No assessment given	∧ Medium confidence of increase

Figure 1. *Observed trends and projected changes in primary climate impact drivers in North America (Source: EPRI [1]). Note that the "Observed Trends" may apply to trends in intensity, frequency of occurrence, or both; additionally, this table lists primary drivers and is not exhaustive.*

Both thermal and renewable generating assets already face climate impacts that regularly threaten grid resilience [1, 8, 9]. Droughts and associated water scarcity threaten cooling efficiency and environmental compliance of thermal generating stations. Insufficient water supplies can also impact hydropower generation, as can excess water supplies in terms of flooding. Changing precipitation patterns, including snowfall and icing events, can threaten reliability of solar facilities. Wind variability severely impacts win turbine output as low winds can decrease production and high winds can threaten infrastructure. Transmission and distribution assets are also impacted by high winds among many other climate-related variables such as flooding and extreme air temperatures [1]. Similar to these core energy assets, consumer and utility products that are powered by electricity as well as distributed energy resources such as rooftop solar and batteries can also be impacted by extreme weather events. These impacts can in turn influence the resilience and reliability of the power grid.

Associated with ensuring grid reliability during the energy sector's transition to a low carbon future, adoption of DER and energy storage has been increasing rapidly over the last decade (Figure 2 and Figure 3), driven by government incentives and falling costs [10]. The Energy Information Administration (EIA) estimates that distributed solar contributed 360 MW in 2021 [11]. Distributed battery capacity for 2020 was estimated to be 0.8 GW/1.6 GWh [12], and large-scale battery capacity for 2019 was 1022 MW/1688 MWh [13]. DER and energy storage are expected to continue growth with support from the federal government (Figure 2 and Figure 3). The Inflation Reduction Act passed in 2022 incentivizes standalone energy storage by including it in the investment tax credit, a measure previously only available to solar and coupled batteries [14].

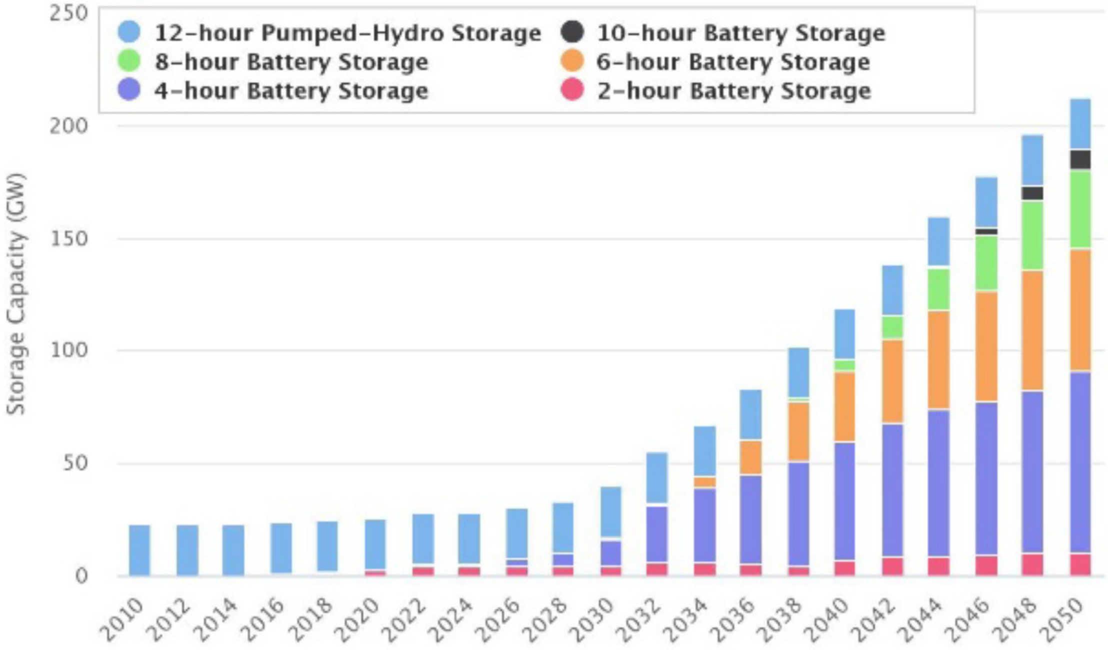

Figure 2. *Utility-scale energy storage projections through 2050 with reference cost case. Source: NREL [15]*

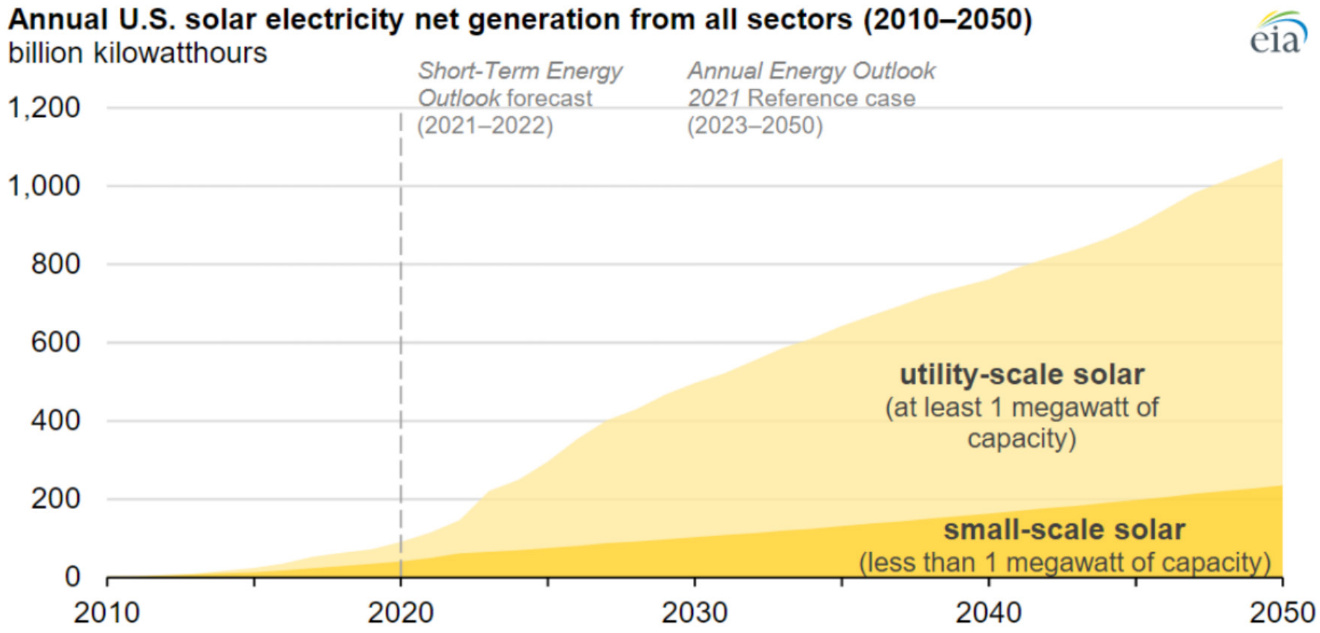

Figure 3. *Solar PV generation projections through 2050 with reference cost case. Source: NREL [16]*

Adoption of distributed solar in the U.S. has been driven by market factors and continued support from local, state, and federal government in the form of rebates, tax credits, net energy metering programs, and other incentives. Energy storage has benefited from decreasing costs as well, but adoption is also driven by customer resilience needs for backup power, utility needs, and policy changes. Utility needs include peak load reduction to extend utility asset infrastructure life, and peak capacity to replace peaker plants used for infrequent peaks in demand. A variety of policy changes have also supported energy storage, including clean energy goals, procurement targets, and financial incentives for energy storage. Regulatory changes have been mandated by the Federal Energy Regulatory Commission (FERC), which released new guidance to support energy storage in wholesale electricity markets [17].

Like DER, primarily in response to the transition to a low carbon future, key electric end-use assets have become more common in recent years and are expected to continue to increase in adoption in years to come. Although these end-use assets, such as electric vehicles (EV) and heat pumps, are becoming more integrated into our daily lives, similar to DER and other energy sector assets, they also have inherent vulnerabilities to current and projected climate conditions. Research related to direct climate impacts on end-use assets is limited, while more attention from related research has been focused on possible effects of switching to various end-use assets on climate trends or on load projections.

1.3 Objective of Literature Review

With growing reliance of the electric grid and society on electric end-use assets and DER like energy storage, it becomes pertinent to examine their possible influence on the vulnerabilities of the future grid in the face of changing climate conditions. For DER assets, this literature review focuses on distributed solar generation as well as distributed and utility-scale energy storage, identifying which research needs have been met and where there are gaps in knowledge of potential vulnerabilities. For end-use assets, the objective of this review is to explore asset and associated infrastructure vulnerabilities to understand how inefficiencies of failure, due to weather, could adversely affect the grid. Key end-use asset categories included in this review are EVs and charging infrastructure, data centers, and space conditioning systems including electric heat pumps and air conditioners.

Recent climate-related asset and grid disruptions across the globe highlight the need for physical climate change vulnerability assessment and adaptation. The DOE's Climate Adaptation and Resilience Plan notes priority actions including assessing vulnerabilities and implementing resilience solutions, enhancing climate adaptation and mitigation co-benefits, institutionalizing climate adaptation and resilience, providing climate adaptation tools, technical support, climate science information, and advancing deployment of emerging climate resilience technologies [18]. There are many different methods for assessing vulnerability and resilience in energy systems and other infrastructure, as well as in communities. This effort seeks to review the findings of various approaches for assessing climate vulnerabilities of key end-use assets as well as DER.

2 APPROACH

2.1 Literature Review Focus and Limitations

The literature review is focused on key sources addressing **what and how current and changing climate can impact key end-use assets and DER**, and what the projected climate-related impacts are anticipated to be. This report is intended to inform decision-makers about climate change risks and assessment strategies. It is also intended to set up the next phase of this research area of READi which involves the development of a framework for climate change risk management. This study focuses on direct and indirect impacts of climate to the assets described above with a consideration of how failure of the assets might impact the grid or micro-grids. Topics such as the effect of growing adoption of electric end-use products and DER on load projections and system-level vulnerabilities were not addressed in detail here but are included more fully in a related READi literature review [19]. Primary end-use products not reviewed here, but discussed in more detail by EPRI [19] include desalination, buildings, and agriculture.

2.2 Literature Review Methodology

After reviewing relevant EPRI literature, a search was performed using tools such as Google Scholar to identify published literature focused on climate change hazards related to end-use and DER assets described above. Search terms included combinations of the following: air conditioning, heat pumps, electric vehicles, EV/fleets and charging infrastructure, DER adoption, DER resiliency, microgrids, solar PV, residential batteries, Li-Ion batteries, battery, climate change, extreme temperatures, climate effects, hurricanes, extreme winds, and flooding.

Upon review of the literature found in the search, additional targeted literature searches were performed to uncover additional information about specific topics or to confirm gaps in the initial literature identified. Efforts were made to include only quality and unbiased sources in this review. This primarily includes sources from reputable government agencies and research organizations along with peer-reviewed publications.

The literature review was performed for works written in the English language. This may have resulted in the exclusion of relevant sources in other languages. A next phase of the asset vulnerability assessments is to engage additional external stakeholders as well as those from other asset classes to further identify sources of information.

2.3 Synthesis and Analysis

Findings from literature review were synthesized and augmented with existing relevant sources from consultants. Section 3 summarizes findings. Definitions are included for key climate change risk terms to aid in clarity. Climate change risks to end-use assets and DER as identified in the literature are discussed. Climate change risks that may impact these asset categories but are lacking in the literature are also noted. A discussion of apparent research needs is included in Section 4.

3 LITERATURE REVIEW SUMMARY AND RESULTS

3.1 Climate Risks for Distributed Energy Resources

Microgrids are a primary way that DER and energy storage can support grid resilience. Although DER and energy storage can be used for customer-level resilience by providing off-grid generation and backup power, these assets can also be pooled to maintain resilience collectively in a microgrid. The US Department of Energy [20] describes the industry-accepted definition of a microgrid as: “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid, and that can connect and disconnect from the grid to enable it to operate in both grid-connected and ‘island’ mode.” In “island” mode, the microgrid generates and distributes electricity to customers within the microgrid, providing resilience in case of a disruption to the grid. Microgrid deployments have been increasing over the last decade with support from the government, following the devastating impact of Hurricane Sandy in 2014 [21, 22].

Microgrids are often used to meet critical loads, which may include critical or emergency services, public services, commercially critical loads, and military needs. This is expected to become an increasingly important way to service critical loads, in the face of rising frequency of extreme climate events. For example, microgrids may provide local resilience amidst power shortfalls that may result from extreme heat waves and can provide electricity and cooling for emergency shelters [8]. Microgrids may also provide resilience during and after hurricane events, powering critical services and homes during times of service disruption from the electric power grid [23]. Beyond providing electricity, microgrids and DER may assist with power system restoration following an outage event. Microgrids and DER located along the restoration path can alleviate congested circuits and provide partial capacity relief, aiding service restoration [24, 25]. Microgrids are reliant upon DER assets which support them, which may include residential solar and batteries. Use of DER to form microgrids is still in the early stages of being adopted by utilities and each system is very unique, making it challenging to generalize their characteristics, operations, and vulnerabilities. This in turn can make it difficult for utilities to use baseline planning assumptions around their capabilities and reliability. However, adoption of microgrids can provide resiliency during climate-related impacts to the grid.

3.1.1 Climate Vulnerabilities of Small-Scale Solar

In general, small-scale solar installations face very similar impacts from climate as do utility-scale installations. For the former, this exercise revealed that to date, there is little to no specific information in the literature characterizing these vulnerabilities. For the latter, a related READi literature review on non-nuclear generating assets, including renewables, covers the potential impacts to utility-scale solar photovoltaic (PV) installations from climate in detail [2] with relevant findings summarized here.

Extreme temperatures, both high and low, can reduce output of PV panels and damage components. Low precipitation can facilitate soiling of panels, reducing efficiency, while excess precipitation can also impact efficiency (reduced irradiance), but can also trigger flooding which may damage electronics and other components as well as causing other problems such as access difficulty and erosion. Icing and snowfall can also reduce output. Wildfires, hailstorms, and high wind events [26] (hurricanes, tornadoes, etc.) can all cause extensive and widespread damage to PV modules and racking systems [2]. It should also be noted here that some evidence suggests that roof and ground-mounted PV may be particularly resilient to extreme weather relative to other infrastructure and other components of the electric power system. Fthenakis [27] provides one example of PV systems surviving an extreme weather event that damaged much of the nearby infrastructure. Examples like this along with the relatively new nature of PV indicate that the ability of the technology to withstand extreme weather events is in need of additional study.

Of the vulnerabilities summarized above, all are relevant to small-scale or rooftop solar as well as utility-scale, although flooding is likely less of a concern, whereas high winds may be more of a concern. Vulnerabilities unique to rooftop solar or solar specifically used as DER were identified in this literature search.

3.1.2 Climate Vulnerabilities of Residential and Industrial Batteries

As discussed earlier, extreme weather events, such as those that result in hurricanes and large storms, are likely to increase in frequency due to climate change. This will likely result in increased flooding events in many regions. Water immersion of any electrical device or equipment can be damaging and potentially hazardous. While flooding risks to residential backup battery solutions, such as the Tesla Powerwall, have not been sufficiently studied in the literature, learnings from EV flooding experiences and testing are applicable. For context, an EV battery can be significantly larger than a residential battery system (e.g., the Tesla Model 3 battery capacity ranges from 50-82 kWh and the Tesla Powerwall 3 battery has a capacity of 13.5 kWh). Immersion of Li-ion battery technologies has been shown to increase the risk of toxic gas exposure and fire [28]. This was observed in some EV batteries after Hurricane Ian in 2022. For this reason, it is advised that water-damaged batteries not be used. Immersed batteries are typically considered irreparable and should be treated as hazardous waste.[1]

Like with flooding impacts, residential and EV li-ion batteries overlap also in vulnerabilities to extreme temperature, resulting in decreased capacity or accelerated degradation. One major difference is the thermal management system. Residential systems that do include thermal management likely use a very simple fan with no liquid cooling and likely no pre-conditioning. Air-cooling is not usually as effective in removing heat evenly. Battery cells may degrade at different rates, which is detrimental for the entire system as more cell-balancing is needed to manage the different degradations.

Extreme temperature and regional climate effects on batteries for automotive purposes have been extensively studied, but there is little research on the impact of climate on stationary battery performance and economics. One

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[1] DEP EV Lithium-Ion Batteries FAQ_10072022_v01.pdf (floridadep.gov)

ongoing study at Sandia National Laboratory is finding that battery energy storage located in regions with extreme winters would have to be significantly oversized, due to parasitic heating, ventilation, and air conditioning (HVAC) loads to maintain an operational temperature [28]. The study has not yet but intends to examine extreme hot climates. Further research is needed on battery performance and economics for future climates.

It is currently known that prolonged exposure to cold weather can have a significant impact on battery performance such as increased internal resistance and slowed rate of charge and discharge due to changes in chemical reaction rates, both of which result in degradation of overall capacity. Similar issues can be seen when batteries, particularly Li-Ion, are exposed to extreme heat for extended periods of time. While heat does temporarily increase chemical reaction time and ultimately the overall storage capacity of the battery, exposure to exceptionally high temperatures for long durations accelerates the rate of degradation and shortens its lifetime. One study by Scientific Reports showed that for the first 200 cycles, battery performance degraded by 3.3% at 77°F, and by 6.7% at 113°F [29].

Emerging energy storage technologies are growing rapidly. These include flow batteries, flywheel energy storage, thermal energy storage, and others. Safety issues and vulnerabilities are still being explored, and there is limited research on how climate change would affect deployment or performance. Assessing the vulnerabilities to these emerging technologies was outside the scope of this literature review, but is to be included in future efforts by READi and/or other related research initiatives.

3.2 Climate Vulnerabilities of Prioritized End-Use Assets

End-use assets refer to any electricity consuming equipment behind the customer meter. End-use assets are subject to a range of vulnerabilities associated with extreme weather events. Asset vulnerabilities in-turn can impact the overall power system with respect to their energy demand and fluctuations.

Various asset types are weather-dependent in terms of their control parameters as well as aggregate demand dependency on weather. For example, the following asset types use measured temperature (e.g., indoor, zonal, tank, or compartment temperature) as a control variable:

1. Space conditioning system (e.g., air conditioner, air-source heat pump, space heater)
2. Water heater (e.g., electric resistance water heater, heat pump water heater)
3. Refrigeration system (e.g., refrigerator, freezer)
4. Air circulation system (e.g., central ventilation system, ceiling fan)

Because device electricity draw to maintain a target temperature or comfort level is dependent on ambient weather conditions (e.g., outdoor temperature), these asset types can experience heightened use during extreme weather conditions. These systems may also contribute substantially to electricity draw in other asset types and classes (e.g., air-conditioned passenger electric vehicles, air-conditioned server rooms within data centers), and thereby contribute to heightened demand of other asset classes.

Additional asset types and classes are also weather dependent but do not necessarily use temperature as a control variable. For example, potable water pumping stations and agricultural pumps may use measured water storage levels or crop conditions to control water pumping or irrigation. Nevertheless, these asset classes tend to be operated with higher power demand during hotter weather, due to heightened water demand during hot dry seasons, which in turn drives higher power demand. Wastewater processing plants also experience heightened operation and power demand during stormy, rainy weather, when rainwater seepage into the local sewage collection systems contributes to heightened demand for wastewater processing, given limited storage facilities for sewage and the risk of spillage.

Although there are many end-use asset types that are weather-dependent, in that temperature drives the aggregate power demand of that asset, the literature review focuses on three primary end-use asset classes: EV charging, data centers, and space conditioning systems. These were prioritized as market ready end-use assets whose growing penetration and operational inefficiencies due to weather impacts have the most potential to impact the grid. For a discussion on the impact of wide-spread adoption of electric end-use products on load projections, please see a related READi literature review [19].

These three end-use asset types can be impacted by severe climate conditions, through efficiency losses under extreme temperatures as well as disruption or damage to equipment operation due to weather events causing freezing, flooding, and/or elevated snowfall conditions. High humidity or wet conditions generally pose risk to sensitive electronic equipment, and can cause damage to control boards found in outdoor compressor units of heat pump systems, electric vehicle charging equipment, and data center server rooms. Moreover, flooding, freezing, and extreme temperatures can lower operational efficiencies of equipment. Potential vulnerabilities to each of the three asset types from key climate drivers are further discussed below.

3.2.1 Air Conditioning Systems

Rising global temperatures are expected to drive increased adoption of air conditioning in more temperate climates, like in northern regions of North America and Europe, where air conditioning is less pervasive today [30]. This in turn leads to a direct increase in energy consumption over summer months as well as increased summer peak demand. The elevated risk of fire in some regions due to climate change may also accelerate the adoption of air conditioning, as residents in fire-risk regions are unable to rely on natural ventilation for cooling due to the increase in atmospheric smoke during summer months. In regions where air conditioning is predominant today, assuming a rise in average, maximum, and minimum air temperatures and all other factors remain constant, summer peak demand is expected to increase as well, albeit at a lesser extent.

Although the growth in energy use may be moderated by more efficient cooling technologies, increased electricity demand due to space conditioning load may lead to more periods of power system stress and associated electric service disruptions. This in turn necessitates engaging air conditioning systems for peak demand reduction in summer peaking regions and heating systems in winter peaking regions, as well as updates to resource adequacy modeling methodologies for end-use technologies to ensure electric supply can meet demand.

Extreme weather events may also increase likelihood of electric service disruptions. Residential air conditioning motors can stall due to low inertia caused by momentary voltage disruptions (e.g., 45% for two cycles, as illustrated in Figure 4). Upon electric service restoration following a grid event, the motors draw substantial reactive power (e.g., due to locked rotors) until thermally tripped. This can trigger under-voltage measures from the power grid during system restoration following a climate-related disruption to electric service. Figure 4 from EPRI [31] illustrates the impact of temperature on stalling of space conditioning motors in reciprocating compressor type equipment. As temperature increases (e.g., with climate change), the stall region increases.

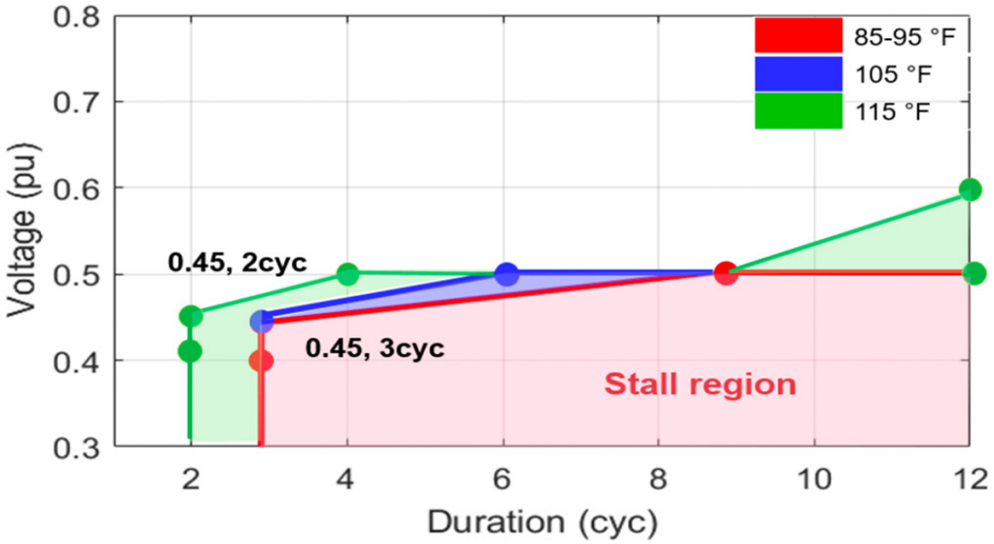

Figure 4. *Temperature impact on stalling of reciprocating compressor-type space conditioning equipment. Source: EPRI [31]*

3.2.2 Heat Pumps

Heat pumps operate using the same principal as air-conditioning in reverse, using the thermodynamic properties of refrigerant to move heat from a colder outdoor to a warmer space indoors. Outside of tropical regions, the peak thermal load to heat a building in winter typically outweighs its peak thermal load for summer cooling load in many climates, particularly in Europe and North America, due to the much larger difference between indoor and outdoor temperatures experienced in winter. Yet to minimize first cost to the consumer, heat pumps are often sized to meet peak cooling loads. Thus, heat pumps often require auxiliary "backup" heat for periods when heating load exceeds the heat pump capacity. The efficiency of operation with electric auxiliary heat is much lower since the resistive elements can only generate as much heat as electrically consumed, whereas a heat pump can move more energy than it consumes.

3.2.2.1 Temperature Impacts on Heat Pumps

The greater the temperature difference between outdoor temperature and desired indoor temperature in both hot and cold extremes, the less efficient the heat pump may be at providing space conditioning. Moreover, capacity and efficiency decrease with lower outdoor temperatures, as the temperature difference that the heat pump must overcome becomes larger. Under extreme cold temperatures, heat pumps may rely on supplemental heat sources when ambient air temperatures drop too low for heat pump operation [32], contributing to higher demand on the grid.

In addition to average temperature changes, climate change may cause the frequency and intensity of extreme heat events to increase—and conversely decrease for cold spells in many regions of the world. This can drive space conditioning units to operate outside of normal design temperature. Their continuous operation at full load in attempts to satisfy the thermal demand of customers, can lead to high-

er peak demand on the power system. In turn, grid assets such as transformers can be driven to operate beyond their design limits under extended periods of time with higher operating temperatures, resulting possibly in equipment failures. Such dynamics of space conditioning operation during extreme weather events are described by EPRI [31].

3.2.2.2 Snowfall Impacts on Heat Pumps

Beyond temperature impacts, some regions may experience an increase in snowfall and ice during heavy winter storms. In regions where heavy snowfall is expected, heat pumps require snow protection, typically in the form of raised platforms and/or roofing to prevent snow from blocking airflow to the outdoor unit, which can significantly reduce heating performance. While such an impact is highly regional, it may require a more careful consideration of the snow protection for peak snowfall events, particularly as heat pump adoption shifts northward. Currently there are limited data and guidance on the snow protection needed for heat pumps based on typical peak accumulation levels.

3.2.2.3 Heat Pumps as a Resource

The increased adoption of space conditioning systems as a result of climate change may present an opportunity for utility energy efficiency (EE) programs through the promotion of more efficient equipment like heat pumps. In addition to energy savings, the low temperature heating performance and demand response (DR) capabilities of select equipment may offer advantages for utilities with a range of customer programs (EE, DR, and electrification). In cold weather, the use of variable-speed heat pumps can significantly reduce heat pump electricity demand by reducing the need of supplemental heating and improving energy efficiency. Peak demand can also be targeted using a standard for demand response such as AHRI 1380 [33], which defines demand limiting modes of operation for compliant heat pumps. Another adaption strategy is to model growth of heat pump systems in system planning models and forecasts to properly account for changing power demand.

3.2.3 EVs and Charging Infrastructure

Extreme temperatures—whether hot or cold—can significantly impact EV performance as well as charging infrastructure performance, which is comprised of Electric Vehicle Supply Equipment (EVSE), also referred to as charging stations. Generally, temperatures beyond manufacturer-recommended ranges can impact battery operation, as well as diminish EV operating range. Extreme temperature impacts can also reduce the efficiency of vehicle charging and EVSE output [34], as well as degrade battery life. Moreover, extreme temperatures can increase overall power demand as EVs require longer times to charge resulting in higher peak demand due to more EVs being connected for longer charge times to replenish vehicle batteries.

3.2.3.1 Temperature Impacts on EVs and Performance

Extreme temperatures can have two main types of impacts on EVs and thus on charging requirements. First, the common way fleet and EV operators experience temperature impacts on EVs is through vehicle operating range on a single charge. The operation of cabin air conditioning and heating—largely powered through the on-board battery—consumes energy, reducing the battery state-of-charge (SOC) that can be used to move the vehicle [35, 36]. In other words, vehicle fuel efficiency suffers because of cabin climate control. This augmented energy demand means that the driving range is reduced, and more EV charging is required to compensate for the faster battery drainage. One way to minimize cold weather impacts is to store the EV in a climate-controlled area [37], or by using functions that acclimatize the cabin while the EV is connected to an EVSE to minimize battery draw [36]. These strategies may be particularly important given that extreme cold weather has been shown to reduce range by over 40% [38]. These solutions help mitigate energy consumption of the battery by climate control functions, thus somewhat improving vehicle operating range on a single charge. In addition to reduced driving ranges, EVs stored outdoors in colder climates will

require what's termed 'pre-conditioning' to achieve the required battery temperature to safely commence charging [38]. To protect the battery, many on-board chargers will not commence charging until the battery warms up [39].

The second and less obvious impact on operators of extreme temperatures is battery degradation. Elevated temperatures accelerate chemical reactions within the battery, allowing for faster rates of degradation [40]. Hot temperatures (above 40°C or 104°F) increase chemical activity and can augment the chance of battery degradation and damage, as well as slow charging time [41]. Cold temperatures (below 0°C or 32°F) degrade batteries, increase their internal resistance, and increase charging time [41]. As a result of prolonged extreme temperatures and battery degradation, EVs will require more frequent and longer charging sessions to compensate for the deterioration of battery state-of-health (SOH) and the inability to hold as much charge as a new battery. This may result in increased range anxiety of customers and also impact the ability of power companies that rely on EV fleets to respond to routine and emergency situations.

3.2.3.2 Temperature Impacts on EVSE and Charging Behavior

In addition to the impacts noted in the preceding section with regard to delayed charging due to battery temperature, EVSEs have functional issues at freezing temperatures [42]. High temperatures can cause EVSEs to overheat, reducing the efficiency and lifespan of EVSE 12 [42]. Nonetheless, NEMA 4-rated EVSEs[2] are enclosed in such a way that the internal parts of the product are protected from the elements and able to work normally from -22°F to 122°F (-30°C to 50°C). Exposure to extreme temperatures outside of this range may decrease the functionality of the EVSE [39].

A study by Motoaki et al. [43] found through simulation that charging light-duty EVs with 50 kW DC fast chargers (DCFCs) from 20% to 80% SOC at 77°F (25°C) takes about 30 minutes. At 32°F (0°C) however, 30 minutes can only increase the SOC from 20% to 44%. The data from the study demonstrate the variability in charging efficiency as a function of ambient temperature; colder climates reduce charging efficiency [43].

EV fleet reliability will also depend significantly on consistent power supply for charging stations, making minimizing blackouts and/or ensuring adequate back up power priorities [44]. EPRI explores resilience options for EV fleet management and highlights examples such as considering indoor charging stations and/or secondary charging hubs to minimize risks [44].

Case studies in Appendix A provide some examples of temperature impacts on charging based on energy and modeling of bus fleets used for public transportation (transit) as well as school buses in Michigan. The appendix contains charts that illustrate significant differences in charging requirements under different ambient temperature conditions. Moreover, charts illustrating temperature impacts on light-duty EV fleet charging based on a load forecasting model for southern Australia, show impacts to a much lesser extent, comparing winter and summer seasons.

3.2.3.3 Impacts of Extreme Weather Events

In contrast to extreme temperatures that can impact the frequency and magnitude of EV charging, impacts of evacuation-inducing emergency events on EV fleets and charging are largely temporal and spatial shifts (load shifts). Extreme weather events, such as storms, flooding, wildfires, and other similar events can have both immediate and delayed impacts on EVs and EVSEs. Disasters and evacuation events can impact charging behaviors, leading to charging spikes ahead of expected extreme weather events. The spikes in EV charging can occur both at evacuation sites and neigh-

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[2] National Electrical Manufacturers Association (NEMA)-4 – A rating system to denote electrical enclosure protection levels. NEMA-4: Gasketed door enclosure intended for indoor or outdoor use primarily to provide a degree of protection against windblown dust and rain, splashing water, and hose directed water; undamaged by ice which forms on the enclosure.

boring locations where evacuees settle. Extreme weather events can also damage chargers, impact their availability, and reduce efficiency and speed of charging, thereby requiring longer charging times or posing delayed access. Impacts identified in the literature include [42]:

- Spikes/congestion in charging in preparation for an incoming weather event, if sufficient warning is provided
- Power outages render EVSE unusable, requiring EVs to drive further to access functioning stations
- Strong winds, flooding, and other externalities can damage EVSE and related infrastructure
- Beyond extreme temperatures, stormy conditions can disrupt access to chargers and thereby slow charging success and thus extend charging periods
- Disruptions to cellular networks can interrupt connectivity between EVSEs and charger networks (loss of visibility and/or control)

3.2.3.4 EV/Fleet Smart Charging as a Resource

The intersection of EVs and climate impacts presents both challenges and opportunities for grid resilience. Cold and hot temperatures significantly affect EV performance, reducing battery function and increasing energy demands for HVAC, leading to more frequent and longer charging events, and more demand on the power grid. To mitigate grid impacts, EVs may participate in smart charging to reduce strain on the grid, including during extreme weather events. Despite the growing literature, there remains a lack of empirical data on the effects of climate emergencies on EVs, their charging, and smart charging applications, with most information derived from modeling. Further investigation is required to understand climate impacts on EV/Fleets, as there is significant uncertainty about the effectiveness of smart charging programs during extreme weather events as opposed to during normal climate conditions.

3.2.4 Data Centers

A data center provides power, physical space, and cooling to enable hosting of information technology (IT) infrastructure. IT infrastructure includes computing servers, storage devices, and networking equipment, which together enable hosting of applications for the business operating in the data center. The general purpose of a data center is to enable high availability of applications to enable continuity of the business for its customers.

Data centers represent one of the fastest growing industries in the United States. The digital transformation enabled through the advent of internet over the last 30 plus years is driving the growth of data centers. They serve as the backbone of many modern business enterprises, providing a centralized location for storing, processing, and managing large amounts of data and applications. They play a critical role in ensuring the availability, reliability, and security of digital information and services in today's interconnected world.

Table 1 summarizes the various type of data centers that exist today. Each data center type can be characterized by purpose, size, and scale, as well as typical physical location and ownership. Data centers can vary greatly in size, from small server rooms within a single building to massive hyperscale facilities spanning hundreds of thousands of square feet or more. In between in size and scale are enterprise and multi-tenant data centers, which host enterprise applications for a single organization or multiple organizations, respectively. Data centers are essential for various purposes, including hosting websites, running cloud computing services, storing and processing big data, facilitating disaster recovery, and supporting enterprise applications and IT infrastructure.

Data centers are generally located closer to cities, so they can provide low latency application response times. In some cases, data centers built for hyperscale size are located closer to power generation sources, which may be remote in location. Moreover, landing station data centers, which provide internet connectivity between continents, are located close to ocean shores.

Table 1. *Taxonomy of data center types*

TYPE OF DATA CENTER	PURPOSE	TYPICAL OWNERS	SIZE AND SCALE	LOCATIONS
Small Server Room	Network point of presence, local office, enterprise campus	Enterprise companies (Fortune 2000)	200kW to 1MW	Within enterprise campus or office
Enterprise	Host enterprise applications to manage business	Enterprise companies (Fortune 2000)	1MW to 20MW	Within multi-tenant data center or enterprise location.
Multi-Tenant	Multiple organizations can host their data centers in a single location	Private equity firms, data center providers	20MW to 300MW+, 100+ acres	Close proximity to large cities
Hyperscale	Application services provided by webscale providers	Cloud service providers, large technology companies	100MW+, 1 million servers, 100+ acres	Remote locations
Landing Station	Provide Internet connectivity between continents	Subsea cable owners	4 to 20MW	Close to ocean shore

Appendix B provides further background on data centers. A functional perspective on stakeholder types within the data center industry and how they are related is illustrated, along with examples of stakeholders and data center load profiles.

Several climate variables may impact data centers:

1. Average temperature increases
2. Drought impacting water availability
3. Extreme heat and cold weather

Climate conditions may also impact insurability, uptime, and overall resiliency of data centers.

3.2.4.1 Temperature Impacts on Data Centers

Climate change is expected to increase average annual temperature in many regions of the world which would increase data center energy use in most climates due to reduced cooling efficiency at high outdoor temperatures. These impacts can be attributed to reduced chiller efficiency at high outdoor temperature (above 95°F or 35°C) [45]. In addition, a warming climate reduces the number of hours that economizers can provide high-efficiency cooling. On the other hand, data centers without an economizer may experience a decrease in energy use in winter due to chiller efficiency, space conditioning loads, and generator block heaters. On the whole, the increase in energy use for data center cooling under warming climate conditions is not expected to cause significant changes to data center load profile or siting.

The frequency and severity of extreme temperature events may increase with climate change, which may impact data centers as well. The cooling capacity and efficiency of the cooling system decrease at high outdoor or extremely low outdoor temperatures and could impact overall data center operations. Given the high heat load in a data center, proper operation of cooling equipment is critical to prevent information technology (IT) equipment from overheating. When extreme temperature events exceed these design conditions there is a risk that the cooling system is not able to satisfy the cooling load. This may cause the cooling equipment to operate continuously at full capacity while temperatures inside the data center potentially rise, resulting in a potential risk of IT equipment overheating as well as cooling equipment failure, depending on the severity and duration of the event. A similar risk occurs with

temperatures below the rated operation of cooling equipment, although the potential and impact of this risk is lower for extreme cold events than extreme heat. As an example, Google's data centers had an unexpected outage during a heatwave in the UK [46]. Similarly, data centers operated by X (formerly known as Twitter) had an outage in California that impacted their service [47].

3.2.4.2 Impacts of Drought

One major risk for water-cooled data centers—which includes many large data centers—is water availability, which may be constrained due to increased frequency and severity of drought. As noted earlier, larger data centers may consume water for final heat rejection through evaporative cooling towers [48]. Such a design offers improved cooling efficiency at the expense of increased water use and maintenance. In regions where drought becomes persistent, there is risk that water use may become increasingly expensive and potentially difficult to secure (for new facilities) [48]. This may lead some new data centers to choose more water efficient technologies, potentially increasing their relative energy use. As an example, Google's permit for a data center in Chile was rejected due to water use in drought conditions [49].

3.2.4.3 Data Centers as a Resource

Despite the relatively flat load profile of different types of data centers, there may be an opportunity for some data centers to provide a resource to the grid through demand response (DR). Strategies for adjusting power demand include utilization of the following equipment.

- **Backup Generators:** To offload some or all data center's load from the grid when grid conditions are constrained. Yet this approach can be subject to operational limits (e.g., number of hours of total runtime or criticality of event) depending on local regulations for emissions (including noise) caused by combustion generators.
- **Uninterruptible Power Supply (UPS)/Battery:** Data centers typically employ batteries as a "bridge" power to IT loads (via the UPS) while the backup generator comes to full operation, typically on the order of 5–10 minutes. Conventional UPS technology using lead acid batteries is limited by the number of discharge cycles it could operate without degradation. However, recent advances in Li-ion batteries integrated into UPS systems, allow these batteries to be discharged more often over the UPS life.
- **IT Workload:** Some non-urgent IT processes can be scheduled to shift IT load. For example, backup storage routines and roll-out of software updates can be conducted to avoid peak demand hours and during times of minimal impact on users.
- **Cooling System:** Raising temperature setpoints inside the data center, can lead to increased IT equipment power use as server fans increase speed to maintain internal hardware temperatures within operating limits. While there may be an initial decrease in chiller power, viability of this strategy may vary by data center type and requires further investigation.

In addition to the direct risks outlined in the sections above, insurability may present an indirect risk to data centers in certain locations. Regions where severe weather events become more frequent or intense, insurance may become increasingly expensive or difficult to acquire for data centers. Certain regions may experience increased frequency and intensity of major wildfires or flooding, both of which threaten buildings and assets of all types. Yet given the risk aversion of data centers, such a threat may make certain regions particularly unappealing, potentially to the point of causing existing data centers to shut down, significantly impacting projected loading on the grid.

3.2.5 Crypto Mining

Cryptocurrency mining is also conducted in facilities dominated by IT loads, yet has several key distinctions from conventional data centers. When mining for cryptocurrencies—notably Bitcoin— computationally intense algorithms are run to cryptographically secure transactions while remaining anonymous and distributed [50].

3.2.5.1 Temperature Impacts on Crypto Mining

Mining facilities are very electricity price sensitive [51]. Unlike conventional data centers, crypto mining is not as sensitive to interruptions, such that these facilities generally do not employ power conditioning (i.e., UPS) or backup power resources. In addition, they typically do not employ active cooling, but instead rely on direct use of outdoor air to cool mining hardware, which can tolerate operation at higher temperatures than recommended for conventional data centers. This makes crypto mines more sensitive to fluctuations in outdoor conditions than conventional data centers, particularly at high temperatures. During periods of extreme heat, crypto mines can experience increased hardware failure rates and may choose to curtail some or all the load to protect the mining hardware.

3.2.5.2 Crypto Mining as a Resource

These facilities can voluntarily shed load during periods of grid stress and have participated in utility load interruption programs. In some cases, participation in utility load curtailment programs can outweigh the revenue from mining during summer peaks [51]. As an example, in Texas a Bitcoin miner was paid more than $31.7M for interrupting power usage during emergency system-wide peak load in August [51].

4 GAPS IN THE LITERATURE AND RESEARCH NEEDS

In general, there is a lack of research on the effects of climate on emerging assets such as distributed energy resources and key end-use products. The proliferation of DER on the utility grid is a relatively new phenomenon and the majority of DER research is focused on safely and reliably interconnecting the DER during normal operation – let alone during abnormal conditions that could result from climate change. Likewise, electric vehicles and their associated charging infrastructure are technologies that have only recently begun to emerge as a key transportation mode globally. And though electric heat pump technology has been around for several decades, its role in a low-carbon future has only been considered much more recently.

It is typically assumed that these technologies are all generally designed to regional specifications, and as such, can withstand local weather extremes without failure or significant loss of efficiency. However, these assumptions must be validated considering a projected changing climate and accelerated presence of these technologies in support of decarbonization efforts. Future research is to be geared to quantify under which climate scenarios failures or losses of efficiency of these assets are likely and to modify existing codes, standards, and best practices and/or to develop other technologies that can help mitigate the effects of extreme temperature and other key physical climate hazards.

5 CONCLUSIONS

Climate change is expected to bring changes in natural hazard risks to DER and end-use assets. Key physical climate drivers to these assets include air temperature extremes, drought, and flooding, although severe storms and other climate variables can also be a concern. Combinations of these changing hazards may create additional risk. Risk varies with geographic location since climate change will impact different regions in different ways, and these assets

are generally designed to current or historical regional specifications. Climate change risks associated with geographic characteristics should be evaluated when considering DER assets or adoption of specific end-use technologies.

DER and energy storage are valuable grid assets that are also capable of supporting resilience, but several questions must be answered to optimize their applications. The lack of a standardized method to measure and value resilience remains an economic barrier to deploying microgrids. The electric power industry has little experience with managing a high DER penetration grid, dominated by inverter-based resources. Vulnerabilities of DER and storage to extreme climate events must be studied and incorporated into system planning. What additional effects does prolonged exposure to extreme heat and cold have on batteries and other DER performance? What kind of events will have the most significant impact on DER? What types of DER are most susceptible to damage from future and more frequent extreme weather events? What can be done to make DER even more resilient to lessen the frequency and effects of grid outages? DER are a growing part of the grid and will play a key role in resiliency as both energy demand and the frequency of climate change related weather events increase, so addressing these gaps will be important as DER and storage adoption continue to grow and the effects of climate change increase.

Similarly, the reliability and efficiency of electric end-use products are projected to have an increased significant effect on standard of living globally because adoption rates are projected to rise as society transitions to a low carbon future. Since climate change is likely to disrupt the normal operation of various parts of the economy, assessing the vulnerabilities of end-use assets will be essential. Characterizing key climate vulnerabilities will help guide mitigation efforts and will inform system planning. Upcoming READi research will characterize adaptation strategies to build resilience of end-use assets and DER.

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APPENDIX A

This appendix provides details on case study examples illustrating temperature impacts on EV Fleet charging. Heavy-duty fleets (transit bus and school bus) are first discussed followed by light-duty fleets.

A.1 Public Transportation Bus Fleets

Public transportation (transit) bus fleets, as heavy-duty vehicles, require substantial levels of energy and power to sustain their operations. It is well known in the industry that weather through HVAC use can diminish the driving range of battery-electric buses [35]. To assess vehicle performance, simulation was conducted to emulate electric school bus performance based on several elements, including route length, topography, duty cycles, passenger loads, and ambient temperatures. The results of energy modeling help inform on-board battery capacity requirements to meet daily vehicle duties, as well as bus charging profiles that inform the type of EVSEs needed and electrical infrastructure required.

Through energy modeling and route simulations of a large bus fleet in northern Michigan, a study by BetterFleet estimated the electrification success rates of buses, or the rate of completion of bus route with at least 20% SOC. The study examined success rates with smaller (435 kWh) and larger (738 kWh) battery packs in response to a variety of ambient temperatures. As indicated in Figure 5 for both battery capacities, success rates were greater on mild (59°F) days (84% for 435 kWh buses and 99% for 738 kWh) and dropped on very hot (95°F) days (65% for 435 kWh buses and 89% for 738 kWh), and fell even further on very cold (10°F) days (39% for 435 kWh buses and 77% for 738 kWh). This observed mitigation of success rates is largely due to the greater use of HVAC to control cabin temperature, which consumes battery energy that would have been otherwise used to move the bus. Larger battery packs improve success rates (i.e., completion of bus routes with ≥20% SOC) because they carry more energy.

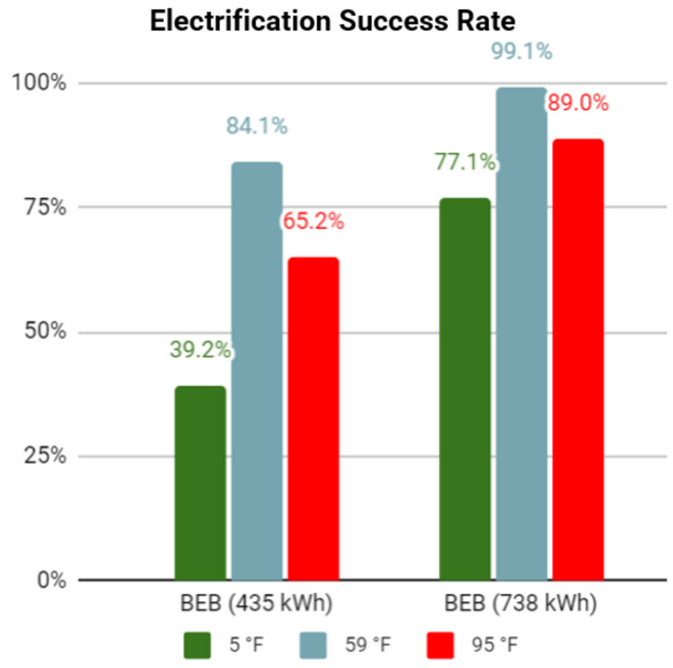

Figure 5. *Success rate comparison under varying temperatures for small vs. large battery electric buses*

To understand the impact of temperature on charging requirements, BetterFleet modeled the charging profiles of the fleet of 145 transit buses on different temperature days. The results in Figure 6 show charging profiles for the 145-bus fleet under an unmanaged charging regime, meaning that buses will charge whenever they are in the bus depot, are plugged in, and need energy. Figure 7 shows results under a managed charging regime that seeks to reduce charging during peak energy rates (denoted by red bands that are based on time-of-use peaks occuring year-round) and minimize peak power demand.

With unmanaged charging, on a mild day, the modeled peak fleet demand is ~5.5 MW, while on a cold day that peak increases to ~8 MW versus to ~7 MW on a hot day (Figure 6).

On the other hand, with managed charging, on a mild day, the peak demand is ~3.25 MW, while on a cold day that peak nearly doubles to 6 MW and increases to ~4.5 MW on a hot day (Figure 7).

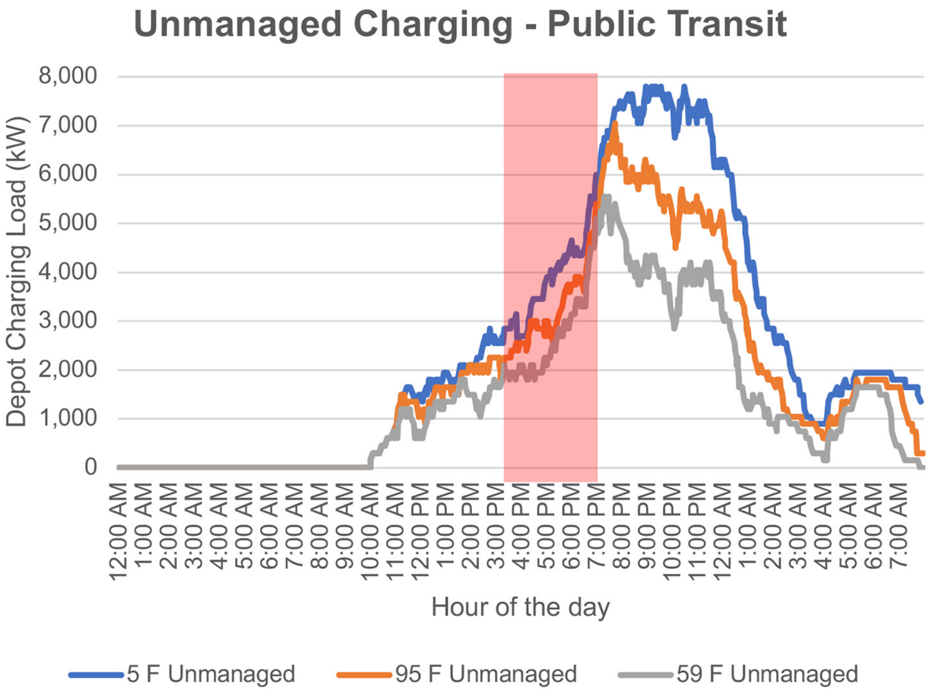

Figure 6. Temperature impact on electric transit bus unmanaged charging load

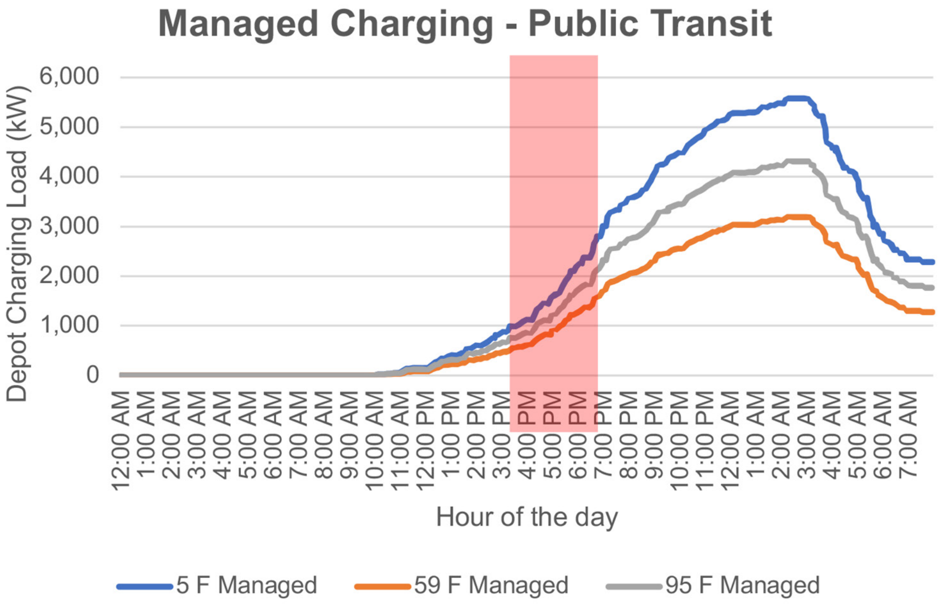

Figure 7. Temperature impact on electric transit bus managed charging load

Regardless of managed vs. unmanaged charging, the result of either hot or cold weather days is that more chargers are required since the occupancy of an individual charger is longer, which therefore increases power consumption and demand.

A.2 School Bus Fleets

BetterFleet also worked with a large school bus operator in Michigan to develop an electric school bus feasibility study to understand whether electric school buses could deliver service as currently delivered by a diesel fleet of school buses. The results of the energy modeling help inform on-board battery capacity requirements to meet daily vehicle duties, as well as bus charging profiles that inform the type of EVSEs needed and electrical infrastructure required.

Figure 8 and Figure 9 show the charging profiles of a fleet of 54 battery-electric school buses simulated on cold and warm days, for unmanaged and managed charging cases, respectively. Managed charging seeks to minimize overall peak power demand, while also shifting or minimizing charging during high energy price periods, indicated by red shading in the figures. (The shaded period represents peak pricing year-round under a representative time-of-use rate). Evaluating 10°F and 77°F ambient temperature conditions on vehicle performance (indicative of vehicle fuel efficiency) resulted in lower SOCs on 10°F compared to 77°F days, and thus greater charging requirements on 10°F days.

In simulated unmanaged charging scenarios (Figure 8), under mild 77°F conditions, fleet power demand during the evening charging session starts to drop off around 9 pm; while on 10°F days, charging continues to have high power demand well into in the overnight period. On colder days without managed charging, power demand is higher for longer.

In contrast, when simulating managed charging, peak power demand is reduced regardless of temperature compared to unmanaged charging. Nonetheless, with managed charging on mild days, the fleet peak demand is ~500 kW, while it reaches ~700 kW on a cold day (Figure 9). This is a result of the need for more chargers and longer charging events to replenish electric school bus batteries that are depleted to lower SOCs on cold days than on mild days due to the HVAC parasitic load.

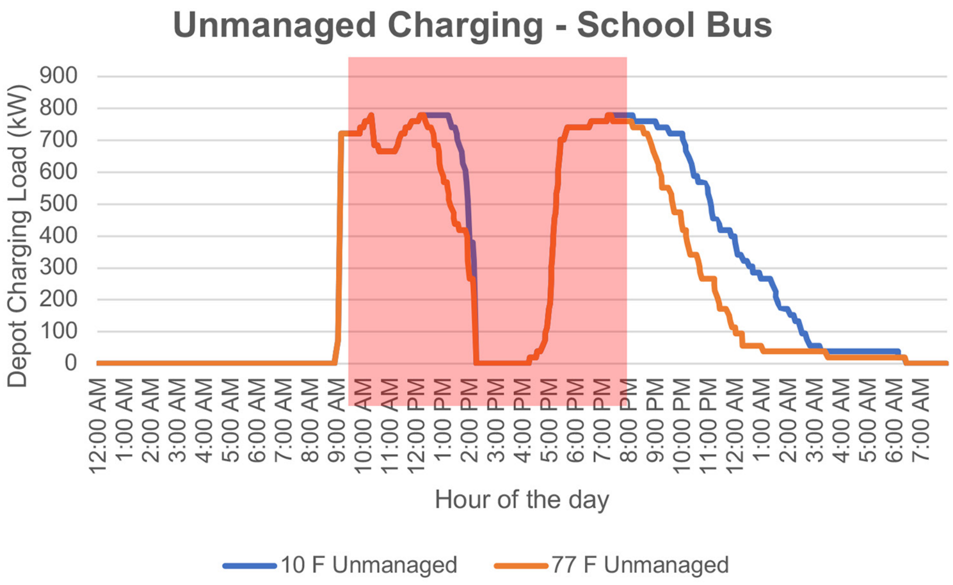

Figure 8. *Temperature impact on electric school bus unmanaged charging load*

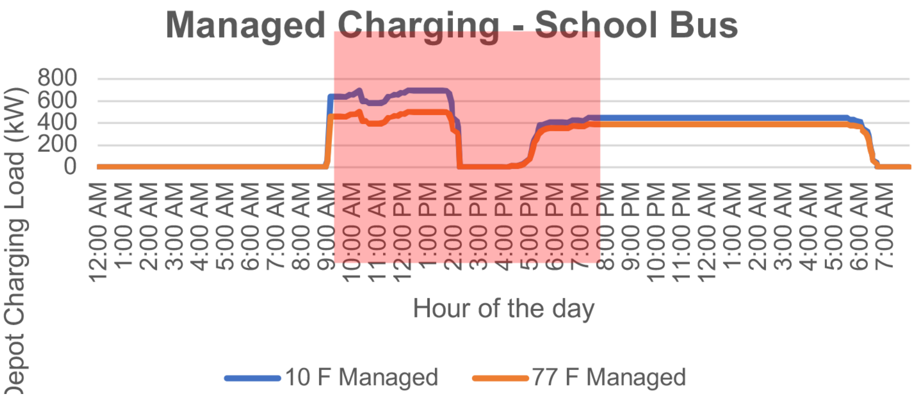

Figure 9. *Temperature impact on electric school bus managed charging load*

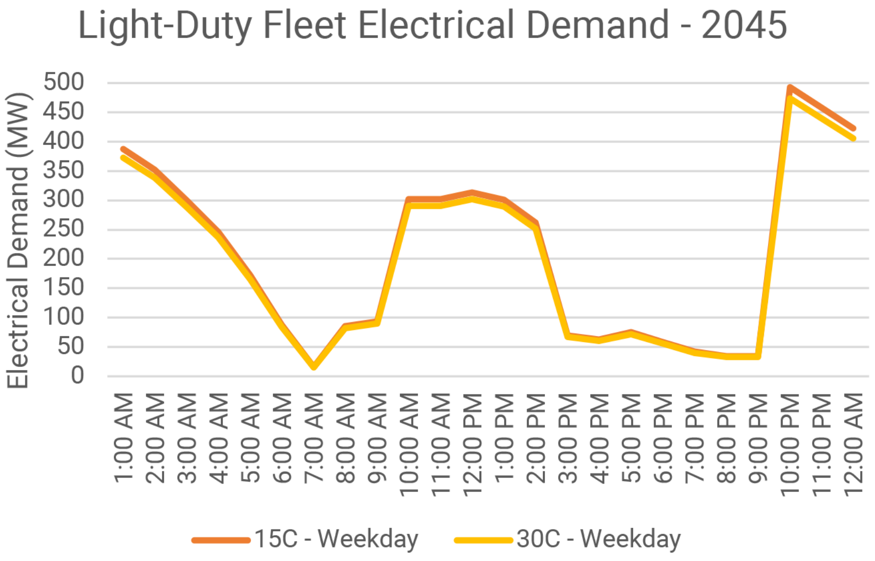

Figure 10. *Load forecast for commercial and government light-duty electric vehicle charging*

A.3 Light-Duty EV Fleets

BetterFleet worked with the electric utility in the Australian state of South Australia, South Australian Power Networks (SA Power Networks), to provide postcode level forecasting for EV uptake and associated electrical demand across South Australia over the years 2025–2045. Simulations were conducted atop a GridFleet™platform that enables electric utility forecasting teams to spatially allocate demand to specific geographical areas. The platform utilizes real, catalogued and emulated data to create load curves for summer, winter, weekday and weekend with a focus on annual peaks. The model considers EV arrival and departure times, EV energy requirement, and EVSE capacity.

The graph in Figure 10 demonstrates the forecasted power load for commercial and governmental light-duty EVs in 2045, based on a fleet typology that employs EV uptake curves over time for different fleet segments. The seasonality impact is modeled based on average temperature ranges for South Australia. A typical summer day is modeled at 30°C and winter is modeled at 15°C.

The forecast demonstrates that charging gradually decreases overnight, and then ramps up during the midday, finally decreasing in the late afternoon and early evening until it picks up again to commence overnight charging. Cooler weather (at 15°C) requires more cabin heating, depleting EV batteries more fully, and necessitating more power for charging. However, compared to the modeling in Figure 8 with more extreme temperature ranges experienced in Michigan, the curves in Figure 10 above demonstrate how the milder winter conditions have minimal impact on electrical demand, with only about a 4% increase in demand at peak times during winter vs. summer.

APPENDIX B

This appendix provides background on the data center industry including key metrics and types of stakeholders, differentiable by function(s) the stakeholder performs. The section concludes with several examples of data center load profiles for two types of data centers.

B.1 Power Usage Effectiveness

Data Center Power Usage Effectiveness (PUE) is a metric used to assess how efficiently a data center utilizes energy. In simpler terms, PUE indicates how much of the total energy used by the facility goes towards powering the actual computing equipment (servers, storage, etc.) compared to the energy used for supporting functions like cooling and lighting. PUE is calculated by dividing the total facility energy consumption by the energy delivered specifically to the IT equipment, as in PUE = Total Facility Energy Usage/ IT Equipment Energy Usage. A perfect PUE score of 1.0, indicates 100% of the energy is used by the IT equipment, with no energy wasted on supporting functions. The lower the PUE the less the data center is using for cooling and other overhead compared to the actual computing power. In terms of industry average, PUE values for data centers can range from 1.2 to 2.0, with lower numbers indicating more efficient facilities.

B.2 Components of a Data Center

The following components and infrastructure are critical in the operations of data centers.[3] Additional components include physical security (e.g., fenced secured perimeter), firefighting system, and network operations center.

B.2.1 Server Room

In the Data Hall, which is a secure room, IT equipment such as compute servers, network devices and storage devices are managed. The data hall is kept air conditioned, climate controlled including humidity and continuously regulated to ensure that the IT equipment can operate and does not overheat or damage. The equipment is interconnected using cabling systems of various types.

B.2.2 Meet Me Room

The Meet Me room is the network connectivity room, where several network connectivity providers and internet service providers connect their network equipment together to enable access across various networks for all users to get access. This room has significant climate control, physical security and automated patch and cabling systems that need to be managed.

B.2.3 Power Chain Including Uninterruptible Power Supply

This is the heart of the electrical supply to the data center and all the data center components. This includes switch gear, distribution systems, generators, UPS, battery systems, energy management and enables power delivery even if one of the energy systems fail.

B.2.4 Cooling System and Energy Management

For the IT equipment to be performing, it is important that constant regulated cooling is provided to the Data Hall, to ensure uptime of all the applications being serviced from the

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[3] https://www.dutchdatacenters.nl/en/data-centers/how-data-centers-work/

data center. The cooling systems in a data center includes equipment such as chiller plant, heat exchangers, distribution systems, air handlers, management systems, and so on.

Efficiency in cooling can have the biggest impact in the overall electricity usage as well as water usage within the data centers. Such thermal management systems are a key component of what is known as the overall building or facility management systems.

B.2.5 Energy Supply

Data centers tend to consume significant amounts of energy to power customer IT equipment as well as facility systems, such as for space conditioning. Energy is usually supplied through the utility provider using a substation that can be onsite at the data center or off site.

B.2.6 Offices and Conference Rooms

Data centers are also building where there are people that come into work and thus require an appropriate office infrastructure such as a working spaces and meeting rooms. This is an important part of the infrastructure to enable remote teams to collaborate with people in the data centers.

B.3 Stakeholder Types

The data center industry is comprised of many types of stakeholders, from data center operators and owners down to real estate developers who hire general contractors to construct or expand data centers. The general contractor in turn contracts with many other supply chain vendors and contractors, including engineering, procurement, and construction (EPC) firms. Each key type of stakeholder can be differentiated by the distinct functions performed for the data center industry. One company can perform a single or multiple functions characterized below, as is the case with big tech, which performs multiple functions, beginning with real estate development an ownership in many cases and ending with data center operations and usage.

Key types of stakeholders include:

1. **Real estate developer:** Acquires land, submits preliminary development plans, and signs power purchase agreement(s) with the utility and/or alternate provider
2. **General contractor (GC):** As a construction firm, signs development agreement with the landowner
3. **Architecture, design, and planning contractors:** Helps the GC design and build the facility physical shell under permits for construction
4. **Engineering, procurement, and construction (EPC) firm:** hired by the GC to manage all aspects of electric infrastructure and interconnection with the utility grid.
5. **Mechanical, electrical, and plumbing (MEP) contractor:** Vendor that builds mechanical, electrical and plumbing systems within the facility shell
6. **Distributors and suppliers:** Hired by the GC to deliver all products, materials, and supplies for build out. Supplies procured span IT infrastructure as well as equipment to provide facility services.
7. **Data center operator:** Responsible for the day-to-day operations of the data center 24x7.
8. **Data center owner:** An entity claiming ownership of the data center and the land on which it sits. Pure owners have a financial interest and do not necessarily hold responsibility for day-to-day data center operations.

Figure 11 illustrates the relationship of stakeholder types, and provides illustrative example of each type.

Figure 11. *Relationship of data center stakeholder types with illustrative examples*

B.4 Load Profile Examples

This appendix concludes with load profile examples from two different classes of data centers: enterprise and multi-tenant.

B.4.1 Enterprise Data Center Load Profile

Figure 12 illustrates a load profile from a mid-size enterprise data center in Ohio, collected over two years from October 2016 to October 2018. This facility used direct expansion type computer room air conditioners for cooling and had no economizer. On the left is the hourly demand history (average kWh/hr) over one month (September 2018). On the right is the demand profile, showing average, 5th percentile, and 95th percentile of demand for each hour of the week. Hourly demand is seen to fluctuate from about 830 kW to 1,030 kW over this month with regular dips to about 430–490 kWh/hr. These dips were determined to be the results of regular generator tests at the site, which occurred between 10–11am on Friday mornings. Over the week, average demand is seen to increase during business hours (7am–5pm Monday–Friday), rising slightly during afternoon hours and dipping slightly at 4am. This site was supported by onsite staff, who had offices and a small break room, which can be attributed for some of the increase during business hours (space conditioning, lighting, and plug loads).

Figure 13 shows how demand at the site fluctuated over the monitored period, with monthly averages on the left. The highest month was July (952 kW) and the lowest month was April (877 kW), a range of just 8.6%. The highest hour was seen on 9/4/18 (1,071 kW), a Tuesday with high temperature of 94°F. This represents a 17.8% increase over average demand over the entire monitored period, which is a load factor of 84.9%.

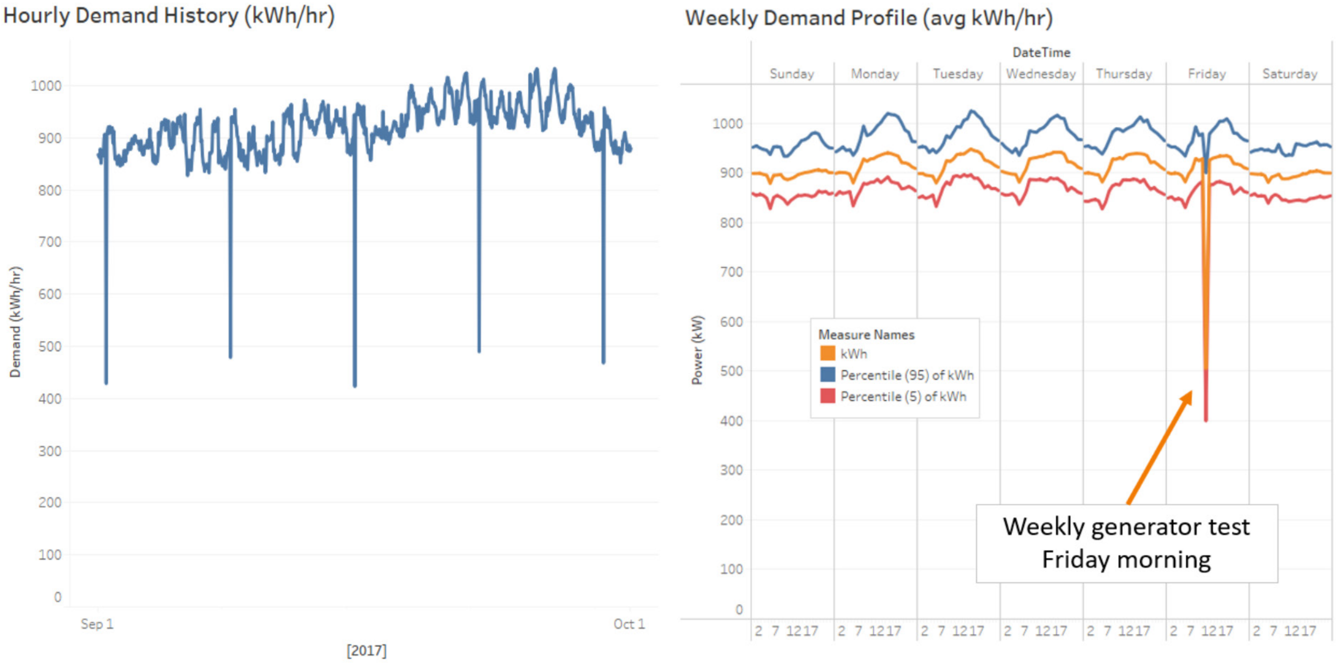


Figure 12. *Load profile example from a mid-size enterprise data center in Ohio*

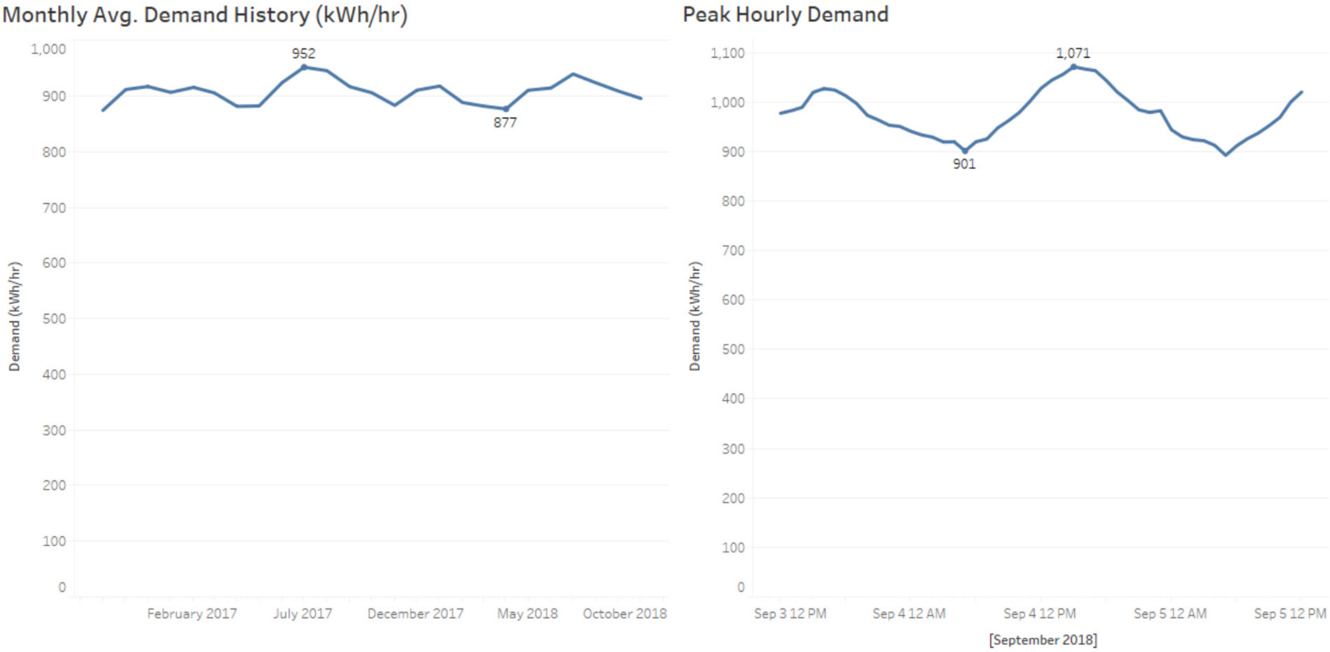
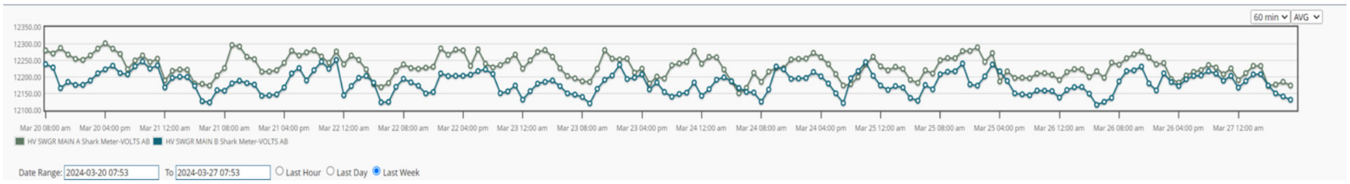


Figure 13. *Example demand fluctuations by month and peak hour*

B.4.2 Multi-Tenant Customer Load Profile

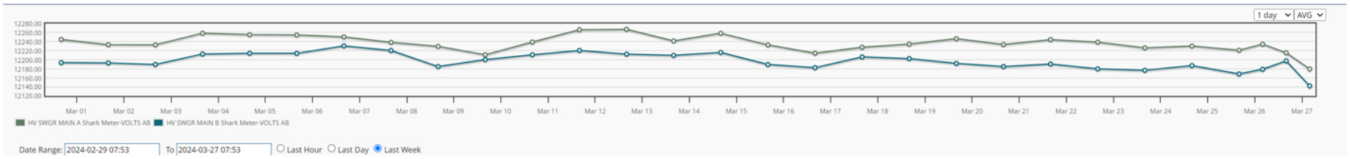
Figure 14 illustrates a load profile from a multi-tenant data center in Silicon Valley, California. This facility is served by two service drops from the local utility for redundancy, and has two onsite backup generators for reliability. Figure 14 provides a snapshot of power consumption measured for one anonymized tenant at the facility. Figure 15 provides a monthly snapshot illustrating minor fluctuations in daily average load.

The load profiles are illustrative and may not necessarily reflect other data centers in the same class.



Date Range: 2024-03-20 07:53 To 2024-03-27 07:53 ○ Last Hour ○ Last Day ● Last Week

__Figure 14.__ Example demand fluctuations for one week



Date Range: 2024-02-29 07:53 To 2024-03-27 07:53 ○ Last Hour ○ Last Day ● Last Week

__Figure 15.__ Example demand fluctuations for one month

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