Quick Insights

Impacts of Extreme Temperatures on HVAC Load and Flexibility Capacity – Implications for Power System Operation

OVERVIEW

Extreme heat events in the U.S. Pacific Northwest (PNW) have pushed air conditioning (AC) loads to unprecedented levels, creating uncommon summer peaks for traditionally winter peaking PNW power systems. These extreme heat events are prompting new research and discussion on how interactions between the operation of heating, ventilation, and air conditioning (HVAC) systems, the thermostats that control them, and the surrounding building envelope potentially drive different residential demand dynamics in extreme temperatures and, subsequently, how this demand affects power system operation.

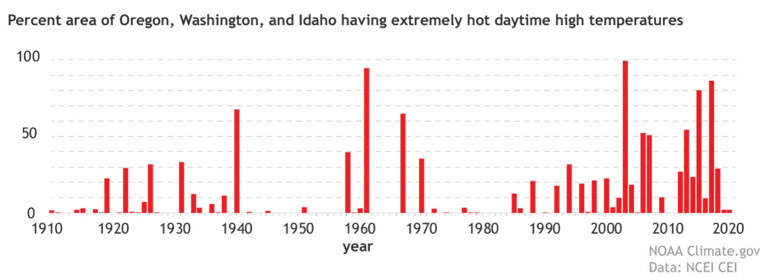

Figure 1: Extreme summer heat in the Pacific Northwest has been increasing in magnitude and area coverage. [5]

This *Quick Insight* examines how extreme temperatures affected power system operation during recent events and how these events have affected flexible load availability of residential HVAC systems. Examples and recommendations are offered on how peak system demand can be managed, and further research areas are identified to strengthen resource adequacy planning of demand-side resource capacity, with considerations for how grid operators may continue to maintain reliability of supply during extreme temperature events.

KEY POINTS AND TAKEAWAYS

- The design approach for HVAC systems may need to be revised by working closely with climate scientists to understand how increasing average temperatures and extreme temperature events may vary across regions in the coming decades. Globally, energy demand for space cooling may triple, due to the projected growth in AC units from around 2 billion units in 2020 to 5.5 billion units in 2050 [1].
- Load flexibility is a valuable resource for managing peaks in system demand; however, prolonged extreme heat or cold events that breach local HVAC design conditions may (A) diminish the ability of programmable and smart thermostats to provide load turn down, and (B) elevate risk of power outages due to thermal overloading of distribution infrastructure as feeder load diversity decreases.
- Building envelope efficiency, and efficient HVAC equipment, may reduce overall energy demand and the magnitude of a building's peak load, to make pre-cooling/heating strategies more effective. Consideration should be given to avoid ramp-related scarcity as HVAC loads come back online after demand response (DR) events.
- While public appeals for load reduction may yield results, it may be difficult to plan for or rely upon a specific load outcome. Increased, diversified flexible load capacity that includes residential, commercial, and industrial loads, as well as energy storage, has the potential to spread out energy reductions and hedge against lower-than-expected response from demand-side resources.

INTRODUCTION

Flexibility from customer-owned distributed energy resources (DER) is an increasingly valuable and cost-effective resource in demand-side management (DSM) portfolios. This flexibility allows power systems to quickly balance supply and demand, manage capacity constraints, and defer investments in traditional infrastructure.

The importance of DER flexibility is growing, as electrification increases, and the number of residential AC units increases globally due to (A) economic growth in emerging nations and (B) rising average temperatures and more frequent and prolonged extreme temperature events in traditionally temperate regions [2]. As AC unit adoption expands, grid operators and planners should consider how climate change may influence peak demand and the effect extreme temperatures may have on the reliability of load reductions from residential HVAC systems with smart thermostats.

Peak system load and load reductions from HVAC during extreme temperature events may depend upon the following factors, some of which will require further research to understand and quantify their potential impact:

1. The duration of time and the total difference between outdoor temperatures and the local American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) design conditions.
    a. How does the difference between outdoor temperatures and the local ASHRAE design temperature range effect the availability of flexible load from HVAC?
2. What share of HVAC systems are correctly or incorrectly sized to the local ASHRAE design condition? How might design approaches be revised so that HVAC systems are sized for the future climate?
3. The number of Demand Response (DR) events that occur over the course of a cooling/heating season.
4. The share of buildings that have a HVAC system, and the share of these HVAC systems that are fixed or variable capacity.
5. The energy efficiency of the building stock.
6. The quantity and diversity of DSM resources.
    a. Quantity: What portion of a systems peak load is available for flexibility services via DSM programs?
    b. Diversity: What portion of a system's flexibility capacity is comes solely from residential HVAC control?

IMPACT OF EXTREME TEMPERATURES

Spotlight: "Heat Dome" in the PNW

Extreme temperature events can occur when the usual west to east flow of air masses becomes disrupted by large areas of high-pressure that stagnate [3]. This high-pressure system blocks the air mass and forces it to move either equatorward or poleward. It also slows the usual transient flow of the air mass, causing it to persist for several days to several weeks [4]. A stagnant high pressure system along with extensive drought across the western U.S. are considered the primary drivers of the recent heatwave in the PNW [5]. The region's topography is also thought to have played a role, with easterly winds dropping from higher elevations and compressing, adding to the heat. With climate change, extreme temperature events are becoming more common; it is estimated that by 2050, Northern Hemisphere cities will have climates similar to those of cities in different climatic regions approximately 1000 km south of them [6].

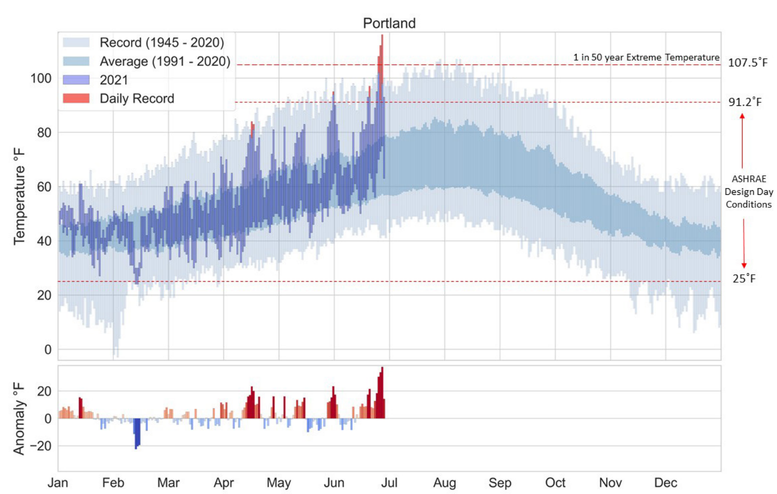

Figure 2: Temperatures in Portland in 2021 compared to the historical record, average, ASHRAE design day, and 1 in 50 year conditions. [18]

EPRI modeling found that when climate warming is considered, all scenarios modeled show increased cooling demand over time in all regions of the U.S. These results demonstrate the anticipated effects of climate warming on future cooling demand and the projected growth of HVAC system adoption in traditionally temperate regions. Revealing the importance of accounting for the climate change warming effect when projecting and planning for future power system demand [7].

The PNW is traditionally a winter peaking power system. Between 1993 and 2011, the annual peak day was seen between November and February [8]. The recent "heat dome" caused extreme high temperatures for five consecutive days, with two days above 110°F, and maximum temperatures of 116°F recorded in Portland on June 28, 2021 (Figure 2). High temperatures resulted in higher electricity demand as HVAC systems worked overtime to try and maintain comfortable indoor temperatures, particularly in urban areas like Portland and Boise, as seen in Figure 3 [9]. Portland General Electric (PGE) saw peak system demands of 4.2 GW and 4.4 GW on June 27th and 28th respectively, shattering the previous 4 GW record from December 1998 [10].

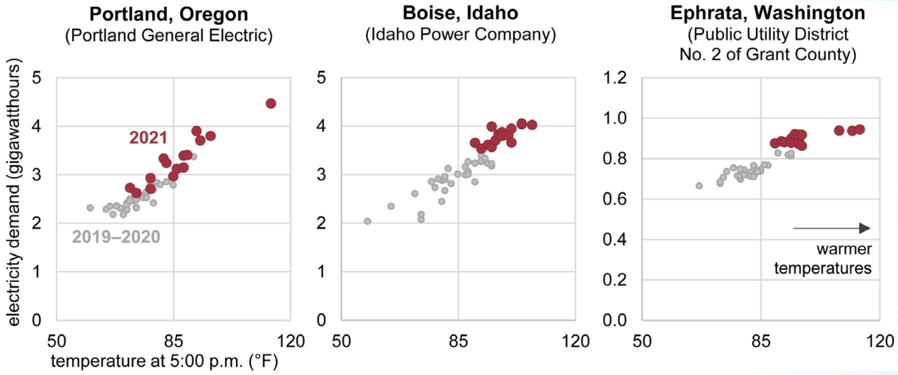

Figure 3: Hourly temperatures in select cities and electricity demand in select balancing authorities during the first three weeks of summer 2019 – 2021. [9]

In this case, grid operators were able to leverage the available hydro resource, power from California, and DR to balance system demand and generation. However, a few utilities reported outages due to strained distribution infrastructure or as proactive measures to prevent equipment failure. Outages were reported by Puget Sound Energy (PSE) affecting 3,400 customers, and by Avista affecting 8,000 customers on June 28th, with more planned outages on the following day [11]. DR in the PNW appears to be underutilized, as an example, the reported potential DR available in 2019 was 62.8 MW for PGE and 35 MW for BPA (at just 1.7% and 0.4% of their respective summer peaks for that year) [13].

The Human Element: In Multnomah County, Oregon, "cooling shelters" were set up to allow people without AC to escape the heat. Still, a preliminary report cited 54 resident deaths attributable to the heatwave, mostly older persons living alone and without AC. The report found that a lack of AC in homes and apartments, along with high nighttime temperatures, was the primary driver of heat-related illnesses and fatalities [12]. In Seattle, only 44% of single-family homes have primary AC installed, while in Portland, that figure sits at 78%. Between 2011 and 2017, the PNW region saw an increase in the share of single-family homes with some cooling system, from 42% to 57% [13].

> In British Columbia a record temperature of 121.3˚F was recorded, 40,000 customers lost power, and over 719 sudden deaths were recorded by Vancouver police. [41]

Research has shown that globally the correlation between per-capita GDP and AC ownership is stronger than the correlation between climate (i.e., number of cooling degree days) and AC ownership. In emerging nations, economic factors are driving AC ownership, while in traditionally temperate regions with historically higher per-capita GDP the changing climate and more common extreme temperatures are also influencing AC adoption [2]. This highlights the equity considerations needed to make efficient AC equipment and building efficiency retrofits accessible for all.

August 2020 Heatwave: California

On August 14, 2020, extreme temperatures drove peak demand 2.2 GW higher than forecast demand, just as solar and wind output lowered. The California Independent System Operator (CAISO) dispatched all available DR resources (~65% industrial, 21% residential and 14% commercial) [23]. Of a potential 1,472 MW, 910 MW of actual load drop was achieved [40], but this was insufficient to balance demand with supply and resulted in rolling outages to 1,000 MW of firm load that lasted 1 to 3 hours. A similar situation on August 15th caused outages to 500 MW of firm load. Following these two days, a state of emergency was declared to conserve energy, reducing peak demand over the next three days by up to 4GW compared to the day-ahead forecasts. This happened in conjunction with other demand reduction measures, and amid lower temperatures than the previous days. Without an isolated experiment, the effect of public appeals is hard to quantify and predict. For this reason, public appeals tend to be leveraged only as a last resort.

HVAC Systems and Demand Response in Extreme Temperatures

A recent EPRI Quick Insight discussed in more detail the operating dynamics of heating and cooling systems in extreme temperatures and the potential effects on power systems. In short, the power input is determined by the difference between indoor and outdoor temperatures, the efficiency of the building envelope, and the type of HVAC system and how it is sized. Newer variable capacity (VC) AC systems and HPs can accommodate wider ranges of cooling and heating loads, and provide more options for DR in extreme temperatures [14].

HVAC systems are sized based on models that consider the efficiency and size of a building, and the regional ASHRAE 'Design Day' conditions that set the heating and cooling temperature range that a region will experience 99.6% of the time [15]. In general, appropriately sized HVAC systems can efficiently maintain comfortable indoor conditions (~65 – 75˚F) when the outdoor temperature is within

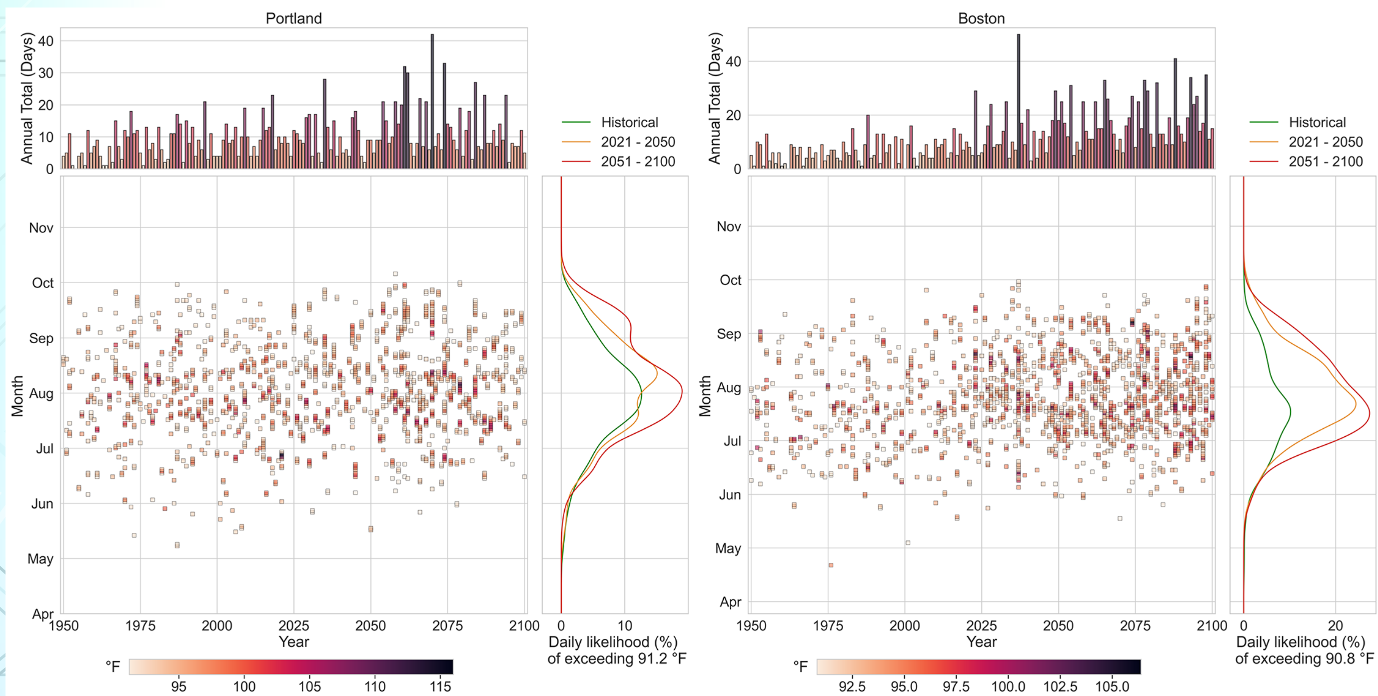

Figure 4: Historical and projected, total annual days, and daily likelihood of temperatures exceeding the local ASHRAE design cooling conditions in Portland and Boston. [18]

the design range. When temperatures exceed design conditions, HVAC systems may struggle to deliver the desired indoor temperature, reducing system efficiency and the ability to shed load. As recently seen in the PNW, temperatures of more than 10˚F to 25˚F above the design conditions caused HVAC systems to run in continuous operation mode at maximum capacity, with no room for duty-cycling. This resulted in consistently high cooling loads, which drove high peak demands and affected load diversity of distribution feeders, breaching transformer capacity limits, resulting in outages, a protection mechanism triggered when systems are at risk of infrastructure failure.

In these instances, DR available from HVAC systems depends on the type of system installed, and whether the system is sized appropriately. Attempting to reduce HVAC load when systems are not sized for the temperature conditions could lead to situations where indoor temperatures for residents are uncomfortable, and potentially effect customer satisfaction, influencing opt-outs and effecting the DR resource.

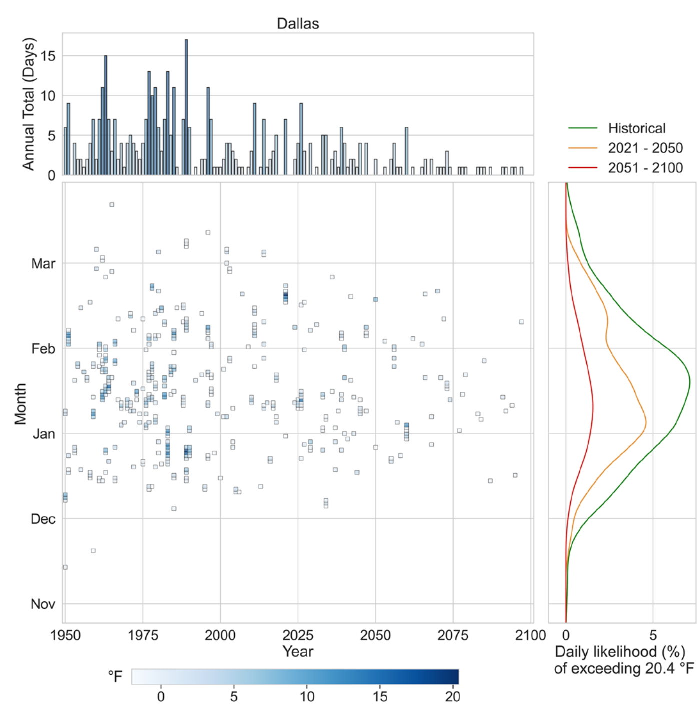

Figure 5: Historical and projected, total annual days, and daily likelihood of temperatures exceeding the local ASHRAE design heating condition in Dallas. [18]

DR from HVAC in Extreme Temperatures – Arizona's 2020 Summer Season

In a record hot summer in 2020 with 10 DR event days Arizona Public Service (APS) avoided power outages. While Arizona is an example of region that regularly experiences extreme heat, it shows that residential HVAC systems can still provide demand response when sized for the conditions, in this case temperatures never exceeded design conditions by more than 8˚F. APS has approximately two percent of its peak load available for demand response via the Peak Rewards program (about 25%) for commercial and industrial loads and the Cool Rewards program (about 75%) for residential thermostats. An analysis of the Cool Rewards program performance in 2020 found [42]:

- 6 out of 10 event days were above the design condition of 109.4˚F, with the 3 highest days seeing max temperatures of 115˚F to 117˚F, on these days there was no clear evidence of reduced load impact, while opt-out rates at between 17.7–19.5% were slightly higher than the average of 15%.
- No strong evidence of increased opt-outs on consecutive day events (i.e., during heatwaves), however opt-out rates were noted to increase later in the summer season (from 14.2% on June 25th to 19.6% on August 18th), potentially due to 'event fatigue'.

In some regions, the way HVAC systems are designed and sized may need to be revised, this includes how the design approaches consider the ASHRAE design conditions. Figure 4 highlights how extreme heat events that exceed the design day conditions will become more likely in the coming decades. While recent cold snaps like seen in Texas in February of 2021 can have similarly drastic effects on power system operation [16], [17], Figure 5 illustrates how in the long run it is projected that extreme cold events will decrease in frequency in Dallas [18].

Evaluating customer needs reveals that, when temperature conditions are extreme, maintaining a livable indoor environment is a chief concern. This means customers may decide not to respond to DR events, energy conservation appeals, or time-of-use (ToU) pricing, as seen this past winter during the cold snap in Texas when customers were hit with extremely high bills for attempting to warm their homes when ToU rates soared [19]. This highlights the need for DR strategies that can be adapted during extreme temperature events to keep customer considerations first while leveraging all available resources (e.g., battery storage, or industrial and commercial DR). EPRI has been working to understand opportunities for residential DR [20], as well effective strategies for DR from commercial HVAC [21] and residential heat pumps to maintain efficiency and customer comfort [22].

MANAGING PEAK SYSTEM DEMAND

The Role of Utility DSM Programs

The increasing digitalization, connectivity, and decentralization of energy systems is driving the fourth wave of energy efficiency, making possible a smart energy system capable of achieving new levels of system flexibility to reduce and manage peak system demand. The fourth wave of efficiency builds upon the continued market-driven adoption of more efficient technologies (third wave), utility DSM programs (second wave), and building energy codes and appliance standards (first wave).

DSM programs can continue to be leveraged and expanded to enable reliable power system operation with projected load increases from the electrification of cooling, heating, and transport. In 2019, utilities invested approximately $1.4 billion in DR programs [23]. The Energy Information Administration (EIA) estimates the life cycle costs of energy efficiency (EE) programs is about 2 cents per kWh of annual savings [24]. Figure 6 highlights the potential effectiveness of EE programs at reducing

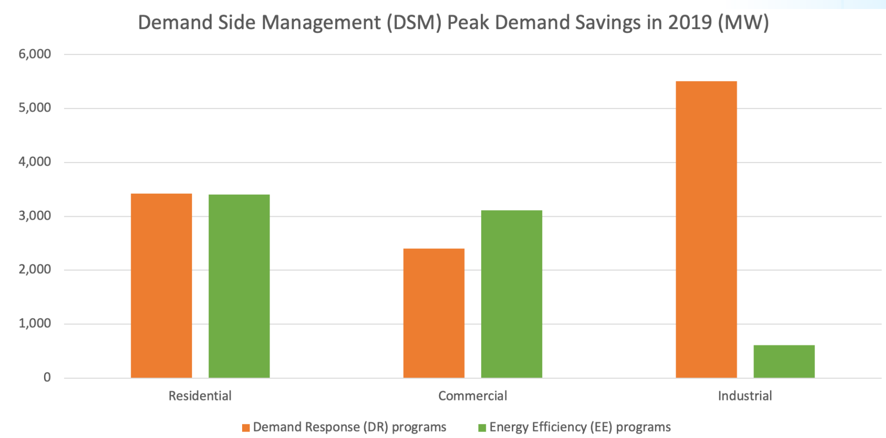

Figure 6: Actual peak demand reduction from DR and EE programs in the U.S. in 2019. Source: EIA [17]

peak load in residential and commercial settings. Total peak load savings from DR and EE programs equated to only around 2% of the total system peak in the U.S. in 2019.

In a recent discussion with a buildings expert at the Bonneville Power Administration (BPA), BPA clarified its understanding of a warmer, dryer future, with more common extreme temperature events. Echoing a burgeoning sentiment, BPA emphasized the need to prepare for scenarios in the PNW where extreme heat strikes, and hydro resources are less reliable. This requires an enhanced focus on demand-side management (DSM) tools. BPA have traditionally focused on reducing system load with EE, work is currently underway to understand the value of displaced demand from select air source heat pumps (ASHP) during extreme temperature conditions, to optimize equipment selection and incentives. BPA is seeking to understand the potential value of DR to cost-effectively manage peak demand and defer investments in physical infrastructure in several demonstration projects. A report found that BPA could feasibly achieve a DR capacity of 18% of summer peak load (2.4 GW) by 2036 [25].

High Temperature Sensitivity of France's Power System

Electrification of heat has been common in France since the 1970's, resulting in 41% of homes with electric heating and the most temperature sensitive energy system in Europe, where a 1°C drop in temperatures can see an increase in demand of 2.4GW in winter months [43]. Historically, peaks in demand were managed using dynamic ToU rate programs (e.g., Heures Creuses) where thermostats were manually programmed or received signals to adjust operation. More recently, in 2014 a DR program known as "NEBEF" was launched for larger consumers (>100kW), with 78GWh deployed in 2017 [44].

The Role of Smart, Integrated, and Efficient Buildings

Designing buildings to suit the local climate is key to maximizing energy efficiency and providing customers built in resilience to extreme weather. In 2018, EPRI worked with Southern Company to develop a Smart Neighborhood in Alabama (Figure 7). In this program, home efficiency was improved by 40–50%, and peak load impacts due to heating/cooling were minimized [26].

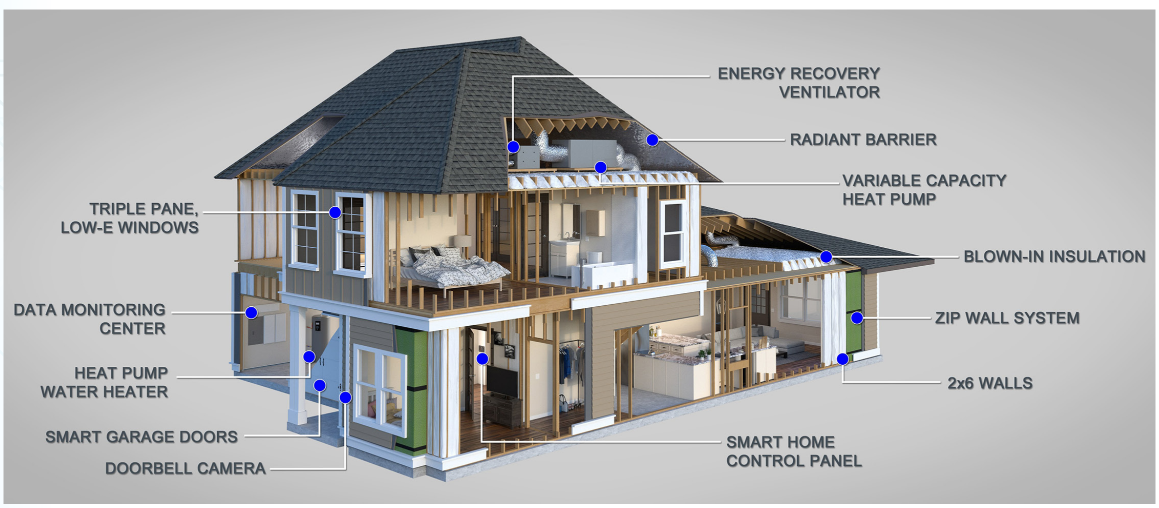

Figure 7: Smart and efficient buildings are key to minimizing impact of cooling/heating loads on grid resources and infrastructure during peak demand hours. Source: [45]

Smart, efficient, grid-interactive buildings and communities with renewable generation and battery storage may provide customers a more resilient supply of power, while becoming a resource for grid operators by reducing energy demand, minimizing the impact on the distribution network with increased electrification, and providing flexible loads for DR [27].

- ***Efficient building envelopes*** are fundamental to overall efficiency. They include high R-value wall and attic insulation with high albedo radiant barriers (e.g., cool roof), efficient windows with active shading, advanced air sealing, and may take advantage of natural ventilation and resources where possible.

An EPRI field demonstration showed that variable capacity HVAC systems with a SEER of 20 or 21 can reduce cooling season load by 30% compared to 15 SEER systems [46].

- ***Efficient electrification***, including ENERGY STAR appliances, LED lighting, connected heat pump water heaters (HPWH), and HVAC with a high seasonal energy efficiency rating (SEER) or HPs with a high heating seasonal performance factor (HSPF).
- ***Smart buildings*** have the potential to optimize energy use based on occupant preferences and maximize flexible load availability via an orchestrated response to time varying rates and DR events. These buildings leverage renewable generation and DER like battery storage, EVs, pre-heating/cooling of water and zoning of space conditioning to offset peak load while maintaining customer comfort.

EPRI has noted a rapidly increasing propensity to incorporate AC into buildings projects that, as recently as two years ago, would not have been so inclined. In one such project, EPRI is working with the City of Santa Cruz to demonstrate all-electric affordable housing. Santa Cruz has a mild climate with an average summer high temperature of 76°F, but a heatwave in 2019 produced a record-breaking high temperature of 110°F. Consequently, AC is being added to 120 homes under this project to promote equity by incorporating climate resilience into affordable housing. This increase in AC installation may be observed across many regions more commonly considered to be temperate.

Renovating existing buildings will play a big role in reducing future electricity demand and preparing citizens for the future climate. In Europe, the Renovation Wave aims to double the rate of renovation of existing buildings as a way to reduce emissions to achieve net-zero goals, enhance quality of life, alleviate energy poverty, and boost economic growth through job creation.

The Role of Thermostat Control Strategies

Over the last five years EPRI has studied and tested common DR strategies from residential HVAC [28][29], as well as DR capabilities from commercial HVAC [21]. EPRI's smart thermostat collaborative worked with several utilities on residential pilot projects to evaluate the response of connected smart thermostats paired with HVAC systems to time-of-use (ToU) rates and DR events [30]. The results showed an average improvement of between 3-6% in total building efficiency for residents with smart thermostats, with 10-20% energy reduction on HVAC alone. Results for peak demand reduction with various strategies are shown in Table 1.

Table 1: Peak load reduction via DR events and ToU rates from three smart thermostat pilots

	Peak Load Reduction
Gulf Power Energy Smart Pilot (400 thermostats) [31]	***DR***: 1.21 kW (38%), Snapback of 5.1% ***ToU***: 10%
Baltimore Gas and Electric (BGE) Wi-Fi Thermostat Pilot (2,236 thermostats) [32]	***DR***: 0.75 kW to 0.98 kW (26%–34%), Snapback of 11% to 14%
Lincoln Electric System (LES) Demand Response Pilot Evaluation (400 Thermostats) [33]	***DR***: 1.20 kW (63%) without pre-cooling ***DR***: 1.22 kW (68%) with pre-cooling ***DR***: 0.49 kW (34%) with 15off/15on cycling ***DR***: 0.53 kW (42%) with 22.5off/7.5on cycling

While these results are not totally representative of performance during extreme temperatures, they do offer insight into the potential value of broader adoption of smart thermostats. Currently, smart thermostats are deployed in 33 million homes (roughly 28% coverage) in North America. In the Arizona case study discussed above a pre-cooling strategy was leveraged for DR events. An analysis of the response of OhmConnect during the August 2020 California heatwave found that a net demand reduction of 19.3% was achieved [34]. OhmConnect has recently announced it is giving away 1 million free thermostats to increase the flexible load capacity available to help California avoid future rolling outages [35]

The Role of DER and DERMS to Enhance Flexibility and Manage Grid Constraints

DER and the proliferation of connected devices across the grid edge may offer opportunities to defer energy and capacity infrastructure investments and manage energy supply and demand from the distribution level up by deploying DER management systems (DERMS). DERMS have the potential to coordinate the deployment of DER and demand-side resources like connected thermostats, battery storage, and electric vehicles (EV). However, recent events highlight the importance of maintaining customer comfort levels when temperatures are extreme, indicated the value in having a diverse array of DER to maximize system flexibility potential. It is estimated that, in the U.S., flexible DER could save more than $10 billion per year by 2030 [36]. Also by 2030, it is projected that the U.S. will have 200 GW of demand-side flexibility, a share equivalent to 20% of the expected peak load [37]. In Europe, the capacity for grid balancing with DER is expected to reach 160 GW (28% of peak load) by 2030 [38].

The Role of Resource Adequacy Assessments

Work is underway at EPRI to develop representations of DER and flexible demand in resource adequacy (RA) assessments for the bulk power system [36]. This work aims to develop a framework for integrating distributed flexibility into RA models, classifying distributed resources according to behavior and defining appropriate metrics and baselines for comparison. This framework is intended to allow for modeling for distributed resources in RA for different types of power systems (e.g., solar, wind, or hydropower dominant systems). With power systems quickly becoming more decentralized, this work may be critical to informing potential investment reductions in traditional infrastructure and promoting power systems that can accommodate future flexibility capacity, to better plan for the needs of the future power system.

CONCLUSIONS

HVAC design approaches may need to be revised. Average temperatures are increasing, with extreme heat events that exceed ASHRAE design conditions becoming more frequent, intense, and prolonged in many regions. The effect of climate change will differ regionally, so there is a need to work with climate scientists to understand how design approaches for HVAC systems can be adapted, and if the way in which ASHRAE design conditions are predicted should be improved. This will be important to prepare regions around the world for the projected growth in HVAC systems and resulting energy demand, so that comfortable indoor temperatures can be maintained while still providing grid operators the ability to flexibly manage peaks in demand when needed.

There is an ongoing research need for resource adequacy assessments. Uncertainty persists around the behaviors of different HVAC technologies and customers during extreme temperature events, and how this affects HVAC flexibility. What portion of HVAC load is considered flexible? How does the difference between the outdoor temperature and the local ASHRAE design limit effect the availability of flexible load from HVAC? What portion of HVAC systems are sized to the local ASHRAE design conditions? How often are HVAC systems oversized? Should HVAC loads convert to "firm" loads when temperatures are extreme? EPRI is continuing work to develop a more detailed and dynamic modeling framework that aims to address the uncertainties of integrating flexibility from DER into RA assessments. This research may help to enhance understanding of the role and potential value of different flexible resources in the future power system.

Advanced grid operations and planning can benefit from considering extreme weather events. Planning and designing the basis of the future power system requires consideration of future climate scenarios and the increasing frequency of extreme weather events. This future system may involve using DER and DERMS to maximize system flexibility and optimize supply and demand balancing from the bottom up. Effectively planning and leveraging the increasing system flexibility has the potential to reduce or defer some infrastructure investments, while identifying any necessary investments for a reliable modern power system.

With higher penetrations of DER, accurate, granular, and reliable data from the increasing digitization and connectivity of the grid edge could provide a deeper understanding of how energy is being consumed, generated, and transmitted across the power system on a moment-to-moment basis. This could be integral to power system operation in a future with more variable climate. This type of data could also help improve understanding of how flexibility from HVAC systems is affected when temperatures climb well above the local ASHRAE conditions for prolonged periods of time.

Expansion of DSM programs can increase flexible load capacity. Flexible load will have an increasingly important role in supporting the grid throughout future extreme temperature events. If the projected overall system flexibility of 20% is to be achieved by 2030, DSM programs may warrant special focus. This will require:

- Increasing residential flexibility by continuing to deploy smart thermostats and connected devices in homes.
- Targeting regions with capacity constraints to deploy efficient and controllable HVAC equipment. EPRI is currently testing 120V HPs that can prevent high infrastructure upgrades and related costs associated with electrification like panel upgrades [39].
- Prioritizing weatherization incentives in EE programs to improve the efficiency of the existing building stock.
- Diversifying the flexibility portfolio with a variety of DER, so grid operators have options during extreme weather events.

Building efficiency matters in grid modernization and decarbonization efforts. Poorly weatherized buildings today may be insufficient to address tomorrow's climate. Efficient, smart, and grid integrated buildings with renewable generation and storage can have value for both grid operators and customers. Energy codes for new and existing buildings may help to advance buildings as a valuable tool for modernizing the grid edge and reduce the strain of cooling/heating loads on grid assets. Building codes can also support tripling the rate (3X) of U.S. energy-related carbon emissions reductions to achieve 2030 economy wide decarbonization goals.

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