CalFlexHub
Advancing Dynamic Energy Management

Building Electrical Capacity Management: The Missing Element to Enable a Sustainable and Resilient Grid

Bruce Nordman[1], Daniel Gerber[1], Omkar Ghatpande[2]

Lawrence Berkeley National Laboratory[1]
National Renewable Energy Laboratory[2]

Energy Technologies Area
August 2024

BERKELEY LAB

CalFlexHub's work is made possible by the California Energy Commission and funded through the Electric Program Investment Charge (EPIC) Program. It is administered by Lawrence Berkeley National Laboratory (Berkeley Lab), a Department of Energy (DOE) sponsored Office of Science laboratory.

Acknowledgments:

This work was supported by the California Energy Commission under the Electric Program Investment Charge (EPIC) Program. Solicitation GFO 19-309 entitled California Load Flexibility Research and Deployment Hub (CalFlexHub) Project, that was awarded to Lawrence Berkeley National Lab for the work herein.

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Bruce Nordman, Daniel Gerber, Lawrence Berkeley National Laboratory[1]

Omkar Ghatpande, Willy Bernal Heredia, National Renewable Energy Laboratory

ABSTRACT

In years past, advances in building technology focused on increasing performance or reducing total energy consumption. With the advent of demand flexibility, managing the timing of energy use added a new dimension. However, the picture is only complete with the management of electrical capacity constraints that are increasingly appearing at customer main panels and service connections, though it also can arise in subpanels and electrical components like cables, circuit breakers, and busbars. There is also increasing attention to constraints in the utility distribution system, which can impose temporal needs to limit customer demand or export. To date, capacity management has been dominated by forecasting worst-case scenarios and installation of limiting devices accordingly. This results in frequent investments in unnecessary additional capacity and a failure to use much of the capacity that exists already.

Electrical capacity management has already been implemented for Universal Serial Bus (USB) and Ethernet to prevent overloading electronics, cables, or power supplies. This highlights the need for effective and interoperable solutions for capacity management at all scales. This paper will present solutions at each of these scales, with a deeper dive into the panel capacity topic, which is the most urgent and easily solved scale. It will show the results of work to demonstrate capacity management with specified loads that can be dropped or modulated to maintain compliance with limits in simulation and hardware demonstration at multiple power scales. It will conclude with recommendations for regulation, utility operation, and further technology development.

Introduction

Modern policy for energy and buildings has addressed various problems that emerged as important individually over time. Efficiency dominated for several decades almost alone; efficiency addressed multiple concerns in parallel including pollution and energy bills. Demand flexibility emerged later and is now a major area of work, primarily for reducing costs and enabling integration of greater renewable generation. More recently, constraints in electrical distribution systems have highlighted capacity as a problem. These problems do not replace each other, but rather operate in parallel, occasionally intersecting.

Capacity constraints occur any time there is a cable or piece of equipment with a limit on how much power it can transmit or with which it can operate. This applies everywhere, from transmission lines and substations to distribution systems to customer service wires to main electrical panels, subpanels, and individual circuits. It also applies to such small scales as the

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[1]This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. This work was also supported by the California Energy Commission under the Electric Program Investment Charge (EPIC) Program, Solicitation Grant Funding Opportunity Number: GFO-19-039, entitled, California Flexible Load Research and Deployment Hub, that was awarded to Lawrence Berkeley National Lab for the work herein.

USB ports on a computer. The traditional approach to capacity management sets conservative assumptions about capacity requirements to avoid possible nuisance tripping of circuit breakers or equipment damage. While this was likely the best choice then, given the available technology, it leads to very low capacity factors for many circuits and devices the vast majority of the time. It also precludes adding loads (and often precludes adding generation) when doing so would realistically not create problems.

Luckily, technology has advanced in the last century, and there are good solutions quite feasible today that were previously impossible. Most technologies begin at a small scale and are scaled up when proven to work. Capacity management is no exception. The USB standard (and, more recently, Ethernet) has employed a permission-based capacity management mechanism for several decades. USB and Ethernet likely adopted this because communication was already central to the technology, and the electronics industry is well accustomed to fine-tuned optimization.

This paper reports on the progress of a project on panel capacity issues as well as work related to coordination with the grid for demand flexibility. The paper is organized as follows. The first section covers "link" capacity management—between two devices or a small number of devices sharing a common cable. The second section addresses capacity management at the main panel of a building, including an example algorithm and initial results of simulations. Then, a description of the challenge and solutions of the capacity limit problem and its interaction with the utility grid. The paper ends with the next steps and conclusions.

Link Capacity Management

Link capacity management refers to the use of communications to control the power flowing between devices. Currently, its most common usage is in point-to-point (two-device) power-distribution protocols such as USB or PoE, though multi-drop protocols also exist for managing the power flow to multiple devices on the same cable. Today's examples generally involve the transfer of DC power, controlled by power electronics or current-limiting switches. The mechanisms can be applied to AC power links.

While USB (Universal Serial Bus) is centered around high speed data communication (hence its name), power was always part of the technology. Peripheral devices like a keyboard or mouse could not reasonably have their own AC power supply—the cost and inconvenience would be high and the power levels delivered very low. USB began with 2.5W of capacity (0.5A at 5V) (USB-IF, 2000). USB-A was also designed to facilitate tree structures of devices hanging off a single USB port, which could be created by any combination of powered or unpowered hubs. Both would relay data between the root device and downstream devices. While powered hubs could provide each downstream port with up to 2.5W of power, the unpowered hubs had to allocate the available power to the collection of downstream devices and the hubs' own needs. To ensure reliable and safe operation, a mechanism was created so that if a device wanted more than a *de minimus* amount of power it would have to request authority to consume it, and only do so if the request was granted. The request could be granted fully, granted partially, denied, or later changed. The amounts of power involved were initially often just fractions of a single watt.

Over time, the ability of the USB standard to carry higher levels of power grew, initially by raising the current limit to 3A, and with USB-C, enabling the current to rise to 5A and the voltage up to 48V, if both sides are capable (USB-IF, 2021). Thus, the standard scaled in power from 2.5W to 240W—nearly two orders of magnitude. A feature of USB that is not well known is that for power requiring more than 3A of current, the cable itself needs to identify to both ends of the link that it is a 5A cable (not the typical 3A). One could say “even the wires are talking” which would be truly incomprehensible to Thomas Edison.

The Ethernet standard added power years after it was first introduced, as it was clear that doing so would reduce costs and increase convenience, by avoiding having to separately supply AC power to devices such as desktop phones, security cameras, and Wi-Fi access points. The available power scaled from 13W to 91W over several revisions[2] and many years (IEEE, 2023b). 4-pair Ethernet technology only has two devices on each link and so each port powers only one device. While each cable is always capable of the maximum port power, the supplying device might not be capable of supplying all ports at maximum power simultaneously. Such “oversubscription” is common in communications and power distribution since most devices consume less than the maximum power (or data) and many devices do not consume the same amount of power all the time. For these reasons, Ethernet has a power capacity management similar to USB.

More recently, single pair Ethernet has been introduced, including versions with “multidrop” capability[3], so that many devices on a single link/port can be powered. This further increases the need for capacity management to preclude applying more power to a link than the cable is rated for.

A key insight is that digital/dynamic capacity management is all around us in residential and commercial buildings. It is automatic, works, and almost never intrudes on daily life. The mechanisms employed are simple and confined to the link.

Panel Capacity Management

As interest in building electrification has increased, more and more building owners have been told that they need to increase the capacity of their main electrical panel and/or service line from the street to the meter. The National Electrical Code (NEC) has conservative assumptions about how much panel capacity is needed. These assume that many devices will be operating simultaneously, and using the maximum capacity of the circuit they are on. This goes as far as requiring that a heating system and a cooling system for a house be able to be powered at the same time, even as it is likely that the intended occurrence of this is extremely remote. Studies have found that when customers increase their capacity due to increased electrification, they usually stay within the original capacity (Less, Casquero-Modrego & Walker, 2022); thus, the capital and time investment in these deployments is wasted.

The NEC has a provision for automatic controls to reduce capacity requirements, and there are products on the market today that do this (see ‘Existing products’ section below). How widely these are utilized for code compliance, and the fraction of local building officials that understand this, is unclear. The fundamental principle of operation of these systems is for a control device to monitor the power flow at the meter, and if the power level gets too close to a specified limit, it can drop—or modulate down—one or more loads to ensure that the capacity limit is respected. Dropping loads can be done with a controllable circuit breaker, a downstream

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[2] The first Power over Ethernet (PoE) amendment was 802.3af and provided for up to 13W. Later came 802.3at which increased this to 30W. Finally, 802.3bt used all the wires (to increase capacity and efficiency), raised the limit to 91W (at least for power supplied to the cable) and added several other features, including a power price index.

[3] There are multiple versions of Single Pair Ethernet (SPoE). Some are optimized for vehicle or industrial applications. Most notable for buildings are 802.3cg, to power a single device on a SPoE link, and 802.3da, to power multiple devices on the same link, is in the final stages of standardization.

relay, or by communicating with the device (for those capable). Modulating the device requires communication.

The same principle can be applied to a subpanel, and a controller could readily be designed to manage multiple panels with an understanding of their powering relationships and capacities.

Panel replacement costs are in the thousands of dollars (Less, Casquero-Modrego & Walker). Service line replacement can cost tens of thousands of dollars if the cable is underground. These are significant motivations to manage capacity rather than increase service/panel capacity, but sometimes a request to add load to a building is denied by a utility due to concerns for the local distribution network (wires and/or transformers). In this case, local capacity management may be required to add the load at all. Electric vehicle chargers are a particularly common load to raise this problem.

Existing products

Several products are available today that can practically manage capacity at the electrical panel. These technologies can be a smart panel (e.g. Span, Lumin) with sensors and actuators or an NEC-compliant EMS with sensors and controllable actuators that assure compliance with capacity limits. Many of the available solutions may only use proprietary communication protocols and may not be interoperable with other system components. Example systems are available from Emporia, Rainforest Automation, Stepwise, and dcbel. Smart panels can be a very expensive solution and panel replacement is almost always done by a certified electrician.

NEC considerations

The NEC (National Electric Code) (NFPA, 2023) has many requirements about capacity requirements. Section 750 describes the installation requirements for capacity control solutions; these are mostly considered to be Energy Management Systems (EMS). The load managed by an EMS is to be treated as a continuous load, thereby limiting the EMS current setpoint to 80% of the panel capacity rating. In the 2023 code cycle, service and feeder load calculations were introduced in Section 220.70; these EMS must have a maximum current setpoint to be used in load assessment.

Proposed Standard

Capacity management solutions for sale today use proprietary technology and/or have high equipment and installation costs, and therefore will have limited market penetration. One way to reduce costs and increase flexibility is to define a standard way for component devices to communicate; with this, components could be purchased from multiple companies and then combined into systems with an assurance of interoperability. Figure 1 shows such a system architecture, with component elements being sensors, actuators, and a controller. Sensors can be in loads, the meter, circuit breakers, outlets, or on wires (e.g., current transducers). Actuators can be circuit breakers, controllable outlets, or the operation of device controllers or loads via direct communication. Note that a 'smart panel' can do this, but with the requirement to replace the panel and buy a smart panel (usually several thousand dollars); the system described here adds or replaces only a few specific devices, at modest cost, in the existing panel, vastly reducing the total cost compared to a smart panel.

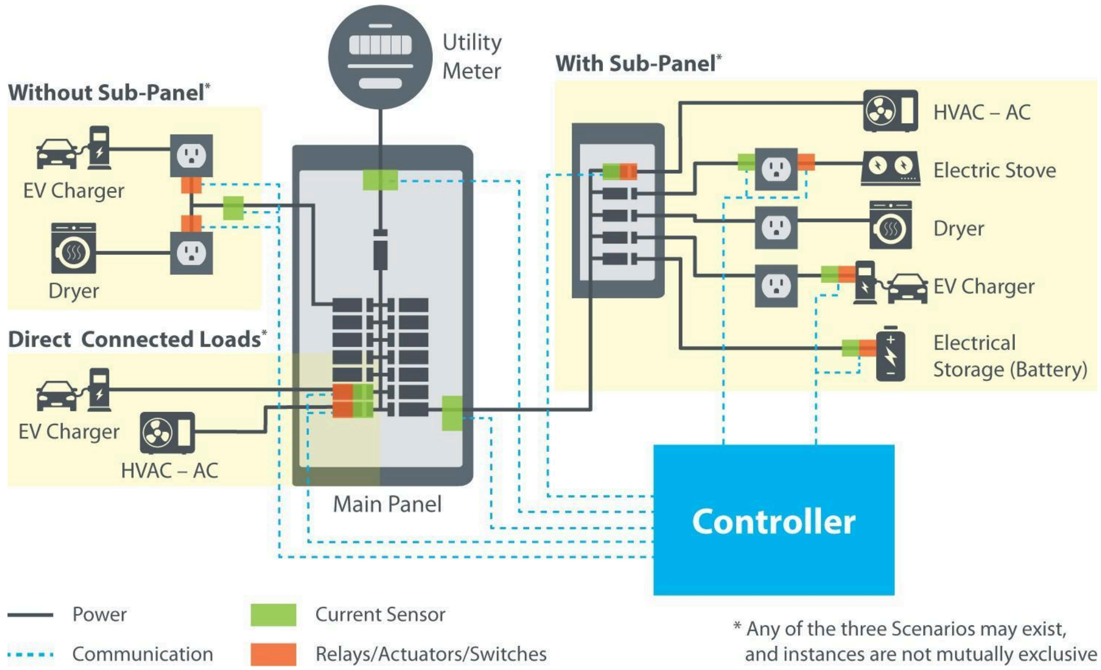

Figure 1. System architecture for panel capacity management

Panels are not intended to operate above 80% of their rated capacity "continuously"—that is, for more than three hours at a time. Shorter exceedances are allowed. An automated system will likely aim to avoid exceeding the 80% value for more than a few seconds at a time; such a goal is readily achievable, even if excessively cautious. Also, if a single load that might come on unexpectedly draws more than 20% of the panel capacity then keeping the panel to a lower limit may be needed to avoid even momentary exceedances of the 100% level. Such systems could also be integrated with demand response systems to shift load. There is no reason to exclude this (and there are some advantages to doing so), but the systems can also be deployed strictly separately (in parallel).

Algorithm

The process to create a public (non-proprietary) system for panel capacity management had the following primary components:

- Develop an example capacity management algorithm
- Evaluate the algorithm in simulation with real metered whole-house data
- Evaluate the algorithm with scaled-down power levels but real hardware—simulated devices (fixed or programmable loads) and relays (for circuit breakers)
- Evaluate the algorithm with full power levels, real loads, and controllable circuit breakers

Our current algorithm is shown in Figure 2. At each update interval, if the power level is above a criteria threshold, then a process ensues to drop or modulate loads on the Priority List to bring it down below another threshold that is sufficiently low to provide an adequate safety margin. If the power level is below a second threshold then consideration is given to modulating up a load or adding back a dropped load. All the quantitative values are subject to improvement (as we do more experimentation) and adjustment by the local site.

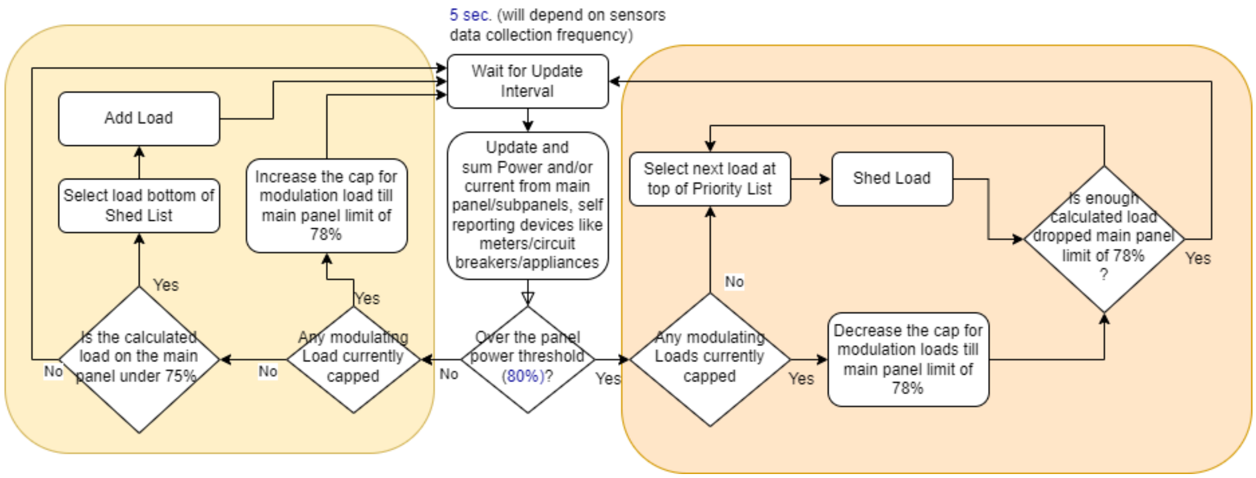

Figure 2. Example panel capacity management algorithm

The algorithm takes a capacity limit to maintain, and a list of devices that can be dropped or modulated, ordered by priority or criticality. Most circuits and loads will not be on the list; only a few high-power loads (or circuits) will be. Many EV chargers can be communicated with and set to a maximum charge level and so are suitable for modulation. Stationary batteries and a few other devices can similarly modulate. Other devices might have their load cut entirely, such as a pool pump, hot tub/spa heater, resistance water heater, or clothes dryer. Many loads are not suitable to frequent disconnection this way and so should not be included in such lists.

An interoperability standard for capacity management would define a small number of standard interfaces between sensors and a controller, and actuators and a controller. There should be several Internet Protocol mechanisms defined for each, as there is no hardware burden once there is a single IP physical layer interface (e.g. Wi-Fi or Ethernet). One or more simpler interfaces should also be defined for sensors and actuators in the same panel or otherwise physically near to the controller. Many IP devices will be both a sensor and an actuator.

Example Results

The algorithm has been tested with one-second measured whole-building data provided by Lumin[4] for one day for a residential building. Figure 3 and 4 shows example data for baseload power for our simulation; the dataset is for one day in winter. The disaggregated load shows that the EV charger is the highest contributor to the demand. On this day, the HVAC demand was very low during the daytime. To test the effectiveness of the algorithm, we applied a fictitious panel capacity of 7200W (30A @ 240V). Figure 5 shows the load profile with the new panel capacity. In this simulation the EV charger was assigned as a controllable and modulated load while all other loads were uncontrolled. The EV charger lowered its power to limit the whole panel under the new limit and charged with the same profile when the capacity allowed after other loads dropped off.

[4] https://www.luminsmart.com/

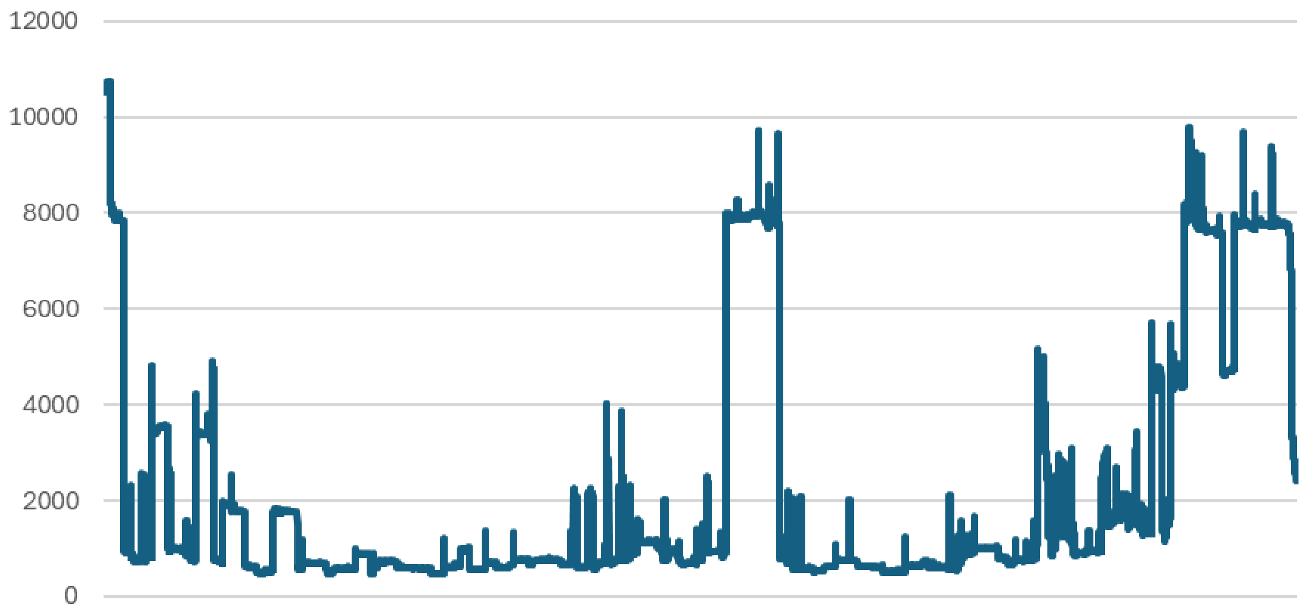

Figure 3. Example data for baseload power (before controllable loads added) (source: Lumin)

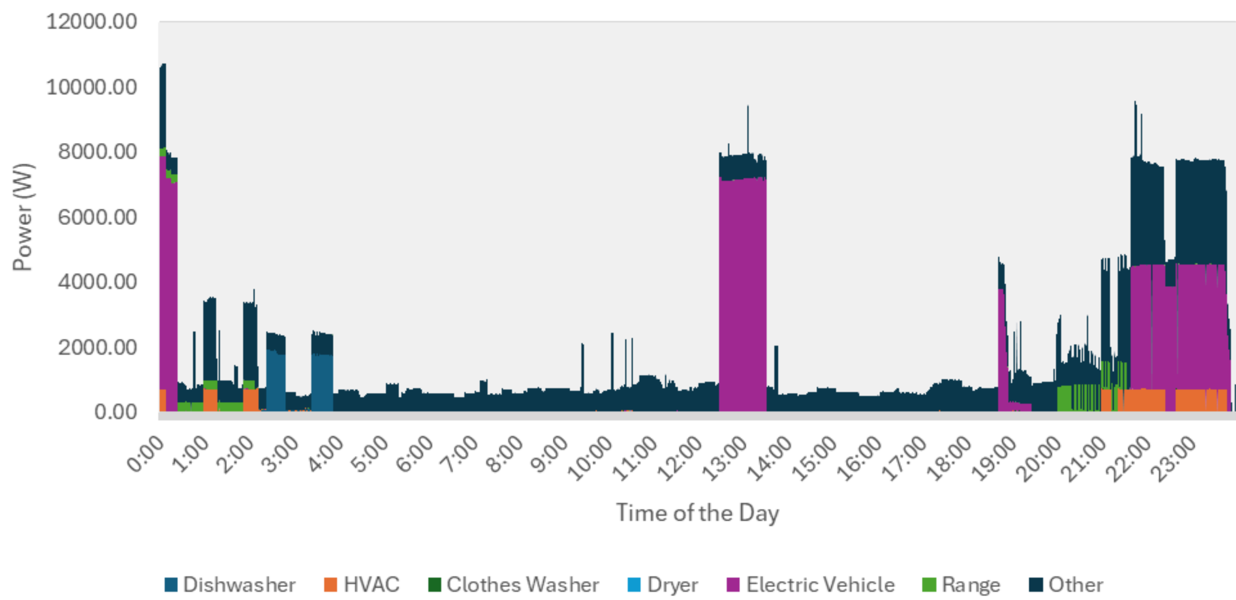

Figure 4. Disaggregated example data from Figure 3 for baseload power.

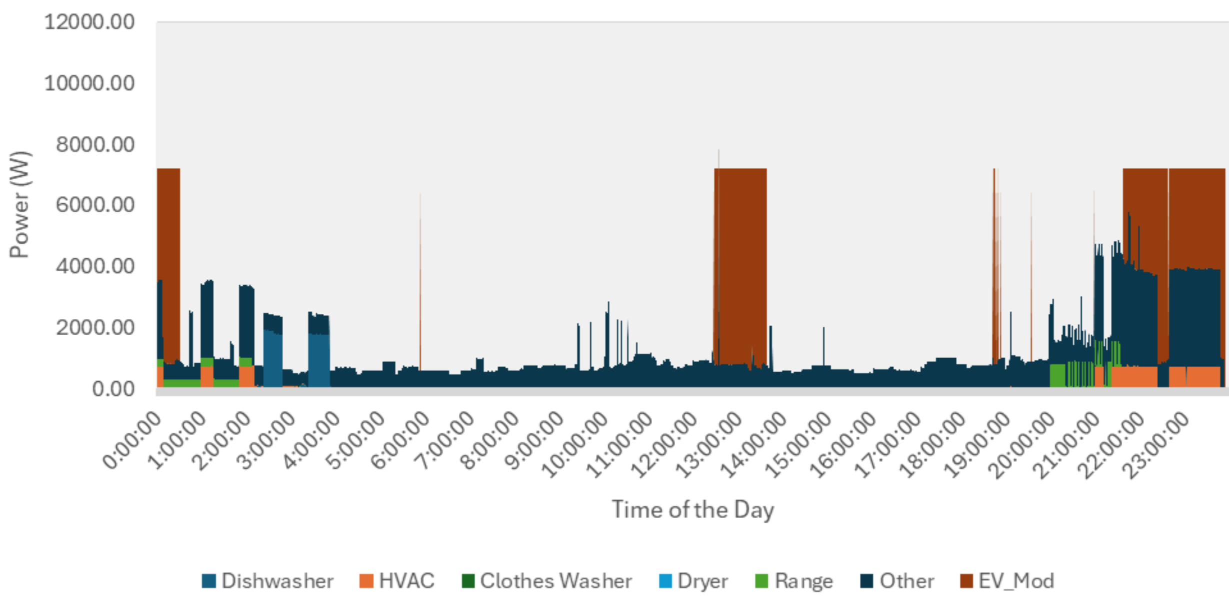

Figure 5. Controlled panel load (Limit = 7200W); EV is modulated

Path Forward

In the coming months, we plan to test the algorithm with more device scenarios and refine it as necessary. We then plan to conduct the two hardware tests to confirm that the algorithm works in reality as it does in simulation. The code that implements the algorithm could be released as open source to simplify use of the algorithm by others. Note that future products compatible with this standard do not have to implement exactly this algorithm. If a manufacturer believes that they have one that has advantages over the reference algorithm, they are free to use it without compromising the interoperability of components. The controller could be a dedicated device, or be a function implemented by a device with a primary or other purposes that are different. As more sensors and actuators use IP communication, the physical location of the controller becomes less important (though it should be at the customer site, not in the cloud, for latency and reliability purposes). If a controller is disconnected or otherwise fails to operate, buildings still have circuit breakers to assure safety.

Customer Capacity Management

In recent decades, individual customer capacity requirements have not changed dramatically and averaging loads across customers allows much of the 'peakiness' of individual customer demand to be significantly reduced. This has allowed distribution systems to be largely stable, primarily changed only when new customers were added. However, at an increasing rate, some circuits are reaching capacity limits and/or customers are being denied the ability to add load or generation to avoid such limits.

Utility distribution system capacity values are presently set based on static worst case assumptions. Given the technology available when this began, on the utility and customer sides, this approach was perfectly understandable, but it does result in relatively low average capacity factors. One analogy to this is if drivers licenses in a community were only allocated up to the point where one more driver might lead to a traffic jam on the freeway very occasionally. To put grid capacity into perspective, the average US household consumes about 10,000 kWh/year. A common electrical panel size is 100A (the average is considerably higher). Such a panel can be operated at up to 80A on a continuous basis, and at 220V this is over 17 kW, which for a whole year would amount to over 150,000 kWh/year—fifteen times the typical average. Two things have changed in recent years: the entrance of new devices that can introduce a high peak (EVs and PV), and technology to coordinate capacity needs has been developed.

Recently we have seen an increasing number of studies on the potential issue of distribution capacity constraints interfering with planned electrification (especially EV charging) or the costs of doing the assumed necessary capacity expansion. One study found that without mechanisms to coordinate with customers, California could need $50 billion of distribution system investments to meet its needs under a 'High DER' future (Kevala, 2023). Another study found that (Brockway, Conde & Callaway, 2021) found that in California, for the two largest utilities, fewer than half of customers could add PV and many would face issues integrating EVs with the existing distribution system and (lack of) coordination technology.

Dynamically managing customer capacity can allow much more load to be connected to a piece of the distribution system than with static assumptions, can more reliably prevent exceedances, and can eliminate or postpone expansions in distribution system capacity. The latter may require capital funds and/or transformers that are not even available. Thus, deploying such automation should be a priority to meet our climate goals.

Dynamic Operating Envelopes (Limit-based capacity management)

In recent years, an increasing number of people in Australia were being told that they could not install rooftop PV due to feeder overloading from the excess power (this also occurs occasionally in the US). Australia has the world's highest penetration of rooftop PV, about one third of homes nationwide (much higher on some feeders), so it is no surprise that this first emerged as a significant issue there. In response they developed the Dynamic Operating Envelopes (DOE) mechanism which broadcasts interval export limits to each customer on constrained feeders (ARENA, 2021; AEMC, 2023; Energex, 2024) . The export limit is tailored to each customer and can be different every day. DOE was first added to IEEE 2030.5 (IEEE, 2023a), but support for it in OpenADR 3.0 (OpenADR, 2023a) was added soon thereafter. DOE is "limit-based" Australia is presently commencing a study on managing import capacity.

Permission-based Capacity Management

EV charging raises the opposite potential problem—exceeding import constraints. A Level 2 EV charger can easily use more power than the rest of an all-electric home uses for all other loads at any time—and many times the average load. The load is not constant—it only lasts for a few hours. EV charging can also be synchronized across customers due to rates with sharp drops in prices, human behavior, and other reasons. This all means that concentrations of EVs in a distribution system can readily drive wires or transformers over their rated power levels. EV charging stations—with many stalls and very high power levels—raise the same issue but at a greater scale.

One possible solution is to take a cue from USB and Ethernet and make capacity *permission-based*. We know that "ordinary" loads (those present in wide numbers before 2015) do not pose a problem, so there is no need to involve them in this, in either changing electricity prices or their behavior. We only need to manage the impact of the bursty loads (and new customers such as EV charging stations).

In a simple permission-based system, each customer has a subscription to an amount of capacity that their traditional devices collectively do not exceed. This can be assessed through examination of recent smart-meter data (capacity management requires a smart meter to work at all). This subscription might be changeable annually, and would likely have a fee associated with it (though the first few kW could be free). This subscription is likely to be several times the average consumption—that is, typically the margin between current use and the subscription will be (much) larger than the current use.

When the customer acquires an EV, a local controller[5] can monitor the current at the meter, and modulate the maximum EV charging rate to stay at or below the subscription level. If the customer wants to charge faster, a request can be made to the grid for a reservation of more capacity, with a specified start time and duration, and a specified additional amount of power. The grid's response could be any of:

- Granted. The customer has the reservation.
- Denied. This is a peak time for capacity at this location and so a fee is required.
    - The customer can submit a new request with the appropriate fee.
- Denied. There is no capacity to allocate.

Whenever a request is made, the grid responds with a list of intervals with availability and cost for each. With this, a customer may choose a different time and/or incremental value. Multiple reservations can be made to span times of different reservation prices. The specifics of this exchange are described in the OpenADR 3.0 User Guide (OpenADR, 2023b)

Figure 6 below shows an example of a house load, EV charging layered on top unconstrained, with a reservation with additional capacity for a portion of the time, and with no capacity beyond the basic subscription. Charging at a reduced capacity level naturally increases the overall time for charging over what a less restricted scenario provides.

Implementation of this on the customer side would be simple, and only requires the same technology described in the previous section on panel capacity management plus simple communication with the grid. Implementation on the grid side relies on smart meter data to track customer compliance and inform algorithms for setting limits and any fees for reservations. Many customers will be using much less than their subscription most of the time, so the grid could over-allocate capacity to some degree based on experience with smart meter data; such algorithms can be updated daily based on the previous days' operation. Smart meters report power levels as averages over a time period (e.g. 5 or 15 minutes), not by individual minutes or seconds. This is in general not a problem for capacity constraints since they are driven by heat buildup which occurs over many minutes or even hours, not over seconds or a few minutes. Sensing data from grid equipment may be needed to understand power flows within the distribution grid, particularly when grid devices can be fed from more than one source.

[5] This could be a function of the utility meter, the EVSE, or another device. It could be the vehicle itself, but it would likely be more challenging to reliably get the meter data to the vehicle.

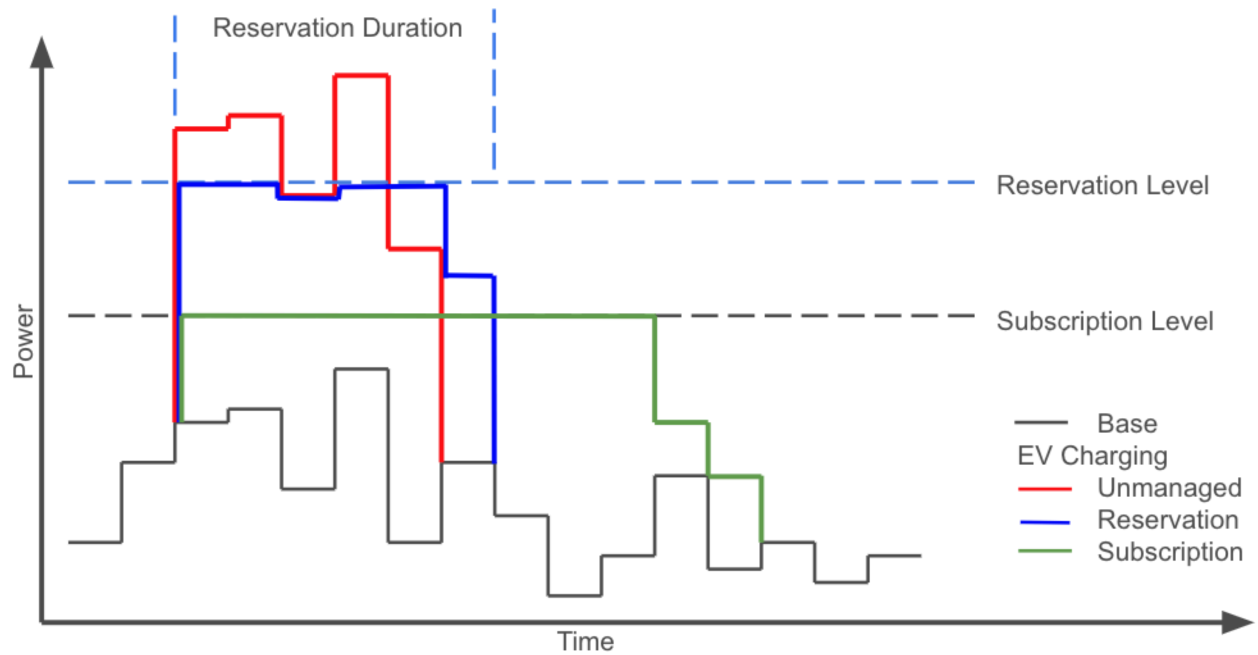

Figure 6. Schematic load of a house load with EV load, subscription, and reservation

The mechanism described above is proposed as a candidate to test, along with others. Choosing what mechanism is ultimately used in the long term should be driven by empirical testing. There could be variations used in different places, but the total set should collectively be simple for any controller to implement.

Possible issues/extensions

There will need to be some consideration of customer exceedances of their allotted capacity, whether deliberate or accidental. Allowances or fees could be set to ensure that only routine or extreme such behavior has consequences.

Extensions could be made for customers to voluntarily reduce their subscription for a reward—essentially a reverse registration. Even more complex would be to allow customers to relinquish previously made reservations but that would introduce the possibility of people trying to game the system.

In addition, fees collected could be redistributed periodically to all customers in the affected part of the distribution system (or dedicated to expanding capacity there), so that customers in places with undercapacity or with 'greedy neighbors' will get some benefit from the system.

Once this capability becomes widespread, it introduces the possibility of forced reductions in customer capacity in emergency situations. This could be for grid emergencies with significantly reduced supply, black start operations (resuming operation after the grid has gone down), and facilitate microgrid operation where the microgrid has supply capability less than potential demand. It is widespread practice—fortunately only occasional—to black out segments of a grid on a rotating basis when demand exceeds supply. Capacity management can instead reduce many customers' demand by a modest amount rather than cut power entirely to a few customers. Most people would rather lose 5% of their power all the time than lose all of their power 5% of the time in such situations.

Path Forward

Key next steps are to test out several possible mechanisms (including the one described here), initially in simulation and then in small scale deployments. This also needs evaluation of how it could work with distribution systems, which do vary geographically. In most places in the U.S., regulators would also need to allow these to be deployed and specify any local constraints. While there could be local variations (e.g. a maximum fee per kWh), the basic mechanism should not vary. Otherwise, equipment that will work in most places will not work in that locale.

Pricing and Capacity Management

Use of Highly Dynamic (Retail) Prices has the potential to be a universal mechanism for balancing supply and demand of energy (Nordman et al., 2022). It manages this at a regional scale, with each region having its own set of prices. For various reasons, regions are unlikely to be “small” (e.g. having fewer than 10,000 people within them) and even if they were, this is not enough to guarantee that capacity constraints will not be exceeded. Some constraints are hyperlocal. This is where capacity management comes in as a complement, working in parallel, and not directly interacting.

Pricing and capacity management are the only mechanisms that can work at any scale. Pricing and capacity issues exist in wholesale markets; capacity constraints exist all over the transmission or distribution systems. Pricing exists at every utility meter—and if a mechanism such as the one described above is implemented, capacity management also will. Capacity constraints can exist within buildings as defined by panels, circuits, or other power domain determinants (e.g. DC power domains). And finally, price and capacity can exist on individual cables; the Ethernet standard today has both (though it is not known if any commercial products use the price mechanism).

Conclusion

Dynamic capacity management in general is a nascent but critical mechanism for cost-effective and high performing operation of customer sites and distribution grids. It can facilitate the needs of both customers and the grid, to reduce cost and increase capability, and often both at the same time. Traditional capacity management is static and consists of circuit breakers to avoid conditions that are unsafe for people or equipment, and extremely conservative rules about capacity requirements that guarantee low usage.

Dynamic capacity management needs to move quickly from concept (at the customer/grid interface) and very niche implementation (at the panel) to standardization and widespread use. However, by keeping the technology as simple as possible, progress could be quick.

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