DOCKETED

Docket Number:	19-AAER-03
Project Title:	Power Factor
TN #:	232241
Document Title:	California Investor Owned Utilities Comments - Technical White Paper on Power Factor Energy Savings Opportunities
Description:	N/A
Filer:	System
Organization:	California Investor Owned Utilities
Submitter Role:	Public
Submission Date:	2/27/2020 9:33:36 AM
Docketed Date:	2/27/2020

Comment Received From: California Investor Owned Utilities
Submitted On: 2/27/2020
Docket Number: 19-AAER-03

Technical White Paper on Power Factor Energy Savings Opportunities

Additional submitted attachment is included below.

A New Factor In Efficiency:

Energy Savings Opportunities Through Improved Power Factor

February 2020

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Executive Summary

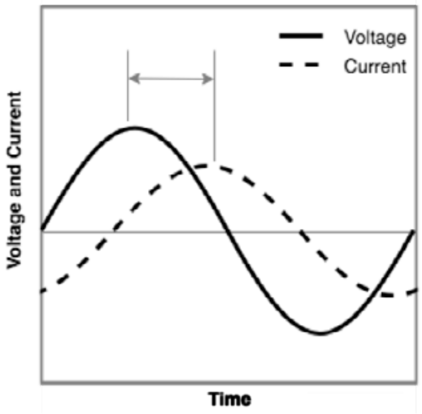

Figure 1: A load with a power factor less than 1 will draw current out of synchronization with the voltage waveform supplied by the AC grid.

The energy efficiency community has traditionally focused on programs and policies that encourage direct reductions in electrical consumption and demand at the point of use. The energy losses that occur while transmitting and distributing electricity to end uses — estimated at about 5 percent[1] — are assumed to fall outside the scope of appliance efficiency policy. This is a highly practical assumption. End users of electricity have almost no influence over the systems that supply energy to loads, especially the upstream components of the transmission and distribution grids. But electrical losses can be impacted based on how a device draws power from the alternating current (AC) grid, particularly in the lower capacity wiring found at the edge of the grid and in buildings. A load can be intrinsically efficient — providing its required lumens, computing capacity, or tons of cooling with relatively little power from the grid — but may interact with the broader AC power system in such a way that those watts are delivered inefficiently.

Power factor is a key indicator of the efficiency of power delivery to a load. A "perfect" power factor of 1 shows that a load consumes power in perfect synchronization with the AC voltage supplied by the grid. The current that it draws aligns perfectly with the peaks and troughs of the grid's AC voltage waveform. Devices with lower power factor consume power in an unsynchronized manner and require more current to flow through the grid to supply a given amount of power at the load. This extra current flow can increase electrical losses in building and distribution wiring, resulting in additional energy use and expense. Although losses for any single product may be small, in total and across millions of products, the losses add up and represent a sizable opportunity for energy savings.

The California Investor Owned Utilities, herein referred to as the Statewide Codes and Standards Enhancement (CASE Team) is currently examining the energy savings associated with power factor in conjunction with the California Energy Commission's (CEC) roadmap.[2] This white paper disseminates Statewide CASE Team findings from two years of power factor research, including order-of-magnitude estimates of energy savings potential resulting from power factor improvements in a set of end-use products used in homes and businesses across the U.S. This paper's aim is to identify some of the top opportunities for energy savings and, in so doing, promote broader discussion of end-use power factor correction in the energy efficiency community. To produce results that can be widely leveraged, the Statewide CASE Team conducted its primary analysis on a national scale, including analysis of climate sensitivity, and also analyzed California-specific impacts (found in Appendix K).

The Statewide CASE Team considered a diverse range of electrical loads found in the residential and commercial sectors, from consumer electronics to packaged HVAC systems. This study examines the potential size of technically achievable energy savings on an order-of-magnitude basis. In other words, the main physical impacts of power factor improvements are captured in a simplified manner that can be generalized to large numbers of buildings and devices. The Statewide CASE Team leaves detailed sensitivity studies and more granular, dynamic simulation studies to future efforts on specific product opportunities. This study identifies the most promising loads to capture savings; analyzes the amount of economically achievable savings; explains the basic technological paths for correcting power factor issues in different types of electrical products; and identifies key barriers to the development of the power factor correction opportunity.

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[1] U.S. EIA, 2018. "Frequently Asked Questions: How much electricity is lost in transmission and distribution in the United States?" Available at: https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

[2] http://www.energy.ca.gov/appliances/2017-AAER-06-13/17-AAER-12.html

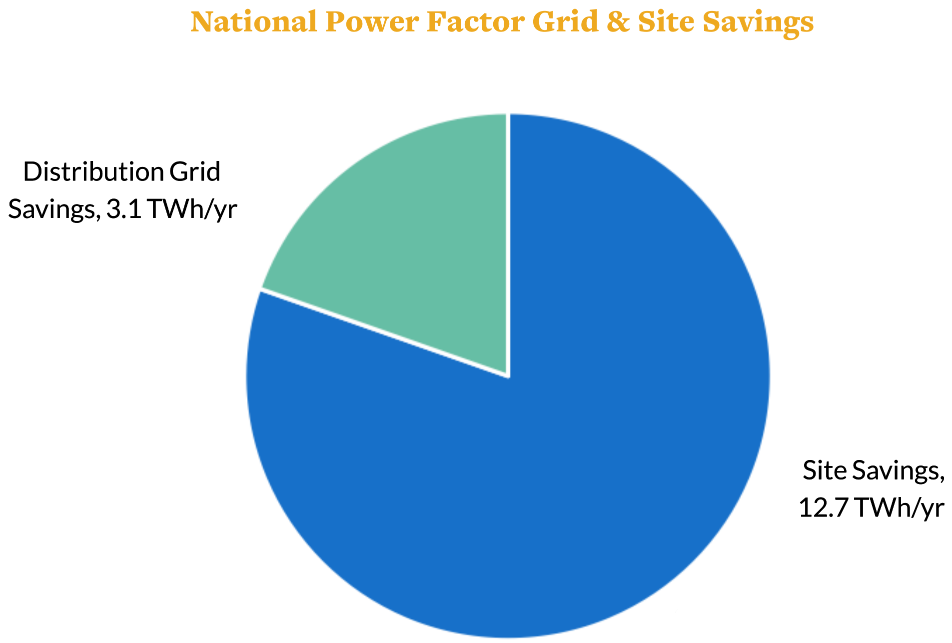

Figure 2: Power factor correction of the 42 loads examined in this study could save 12.7 TWh per year, with an additional 3.1 TWh per year in savings on the distribution grid.

There are still uncertainties associated with Statewide CASE Team estimates, mainly due to a lack of quality data on the power factor of typical equipment sold today. Further study and sensitivity analysis will be required to fully validate the savings opportunities for individual loads, but this research serves as a foundation to guide future efforts.

The research shows that improving power factor in electrical loads represents a nationwide energy savings opportunity as large as 15.8 TWh per year, enough electricity to power Philadelphia for a year.[3] The Statewide CASE Team estimates that improving power factor in commercial and residential electrical loads could save 12.7 TWh per year in buildings (behind the customer meter) and an additional 3.1 TWh per year on the distribution grid. The behind-the-meter savings alone could power nearly 1 million typical U.S. homes for a year. Power factor correction also generates non-energy benefits, such as providing reactive power support to utilities who otherwise must provide such services through equipment installed on the grid (often referred to as VAR support).

A half dozen large, motorized loads account for over 90% of the technically achievable savings. Residential loads, including central split air conditioning systems, furnace fans, and window air conditioners, represent 75% of the savings given their large installed base. Commercial loads, such as split air conditioners, packaged rooftop units, and packaged terminal units, round out the top six opportunities.

About 50% of the technically achievable savings are economically justified using traditional appliance efficiency cost effectiveness tests, but by including grid-side economic benefits, 80% of the overall savings become economically justified. The collective lifetime benefits to building owners and grid operators resulting from improved power factor total over 5.7 billion dollars, according to the Statewide CASE Team's research. Traditional appliance cost effectiveness calculations weigh the lifetime value of energy savings generated at the point of load (and behind the customer meter) against the incremental cost of an efficiency measure to consumers. However, power factor correction generates savings both in buildings (behind the meter) and on the distribution grid. Consumers pay for the former directly and the latter indirectly (grid

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[3] According to the U.S. DOE, Philadelphia is estimated to consume approximately 11.7 TWh per year. See: http://bit.ly/2wOCYCI

National Electricity Savings Scenarios for Power Factor Corrected Loads (TWh per year, building and grid savings)

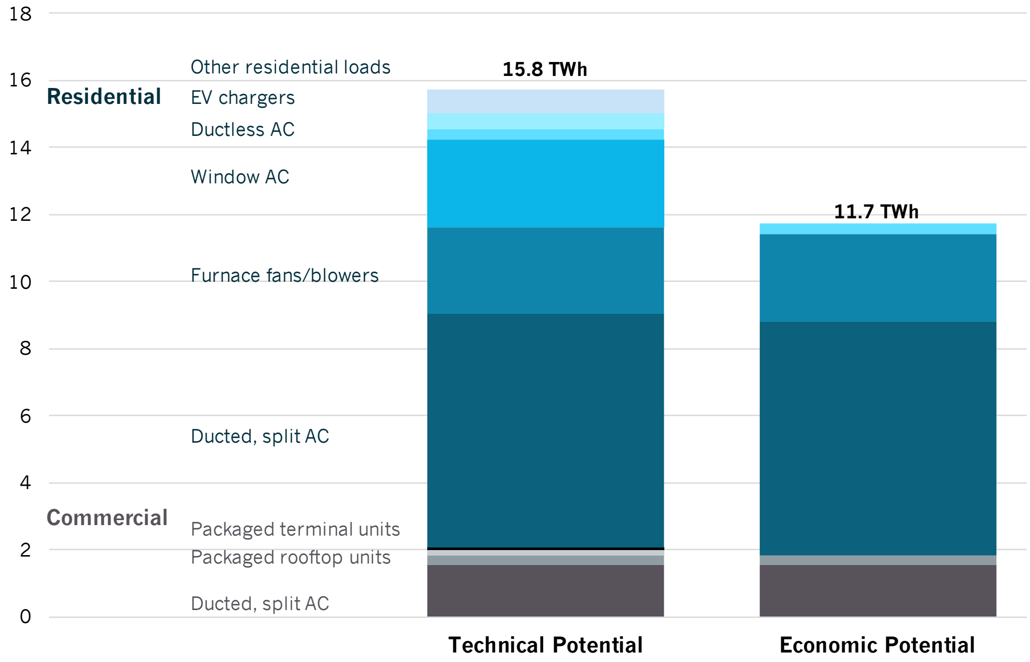

Figure 3: By considering the holistic, grid-side impacts of power factor correction as well as behind-the-meter savings, the Statewide CASE Team estimates that 80% of total savings opportunity can be economically achieved by addressing a handful of loads.

losses are simply part of the overhead cost associated with delivering electricity). The Statewide CASE Team therefore takes a more holistic approach than other energy efficiency measures by evaluating benefits that occur on both sides of the meter.

The most cost-effective loads are also the largest savings opportunity. These include split air conditioners, furnace fans, ductless air conditioners, and commercial rooftop HVAC units. HVAC products represent the most cost-effective saving opportunities. Because climate impacts HVAC load, it similarly impacts the energy savings potential and cost effectiveness associated with power factor correction for those same loads. For example, the analysis shows that power factor correction in commercial packaged rooftop air conditioning units is cost-effective in hot-humid climates without considering grid-side benefits; however, when examined on a national basis, it is only cost-effective when incorporating grid benefits. Future analyses of individual product categories should more deeply explore these climate sensitivities.

Heat pumps merit additional data collection and investigation. Ducted/split and ductless/mini-split air conditioners rank among the best power factor improvement opportunities. Given their mechanical similarity to air source heat pumps, it stands to reason that heat pumps may also yield additional savings potential from power factor improvements. Unfortunately, scarce information is available on the power factor characteristics of heat pumps. Additional research and data collection should determine whether heat pumps present the same energy savings potential that the Statewide CASE Team estimates for air conditioning systems.

Further research is needed to more comprehensively screen individual loads for power factor correction potential and ensure robust policy decisions. To fully vet individual products for power factor correction potential, the efficiency community must acquire further data on the power factor performance of high-priority loads and conduct more detailed, device-specific modeling. Power factor data on currently shipping products is often scarce, despite the fact that it is a relatively easy metric to capture in existing energy efficiency test procedures. It simply needs to be reported. Less is known about the real-world power factor and related energy impacts of devices operating in the field. Field measurements will be particularly important to validate the prevailing power factors and electrical losses associated with different types of equipment in real buildings, not to mention the energy savings impact of power factor correction technologies. Grid impact measurements and modeling will also be required to more accurately capture impacts on the broader electrical system. It is the systems nature of this measure, after all, that makes it so challenging, but also so potentially impactful.

Acknowledgments

The report authors would like to thank the following individuals for their consultation, review, and suggestions in the development of this report and the underlying analysis:

Charles Kim, Southern California Edison

Daniel Gerber, Lawrence Berkeley National Laboratory

David Chen, Director Applications Engineering, Power Integrations

Francisco de la Rosa, Senior Electric Power Systems Consultant

Glenn Aiemjoy, Senior Power Quality Engineer, Pacific Gas and Electric Company

Greg Barker, Technical Director, Energy Solutions

Pierre Delforge, Senior Policy Advocate, Natural Resources Defense Council

Tom Geist, Principal Technical Leader, Electric Power Research Institute

The views expressed in this paper, however, remain those of the authors and do not reflect opinions or analysis provided by external parties.

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I. Introduction

The energy efficiency community has traditionally focused on programs and policies that encourage direct reductions in electrical consumption and demand at the point of use. Efficient lamps produce greater lumens for a fixed amount of power, televisions consume less power for a given screen area, and imaging and laundry equipment consume less energy over the course of a standard workload — all measured at the point where each product connects to AC power.

The energy losses incurred while delivering electricity to these end products — estimated at about 5 percent (U.S. EIA 2018b) — are often simply ignored or, at best, assumed to be fixed and unavoidable, a "cost of doing business." This is mostly a valid assumption. Consumers have almost no influence over the systems that supply energy to end uses, especially the components of the transmission and distribution grids and centralized generation sources. But distribution losses can be impacted by how a device draws power from the AC grid, particularly in lower capacity wiring at the edge of the grid and in buildings. Specifically, devices with low power factor draw higher current to deliver the same power, which can increase the losses in building and distribution wiring. Though losses for any single product may be small, in total and across millions of products, the losses add up and represent a sizable opportunity for energy savings. Improvements to device power factor may represent a nationwide energy savings opportunity as large as 15.8 TWh per year, enough energy to power Philadelphia for a year.

This white paper analyzes the potential size of the power factor energy savings opportunity on an order-of-magnitude basis, identifies the most promising loads to capture power factor savings, and discusses several technical and economic barriers that prevent broader adoption of power factor correction technologies. The Statewide CASE Team envisions this research as a first step in exploring power factor as an energy-saving measure in the United States, and additional research, data gathering, and modeling will be required to make robust policy decisions for specific jurisdictions.

Power Factor Fundamentals

Real power, measured in watts (W), is the power for which most utility customers are billed. It does the actual work of turning motor shafts, producing light, and powering computations in data centers. In direct current (DC) circuits, real power is simply the product of the supply voltage, V, and the current, I, as in the equation below.

$$P_{\mathrm{real,DC}} = I_{\mathrm{rms}} V_{\mathrm{rms}}$$

Equation 1: Real Power

However, in alternating current (AC) power systems, the voltage supplied and current drawn manifest as time-varying waveforms, and these waveforms do not always coincide. In fact, many loads appear to consume an amount of power equal to the product of voltage and current flowing into the load, but they actually consume slightly less real power. Such loads "react" with the AC voltage supplied and return some of the energy to the grid, much like a vehicle's suspension absorbs and releases some of the incoming energy from roadways. This somewhat higher apparent power, measured in volt-amperes (VA), is the product of the time-averaged[4] voltage and current. Apparent power reflects the maximum AC current that flows through a conductor and for this reason is used for rating and sizing grid components like conductors and transformers. Mathematically, apparent power, S, is given by:

$$S = V_{\mathrm{rms}} I_{\mathrm{rms}}$$

Equation 2: Apparent Power

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[4] The time-averaged value of voltage and current is the root mean square or RMS value.

Quantifying the relationship between apparent and real power drawn by the AC load requires a new term, a power factor. Power factor, in its most basic form, represents the ratio between the amount of real and apparent power drawn by a load. For simple resistive loads, like incandescent lamps or toasters, real and apparent power will be equal, because these loads do not "react" with AC power. This results in a power factor of 1. However, for many other products, apparent power will be greater than real power, so power factor will be less than 1. Equation 3 shows the most general relationship for power factor, where P represents real power and S represents apparent power.

$$\mathrm{PF} = \frac{P}{S}$$

Equation 3: Power Factor

Low power factor has two root causes, displacement and distortion (i.e. harmonic distortion), which depend on the types of loads being powered and how they interact with the power system. In the case of displacement power factor, loads interact and exchange energy with the grid, drawing current out of phase with the AC voltage supply. This means that the peaks and troughs of the voltage signal do not align with those of the current (*Figure 1*). Inductive loads like washing machines, air conditioners, and other motorized products exhibit this type of behavior. In inductive loads, the current lags the supply voltage, as shown in Figure 1. Note that the waveform for current peaks later than the voltage. In contrast, capacitive loads, such as batteries, cause currents to lead the supply voltage. In either case, the misalignment between voltage and current waveforms means that less real power can be delivered at the same current (or more practically, that more current is required to deliver the same power).

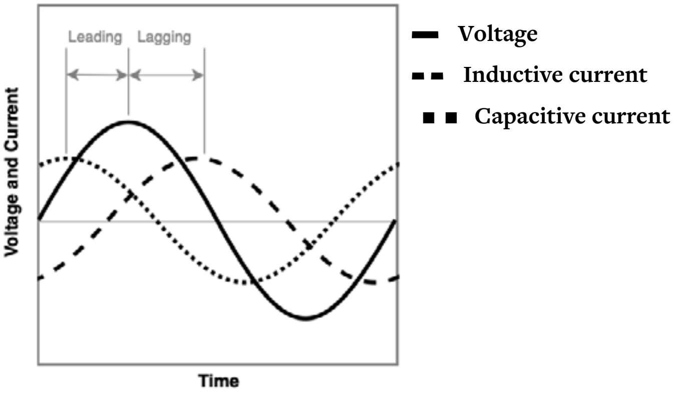

Figure 4: An inductive load exhibiting displacement

In the case of *distortion power factor*, loads draw current in a non-sinusoidal manner and cause harmonic currents in building wiring and the grid.[5] As with displacement power factor, harmonic distortion results in lower power factor. Harmonic distortion is typically generated by the power electronics used in switch-mode power supplies; variable frequency drives; and other non-linear, electronically controlled equipment that operate at high frequencies or segment the waveform in some fashion. Consumer electronics and office equipment often exhibit distortion power factor issues. An example current waveform for a non-linear load with harmonic distortion is shown in (*Figure 2*).

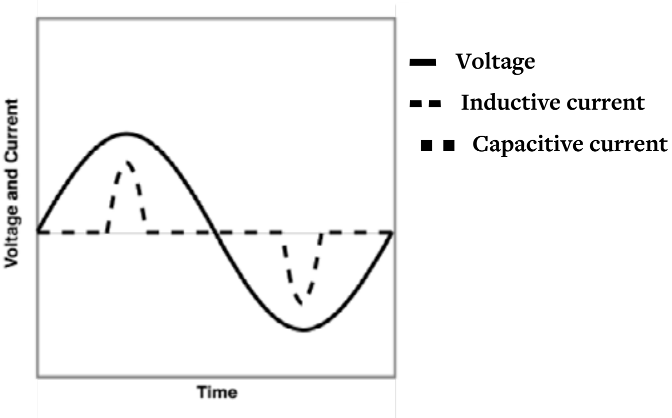

Figure 5: An electronic load exhibiting harmonic distortion

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[5] For North American grids, harmonics have frequencies higher than the fundamental frequency of 60 Hz, and are usually in multiples of 60 Hz.

Even though the distorted current may appear to align well with the supply voltage, a significant amount of the current occurs at frequencies higher than the fundamental frequency (for North Americans, 60 Hz)[6], and these components create a waveform that is not well aligned with the supply voltage.

This means, once again, that it will generally require more current to deliver the same amount of real power to a distorted load, compared to a load with a power factor of 1.

A product's true power factor takes into account the combined effects of displacement and distortion, although in reality, one or the other effect tends to dominate any individual load. True power factor can be captured by the following relationship:

$$\mathrm{PF} = \frac{P}{S} = \mathrm{PF}_{\mathrm{disp}}\mathrm{PF}_{\mathrm{dist}} = \frac{\cos\phi}{\sqrt{1+\mathrm{THD}_I^2}}$$

Equation 4: True Power Factor

where PFdisp is the contribution to power factor associated with displacement, PFdist is the contribution to power factor associated with distortion, f is the phase angle between the load current and the supply voltage, and THDI is the total harmonic distortion of the load current[7]. In practical terms, this equation states that as displacement increases and phase angles approach 90˚, power factor will decrease. Also, as distortion increases and THDI gets large, power factor will also decrease.

The AC power grid is a highly complex and interconnected system in which every load on a circuit and even the wiring itself contributes to the current waveform at the supply or "grid" end of that circuit. Current waveforms add up across an entire building at the AC supply point,[8] and, in the case of larger distribution feeder circuits, at the substation level. Since current flow on an AC grid is bidirectional (through a given AC cycle, it will be both positive and negative), superimposing different current waveforms can yield counterintuitive results. Adding two inductive loads with waveforms of the same magnitude (say, 1 A) that both lag the supply voltage by -60˚ (this causes a power factor of 0.5) produces a combined waveform with a magnitude of 2 A. However, if one inductive and one capacitive load are combined, and their current waveforms are equal in magnitude but out of phase with the voltage in equal and opposite directions (the inductive by -60˚ and the capacitive by +60˚), this results in an overall waveform that is perfectly in phase (a power factor of 1).Thus, the magnitude and direction of loads can play a large role in the resulting current and power factor that the supply wiring eventually "sees". See appendices A and B for a more complete explanation of the Statewide CASE Team's calculations and simplifying assumptions.

Readers interested in a more in-depth primer on power factor as it pertains to harmonic loads are encouraged to examine chapter 5 of "Consumer Electronics and Motorized Appliances" (CEC 2015) as well as CEC's primer on efficient power supplies(CEC 2004). NYSERDA's "At Load Power Factor Correction Report" (NYSERDA 2010) provides further information on displacement power factor, techniques to correct it, and its impact on the electric grid.

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[6] The current waveform can be thought of as the sum of many different waveforms at different frequencies above the "fundamental" frequency of AC grid. These component waveforms, their frequencies, and their relative strengths determine the amount of harmonic distortion.

[7] Total harmonic distortion represents the fraction of the current that occurs at frequencies higher than the fundamental or nominal grid frequency. The higher the THD, the greater the influence of harmonics, and the *lower* the power factor.

[8] This is referred to as the point of common coupling or PCC in many power quality standards and technical literature.

Impact of Power Factor on Energy Losses in Buildings

Devices with low power factor do not *directly* consume more power than other products. Rather, by requiring more current to deliver the same real power, loads with low power factor may generate additional resistive losses upstream of the load. Every conductor on the grid, from the transmission lines to distribution feeders to the building wiring itself, presents some electrical resistance and dissipates power according to the following relationship:

$$P_{\text{loss}} = I^2 R$$

Equation 5: Resistive Power Loss

where P_{loss} is the power dissipated in the conductor, R is the electrical resistance of the conductor, and I is the load current (specifically, the time-averaged [4] root mean square current). Even small changes in current can have a dramatic effect on overall losses due to the squared term. Doubling the current, for example, results in four times the losses.

For a tangible example, consider two different televisions connected to power through a wall receptacle on a 15-amp branch circuit *(Figure 3)*. Both draw 100 W of real power at the wall receptacle, but one has a power factor of 0.5, the other 0.95. As a result, the television with lower power factor will draw nearly double the apparent power (200 VA versus 105 VA) and, therefore, nearly double the current. The additional current draw results in higher ohmic losses through the I2R relationship: about 1 W in the case of the low power factor unit, but about 0.2 W for the unit with high power factor. At a system level in the home, the product with the lower power factor (drawing higher current) will consume more power (0.8 W) due to increased power losses in the branch circuit that supplies it.[9] Although these losses may be relatively small compared to the product's overall power draw, they are ubiquitous, generated by dozens of different product types across millions of buildings. Therefore cumulative losses may be large, as is the case with standby or "vampire" loads.

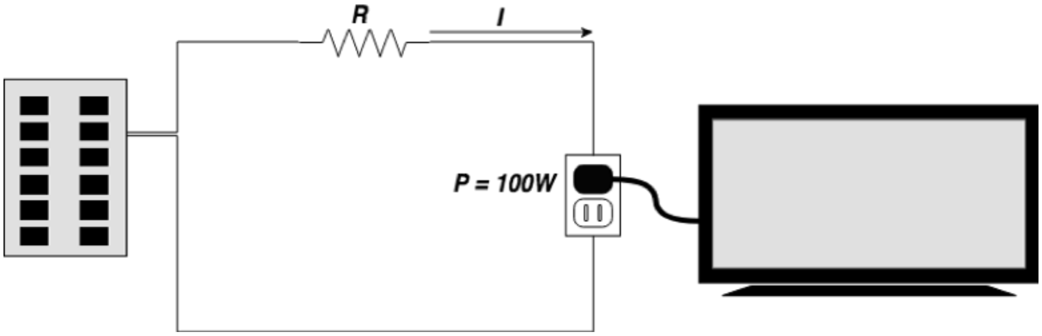

Figure 6: Example branch circuit supplying power to a television.
Resistive losses occur over the entire length (round-trip) of the circuit.

Several studies have examined and quantified the energy benefits of improved power factor in various product types, with a broad range of estimated savings.[10] The California Energy Commission's (CEC) Public Interest Energy Research (PIER) Program has been active in this area for over a decade. In 2006, researchers estimated that power factor correction in computer power supplies alone could save 2.8 percent of the total electricity consumed by commercial buildings in California, equivalent, at the time, to about 300 GWh per year at full stock turnover (CEC 2006). More recently, CEC-funded researchers estimated that 240 GWh per year could be saved by requiring all residential and commercial electronic loads in California with nameplate ratings larger than 50 W to achieve a power factor of 0.9 (CEC 2015)[11].

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[9] The Statewide CASE Team assumes a 75 ft branch circuit (150 ft round trip) rated for 15 A and containing 14 AWG cabling.

[10] This range can be attributed to the differing scopes of the studies as well as the diverse array of considerations that must be accounted for when modeling power factor losses. Since benefits accrue at the system level (i.e., not directly at the load itself), assumptions regarding conductor sizing, circuit layouts, and load coincidence ultimately influence the range of estimated savings.

[11] Note: electronic products with nameplate ratings larger than 75 W must already meet the total harmonic distortion requirements of the International Electrotechnical Commission (IEC) 61000-3-2: 2014 standard.

The New York State Energy Research and Development Authority (NYSERDA) also funded research and development of power factor correction technology around 2010, focusing efforts on motor loads (NYSERDA 2010). The research team installed devices to mitigate displacement power factor on commercial supermarket refrigeration compressors, small industrial compressors and motors, refrigerated vending machines, multi-family residential buildings, and single-family homes. Researchers identified significant savings opportunities in both supermarket compressors and refrigerated vending machines, owing to measured reductions in building line losses, ranging from 1.5 to 3 percent of the end load.

Impact of Power Factor on Grid Losses

The additional current flow to products with low power factor causes losses beyond the customer's meter and on the distribution grid. This includes power flows through service drops, transformers, feeder circuits, and substations (Figure 4). Although losses for any given product tend to drop off significantly moving further up the distribution network, where conductors have far lower resistance and power flows at lower currents, the same basic principles apply as at the branch circuit level. The customer does not pay for these grid losses directly. Rather, the losses represent part of the cost of providing power and must be recovered through electric rates. Thus, grid-side losses and costs associated with power factor are ultimately borne by the consumer.

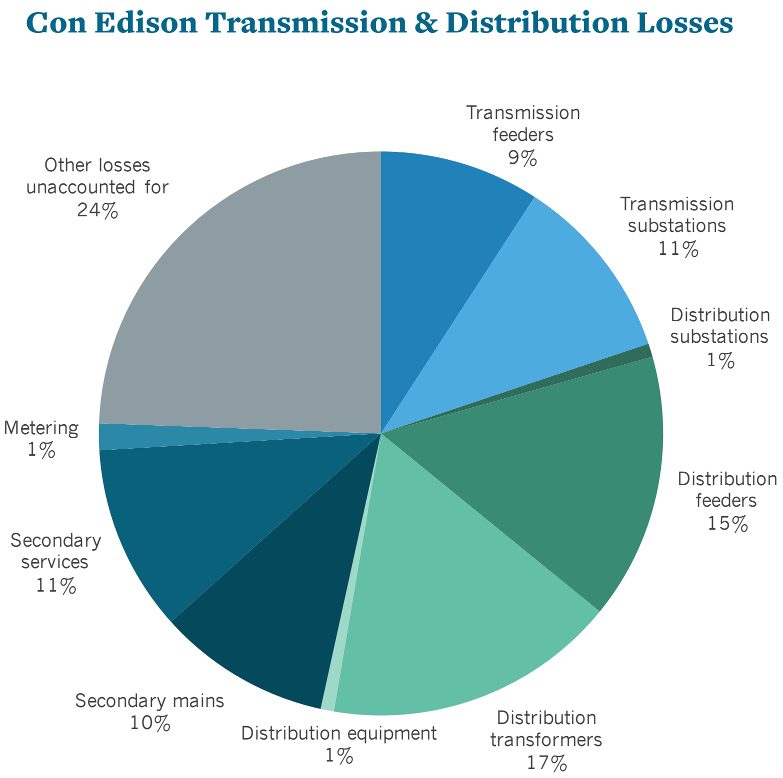

Figure 7: Share of transmission and distribution energy losses for Con Edison. Data source: Con Edison, 2008.

Most prior research has examined power factor impacts that relate to broader power quality concerns, but several studies acknowledge the energy efficiency benefits at grid scale. One recent study (Lombard et al. 2016) analyzed the energy losses associated with harmonic distortion from residential and office loads based on data from South African distribution networks, and estimated losses at 0.1 to 0.5 percent of total load. Similarly, NYSERDA (2010) estimated grid-side losses associated with poor displacement power factor at about 0.3 percent. To put this in perspective, overall transmission and distribution losses in the U.S. amount to about 5 percent of total electricity consumption (EIA 2018b), meaning that poor power factor could account for 2 to 10 percent of overall transmission and distribution losses.

Non-Energy Impacts

Improvements to power factor can provide a host of non-energy benefits as well, including reduced electricity costs, extended equipment life, and increased power quality. Some utilities charge large facilities for kVA (apparent power, measured in thousands of volt-amperes) in addition to demand or energy charges. These facility owners may realize economic benefits by improving power factor and therefore lowering their average monthly kVA. Reduced resistive losses also result in lower heat generation in conductive elements, which can extend the useful life of components like transformers (de la Rosa 2006). Reduced currents and kVA can effectively relieve capacity constraints on existing electrical infrastructure, potentially avoiding nuisance tripping of circuit breakers. Finally, in the case of loads with harmonic distortion, eliminating harmonic currents at the source can mitigate a variety of power quality-related issues that can cause electrical equipment to malfunction, such as flicker in lighting systems or interference on land-based telecommunications lines (de la Rosa 2006).

Table 1 summarizes the various energy and non-energy benefits of improving power factor, some of which accrue directly to ratepayers and others that reduce the costs of operating and maintaining the grid (this indirectly benefits ratepayers).

Table 1: **The Benefits of Improved Power Factor**

	Building-Level Benefits	Grid-Level Benefits
Energy benefits	Fewer losses in building wiring lead to reduced electric consumption and utility bill savings.	Potential for reduced losses in distribution lines and transformers.
Non-energy benefits	**Broadly applicable:** • Reduction of kVA charges for large customers (if applicable). • Extended life of system components, such as breakers and stepdown transformer, by reduction in electrical currents and resulting heat generation. • Increased current-carrying capacity (ampacity) of existing electrical circuits and avoided unnecessary circuit breaker trips. • Distortion only: • Reduced harmonic currents on building's neutral wires, decreasing overheating risk, particularly in older facilities with traditionally sized neutral wires. • Avoided flicker in fluorescent lighting. • Reduced audible noise on telephone landlines. • Lower risk of malfunction in equipment that is sensitive to voltage harmonics, including solid-state relays, solar inverters, and electric vehicle chargers.	**Broadly applicable:** • Extended life of system components, such as transformers, by reduction in electrical currents and resulting heat generation. • Distortion only: • Reduced distorted supply voltages (a side-effect of severe harmonic distortion) and improved overall power quality.

Technologies for Improved Power Factor

The technological solutions to address power quality issues in general and power factor in particular are not new, although solutions are typically implemented at the scale of the grid or larger industrial and commercial facilities. For example, in order to maintain locally acceptable power factor levels and free up capacity on circuits, utilities maintain large banks of capacitors (on the order of millions of volt-amperes reactive capacity) that can compensate for the displacement power factor caused by large inductive loads, such as motors.[12] A substation-level installation is depicted in Figure 5, with a capacitor bank dedicated to each phase. Such installations are engineered and constructed in a site-specific manner as part of overall electrical system design. Large industrial facilities may install such equipment on site to locally mitigate displacement power factor, especially for industries with large motor loads.

Similarly, industrial or large commercial building operators may incorporate harmonic filtering equipment into the design of data centers or large, electronically controlled motor banks to mitigate harmonic distortion and avoid utility surcharges (Figure 6). Such devices are available as packaged equipment from large industrial equipment manufacturers, including ABB, Eaton, Siemens, and Schneider Electric.

Figure 8: A 75 MVAR (million volt-amp reactive) capacitor bank installed at a utility substation.

Figure 9: Facility-scale harmonic filter in housed in cabinets.

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[12] This practice is often referred to as VAR (volt-ampere reactive) support, as capacitor banks provide add reactive power load to balance motor loads.

A variety of companies also market similar products to consumers for whole-home power factor correction. These products typically consist of a large capacitors that can be installed in parallel with the home's electrical supply at the breaker box (Figure 7). The operating principle is identical to capacitor banks installed by utilities, only operated at a much smaller scale. Although the devices can produce energy savings, it should be noted that manufacturer marketing claims — particularly exaggerated claims of utility bill savings – have come under great scrutiny (Misakian 2009). These devices may generate some energy savings upstream of their point of installation, but very small, if any, real kWh savings on the customer side of the meter. Correcting power factor at the point of load, on the other hand, can reduce currents and resistive losses through entire branch circuits and can be expected to yield larger overall savings if applied strategically to the appropriate loads.

The focus of this report is the correction of power factor in a distributed manner by integrating power factor-correcting technologies into end-use devices themselves. Fortunately, the strategies employed are conceptually identical to those already used at larger scales.

As with large-scale power factor correction, the strategies employed in end uses must be tailored to the type of power factor issue at play. Introducing reactive elements (like capacitors) to counteract the phase shift of inductive elements (like motors) can mitigate displacement issues. This approach, when applied to counteract large inductive loads like motor banks, places large capacitors between the AC source and the offending load (Figure 7). In smaller motors, such as those used in appliances and smaller packaged HVAC systems, opportunities exist to correct displacement power factor by integrating capacitors directly with end-use equipment. Likewise, displacement in capacitive equipment could similarly be mitigated using inductors.

Figure 10:
Whole-home power factor correction device (Source: P.E.F.L. Inc.)

Figure 11:
Capacitors for use motor power factor correction (top) and schematic of capacitor placement (bottom).
Source: (top photo) Cos Phi 2017; (bottom drawing) Statewide CASE Team

Distortion power factor must be addressed using electronic filters to smooth the product's current waveform.[13] These electronic components would be integrated as the first stage of the product's AC-DC power supply. They typically have a high pass-through efficiency (over 95%) and low cost (see cost considerations in Appendix I: Incremental Cost Assumptions), but they nevertheless do incur losses that must be weighed against the potential upstream power savings resulting from lower power factor. A variety of vendors, including Power Integrations, ON Semiconductor, and Texas Instruments, manufacture power factor correction (PFC) integrated circuits (ICs) for this purpose. Such PFC ICs scale in size and cost according to the overall power ratings of the end product. Figure 8 shows example active PFC ICs.

Figure 12: Example PFC components designed for consumer electronics applications from Power Integrations (left) and Texas Instruments (right).

Table 2 summarizes two general technology approaches available today to address power factor at the device level, depending on the type of power factor issue.

Table 2: **General Technologies to Improve Power Factor**

Technology	Type of Power Factor Addressed	Description	Applicable End Uses
Capacitors	Displacement	Integrated capacitors counteract the displacement power factor introduced by inductive elements like motors.	Motor-driven loads without electronic controls.
Power factor correction filters	Harmonic Distortion	Electronic component(s) integrated into a device's power supply that actively filter out harmonic currents.	Suitable for any electronic device with a switch-mode, AC-DC power supply or motorized devices with variable frequency drives (i.e., non-linear loads).

Improving power factor at the point of use could theoretically maximize system-wide benefits, because savings could accrue in all conductors upstream of the end load. However, there are some potential downsides to end-use power factor correction that must also be noted. The aggregate impact of poor power factor in end-use products is determined by both the magnitude and the direction of reactive power flows. Capacitive loads work to counterbalance inductive loads if they are used coincidently and are located on the same circuit. This is because the reactive current from a capacitive load opposes reactive current from an inductive load. Improving power factor of one of these loads in isolation might actually reduce overall power factor. However, if loads do not coincide or are significantly imbalanced in their overall current draw, correcting the power factor of the largest loads can produce a net benefit.

Secondly, certain active filter technologies, such as the PFC electronic components described previously, consume power themselves. Generally, for power factor improvements to generate net energy benefits, the reduced conductive losses at the system level must outweigh any increased power consumption by the PFC stage itself. In many cases examined throughout this report, the assumed technical path for power factor correction only involves passive components, like capacitors, so this consideration is ignored; however, it could play a larger role in addressing power factor in electronic end uses.

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[13] Active power factor correction controls the shape of the current waveform such that it matches the shape of the supply voltage and can filter out both displacement and distortion effects.

II. The Power Factor Opportunity

The following sections provide an overview of the Statewide CASE Team's most important assumptions and a general description of the order-of-magnitude energy savings calculations. For readers who are interested in more detailed assumptions, this report contains appendices with product-level assumptions and a more thorough treatment of the calculations.

Sizing Up the Opportunity

Due to the sheer complexity of power flow on the electric grid and in buildings, the scope of the analysis was intentionally constrained in several important ways:

Product types – An exhaustive quantitative analysis of every possible electric load that might appear in a residential or commercial setting was not feasible or practical for the purposes of this study. The goal of this is to capture order-of-magnitude savings estimates, so the Statewide CASE Team focused attention on the most prevalent and frequently used loads in these sectors. The reader should not construe omissions of certain loads — data center equipment, elevators, automatic door openers, and so on — as a verdict on their power factor energy savings potential. To the contrary, large energy savings may be achievable other specialized loads, but it was not practical to include all product verticals in this initial study.

The Statewide CASE Team began with a comprehensive list of 174 residential and commercial end-use products. Of these, 132 products were screened out of the analysis based on some combination of the following factors: low market share, small active mode duty cycle, a high prevalence of power factor-corrected products in the existing stock, and/or resistive load characteristics (resistive loads like electric resistance water heaters have a power factor of 1). This culling resulted in a list of 42 prioritized loads, summarized by sector and end-use category in Table 3.

Table 3: **Products Analyzed**

Commercial Loads	Residential Loads
Appliances	
Refrigerated vending machine	Clothes washer
Commercial refrigerated case	Clothes dryer
Refrigerator	Dishwasher
	Freezer
	Refrigerator
Electronics and Office Equipment	
Desktop computer	Desktop computer
Imaging equipment	Game console
Notebook computer	IP set-top box
Small network equipment	Notebook computer
	Set-top box
	Small network equipment
	Television

Table 3: **Products Analyzed, continued**

	Commercial Loads	Residential Loads
HVAC		
	Central, split AC	Central, split AC
	Packaged rooftop AC	Dehumidifier
	Packaged terminal AC	Ductless AC
		Evaporative cooler
		Furnace fan
		Hot water recirculation pump
		Hydronic circulation pump
		Radon ventilation fan
		Well pump
		Window AC
Lighting		
	Linear fluorescent lamp	Compact fluorescent lamp
	Compact fluorescent lamp	High intensity discharge lamp
	High intensity discharge lamp	LED lamp
	LED lamp	Linear fluorescent lamp
Miscellaneous		
		EV charger
		Pool/hot tub/sauna pump

Air source heat pumps – The case of air source heat pumps merits special mention. Heat pumps were screened from the initial analysis due to relatively low and regionally specific market penetration and an absence of power factor measurements relevant to today's rapidly evolving products. Nevertheless, high-efficiency and cold climate air source heat pumps have gained attention in energy efficiency and building decarbonization circles as a pillar of building electrification efforts. From a mechanical standpoint, central air source heat pumps bear a close resemblance to the central, split air conditioning systems evaluated in this study. They use an electric compressor to drive a vapor compression refrigeration cycle, only they operate the cycle in reverse to provide both heating and cooling. Similarly, ductless mini-split heat pumps are very similar to ductless air conditioning systems. Therefore, it is reasonable to assume that substantial power factor savings opportunities may exist for air source heat pumps as with their split and ductless air conditioner cousins. These similarities are noted in several areas of the report.

Product operational modes – Many products included have two or more operational modes, but this analysis considers active or "on" modes only. Low power modes used in many electronic and network-connected products often draw significantly lower power than active modes, resulting in lower current draw and significantly smaller potential for power factor savings. Recall that resistive losses are proportional to the square of current. Tenfold lower power consumption, therefore, results in hundredfold lower losses. That is not to say that such modes of operation could not generate savings through power factor improvements (in fact, spot measurements indicate that the power factor of products in low-power modes can be very poor[14]). However, unit savings associated with such products and modes can be orders of magnitude smaller than those associated with active mode. For example, consider the television depicted in Figure 3 that consumes 0.1 W of real power in standby mode at a power factor of 0.1. The upstream conductive losses from this TV in standby mode would be 0.026 mW or ten thousand fold smaller than when that TV operates in its active mode. Any savings generated by power factor improvements would be even smaller.

Climate sensitivity – The sizing, duty cycle, and equipment stock of HVAC products are highly climate-dependent. While it was not feasible to conduct detailed power factor savings analysis for each climate region in the country, the Statewide CASE Team analysis does attempt to capture climate effects through operating profiles and, for some loads, regional equipment stocks as well. The Statewide CASE Team developed regionally appropriate duty cycles for residential and commercial heating and cooling equipment using U.S. DOE reference building energy models to establish typical runtimes by climate (see Appendix F for further detail). Then, select climate-sensitive loads are analyzed on a regional basis to disaggregate savings on a regional basis. For the regional economic analysis, the Statewide CASE Team used regional average retail electric rates based on U.S. DOE Energy Information Administration data (U.S. EIA 2018b).

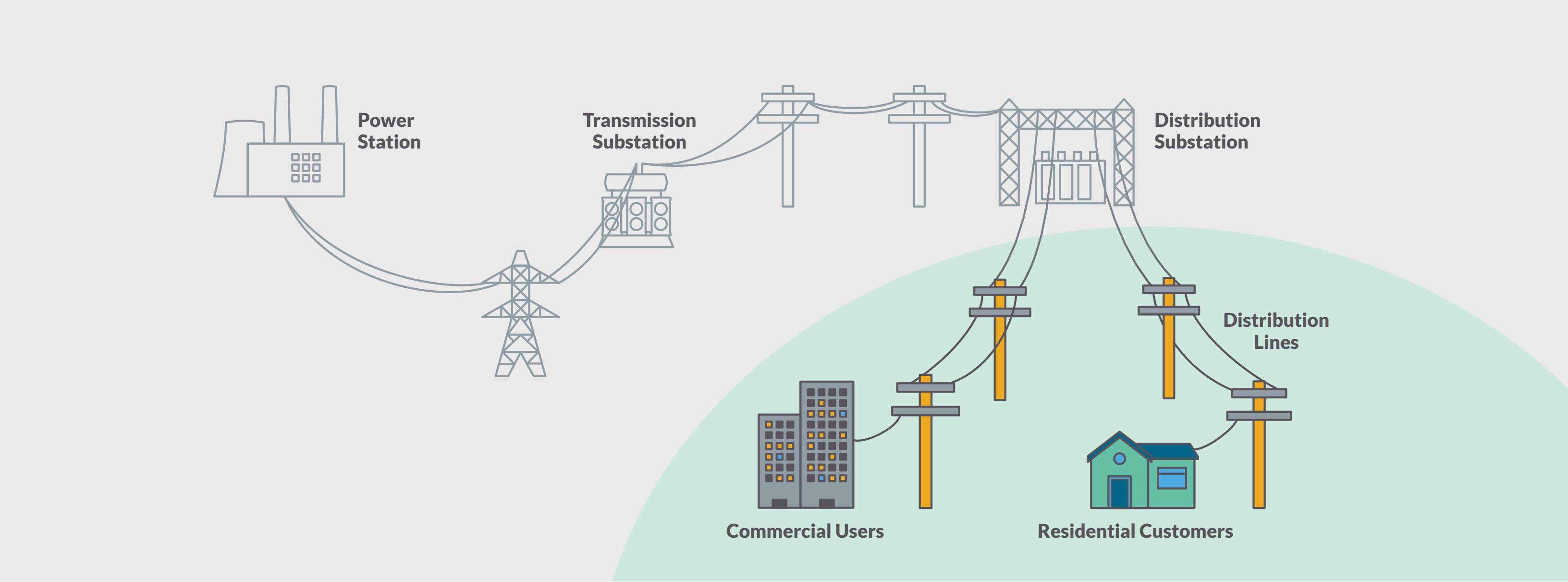

Figure 13: Grid savings analysis was conducted up to the level of the distribution substation, as illustrated in the schematic above

Extent of grid savings – While it is theoretically true that reductions in load current can generate savings throughout the entire transmission and distribution grid, this study only estimates savings up to the distribution level. Specifically, the Statewide CASE Team considered losses up to the distribution transformer level; feeder circuits and substation equipment are explicitly ignored. There are several reasons for this choice. First, the incremental savings from reduced grid losses that occur on the medium- to high-voltage portions of the grid (in the kilovolt range) will be significantly smaller than at the grid's edge, because the conductors used in this part of the network can handle very high currents and, therefore, have commensurately lower resistive losses.[15] In addition, it is extremely difficult to generalize assumptions about grid layout at higher levels of the network due to design choices that are dictated by the local utility, geography, and population density.

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[14] The Natural Resources Defense Council (NRDC) indicates that power factors of less than 0.1 have been measured in the low-power modes of certain electronic products. See: http://docketpublic.energy.ca.gov/PublicDocuments/17-AAER-12/TN219215_20170616T153544_Pierre_Delforge_Comments_NRDC_comments_on_low_power_modes_and_p.pdf

[15] The Statewide CASE Team estimates indicate that even high-power products like HVAC equipment will generate less than 0.5 W of losses in feeder circuits, which is 1 to 3 orders of magnitude lower than in service drops, building wiring, and transformers. On the transmission network, other power loss mechanisms, such as skin effects and capacitive losses, begin to dominate over resistive losses.

Quantification of non-energy benefits – While this study acknowledges several non-energy benefits associated with improved power factor, the goal is to quantify impacts that will generate direct energy and environmental benefits. Therefore, a detailed accounting for the value of non-energy benefits such as extending equipment lifetimes is not provided, although these may be quantifiable in future studies.

Given this scope, the resulting energy model examines the following question for each of the 42 loads: how much can the building- and grid-level losses be reduced by improving the typical power factor of the product while in its active mode? The Statewide CASE Team used simplified electrical loss calculations that examine the direct energy consumption and losses of each product at both the building and grid levels. On the customer side of the meter, it is assumed that losses occur in the building's wiring[16] itself. On the utility side of the meter, this study accounts for losses in service drop lines from the nearest distribution transformer as well as losses in the transformer itself.[17] Figure 9 presents a simple, single-line diagram of the losses considered in the model. The active mode losses (in watts) were translated to annual energy consumption (in kilowatt-hours) using each device's active mode duty cycle (in hours).

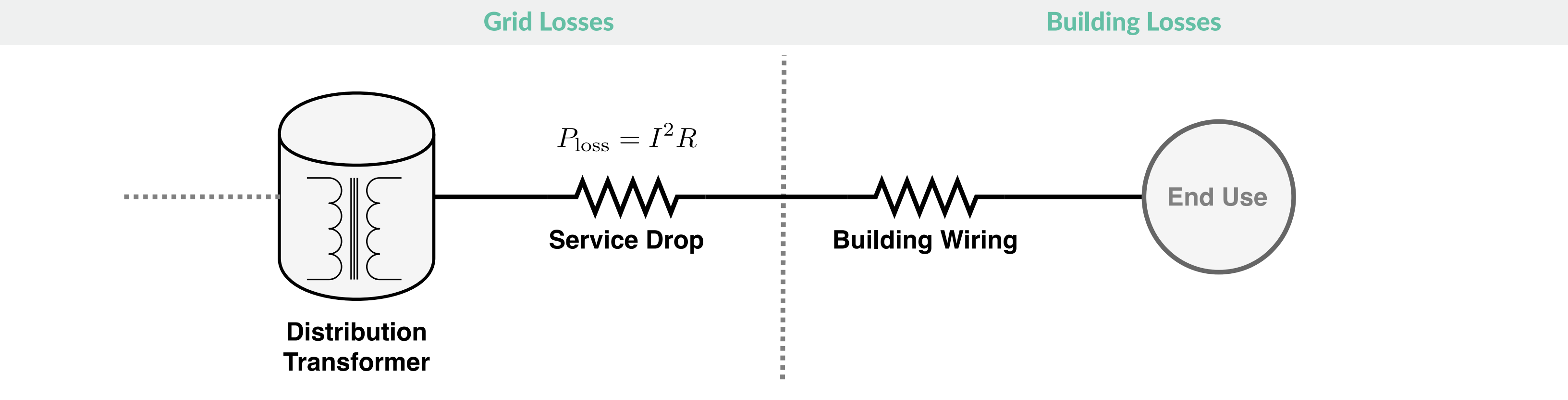

Figure 14: Modeled losses include losses through the windings of the distribution transformer and resistive losses in both the service drop and building wiring. Grid losses upstream of the distribution transformer are not considered.

The Statewide CASE Team stresses that this representation significantly simplifies the physics of real-world power flow in several ways. In real power systems, multiple loads may reside on a branch circuit, multiple branch circuits comprise a building, and multiple buildings may be fed by the same distribution transformer. These loads can "communicate" with each other at points of coupling where circuits join together. As a simplification, the analysis assumes that the reactive load (VAR) from each end device contributes to the total VAR at every level of the grid – customer meter, branch circuit, and distribution transformer – as would be the case if every device were connected via a home run circuit to the primary side of the distribution transformer. The practical consequence is that this study does not consider the interaction between capacitive and inductive loads, which, as mentioned earlier, can work to counterbalance the overall power factor of a circuit.[18]

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[16] Larger commercial facilities may also have a step-down transformer(s) on the customer side of the meter, but this study has ignored the presence of those losses for the purposes of this estimate.

[17] The Statewide CASE Team does not consider skin effects or eddy currents, which are a known loss mechanism in transformers.

[18] The Statewide CASE Team does note, however, that many of the loads with the highest estimated potential for energy savings tend to be large, motorized HVAC equipment. Such devices are typically installed on their own dedicated branch circuits, and so the point of coupling with other devices in the building would be the service panel. As a result, the interactions between such devices would only impact savings *upstream* of the service panel, rather than in the branch circuits themselves. As the analysis shows, the further upstream in the distribution system one moves, the less energy savings potential can be achieved by load-level power factor correction, so these interactions, in effect, impact a minority of the savings opportunity.

Secondly, real-world loads do not necessarily operate independently of one another, so the actual loading of a circuit, as well as the losses that accrue in conductors, will depend on the level of load coincidence. Generally, the greater the degree of load coincidence, the greater the collective and interactive effects of power factor correction will be. To simplify calculations, the analysis ignores load coincidence effects altogether and assumes that devices operate independently of one another.

Finally, the analysis necessarily generalizes a variety of assumptions surrounding typical building wiring. For example, assumed is a certain length of conductor feeding each load, whereas in reality, certain loads may be located closer to or farther from the building's electrical panel. Actual conductor lengths could depend on factors such as building size, electrical panel location, room layouts, and occupant preferences. This study also assumes nominal resistivity for circuit wiring and ignores any capacitive reactance that wiring may introduce. Real-world wire resistances may be higher, especially in older buildings, due to poor contact or corrosion (NYSERDA 2010).

The Statewide CASE Team recommends that future studies investigate sensitivities to these assumptions more extensively, but for the purposes of this white paper, is confident that the calculations are adequate for scoping the power factor energy savings opportunity on an order-of-magnitude basis and for prioritizing individual loads for exhaustive research and analysis. A more detailed mathematical discussion of both calculations and associated simplifying assumptions are provided in appendices A and B.

The Statewide CASE Team translated individual product results to a national level using a simple stock model, with stock derived for each product based on secondary sources. Economic analyses assess the cost effectiveness of the main power factor improvement strategies.

Each stage of the model required the development of a variety of product and infrastructure assumptions, listed in Table 4. Given the uncertainty in certain key assumptions, fields with an asterisk (*) indicate that a low, mid, and high value were documented. By capturing the resulting range of outcomes, the end results contain a low, mid, and high estimate of savings potential. In the body of this report, the mid-range estimate is reported and referred to; however, also provided is a full sensitivity analysis results in Appendix J. Tables of key product, building wiring, and grid infrastructure assumptions and associated sources can be found in appendices C through H. Economic assumptions are discussed in the reports "Economics of Power Factor Correction" section, with the incremental cost model described in Appendix I.

Table 4: **Energy Model Assumptions**

Product	
Saturation and/or stock Baseline power factor* Corrected power factor	Active mode power* Active duty cycle Root cause (displacement or distortion)
Building Wiring	
Supply voltages and phases Wire gage and resistivity	Round-trip circuit lengths
Grid Infrastructure	
Service drop wire gage and resistivity Transformer efficiency	Round-trip service drop length

* Model captures a high and low scenario.

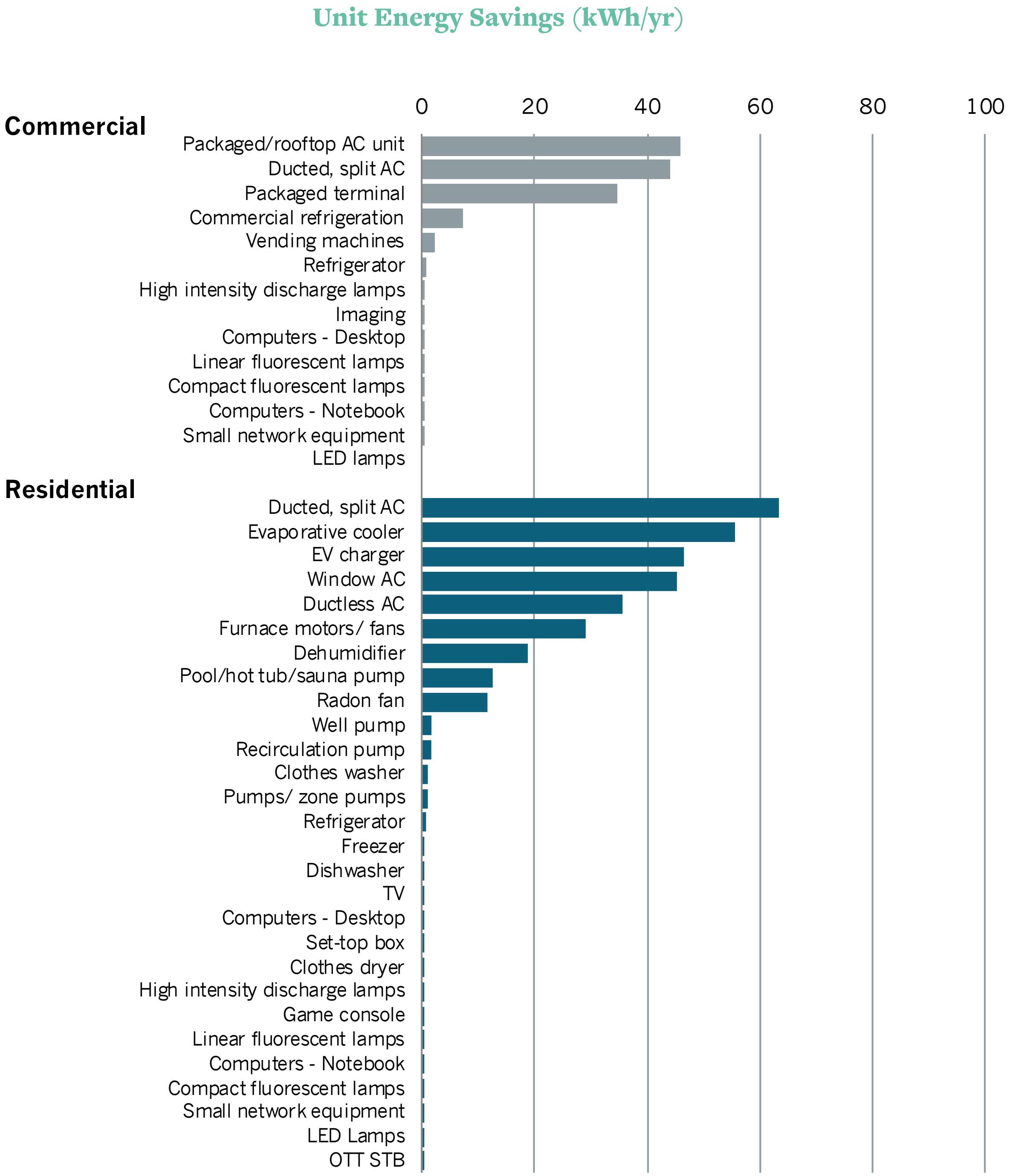

Figure 15: Unit annual energy savings (kWh per year) associated with power factor improvements for select commercial and residential loads. Results reflect our mid-range scenario.

How Much Can We Save?

On the Customer Side of the Meter

Improving the power factor of typical residential and commercial electric loads can generate large savings, especially in products that draw high amounts of power and current in their active modes and that spend a significant amount of their time in active operation. Although the Statewide CASE Team's mid-range savings scenario shows that power factor correction typically reduces direct electrical load by 1% or less, unit energy savings can be significant, especially in high-power, frequently operated products like HVAC equipment. Figure 10 illustrates site or "behind-the-meter" savings for individual residential and commercial loads. A variety of larger loads — mostly motors — could achieve over 20 kWh per year in annual savings.

Based on the savings at complete stock turnover (i.e., the savings if the entire national stock of devices were power factor-corrected), about 12.7 TWh per year could be saved by addressing all 42 products, but savings are heavily concentrated into a few ubiquitous, high-power loads (Figure 11). Despite the large unit savings associated with some commercial loads, residential savings dominate due to the larger stock of certain residential equipment. In fact, about 60% of the energy savings potential (about 7.7 TWh per year) could be captured through residential ducted air conditioners (central, split air conditioning) and furnace fans. The savings from these products alone exceed the estimated savings from several potential updates to U.S. Department of Energy (DOE) standards, including commercial ice makers, dehumidifiers, external power supplies, and battery chargers.[19]

Whether in a commercial or residential setting, the largest savings opportunities also almost exclusively derive from motorized loads, such as HVAC equipment. The one exception is electric vehicle service equipment, which ranks fifth among residential opportunities and seventh overall in terms of energy savings potential.

As noted earlier, air source heat pumps could present a substantial opportunity in the future as building electrification and decarbonization efforts promote their use as a building's primary heating and cooling source. Assuming that there is similar power factor improvement potential in heat pumps as expected in split air conditioning units, one would expect higher unit savings since heat pumps would see greater hours of operation (both summer and winter)

On the Grid

The overall power factor savings opportunity increases over 20% to 15.8 TWh per year when factoring in savings that would occur on the distribution grid as well *(Figure 12)*. The additional benefits mostly accrue in the service drops between the customer's meter and the local distribution transformer. Beyond the distribution transformer itself on distribution feeder circuits, savings would be orders of magnitude smaller (a fraction of a percent of the overall savings potential).

There are other grid-side benefits relating to grid power quality management, some of which may have more immediate value to utilities. In order to maintain locally acceptable power factor levels and free up capacity on circuits, utilities maintain large banks of capacitors that can compensate for the displacement power factor caused by large inductive loads, such as motors.[20] Compensating for those loads on a local level can theoretically reduce the burden on utilities to make larger scale capital investments on the grid scale, while capturing energy savings at the edge of the grid. If all of the 42 products in the analysis were power factor-corrected, this would be the equivalent of installing about 575 billion VAR of capacitor banks in a distributed manner across the grid (about 7,600 of the installations shown in Figure 5), valued at $6.7 billion. Naturally, the cost of mitigation shifts toward to the consumer in this scenario, an effect that is examined in the next section.

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[19] Per estimates of annual energy savings from next-generation standards conducted by the Appliance Standards Awareness Project (ASAP) and the American Council for an Energy-Efficient Economy (ACEEE). See ACEEE (2016).

[20] This practice is often referred to as VAR (volt-amp reactive) support, as capacitor banks provide reactive power to motor loads.

Annual Building Energy Savings at Stock Turnover (GWh/yr)

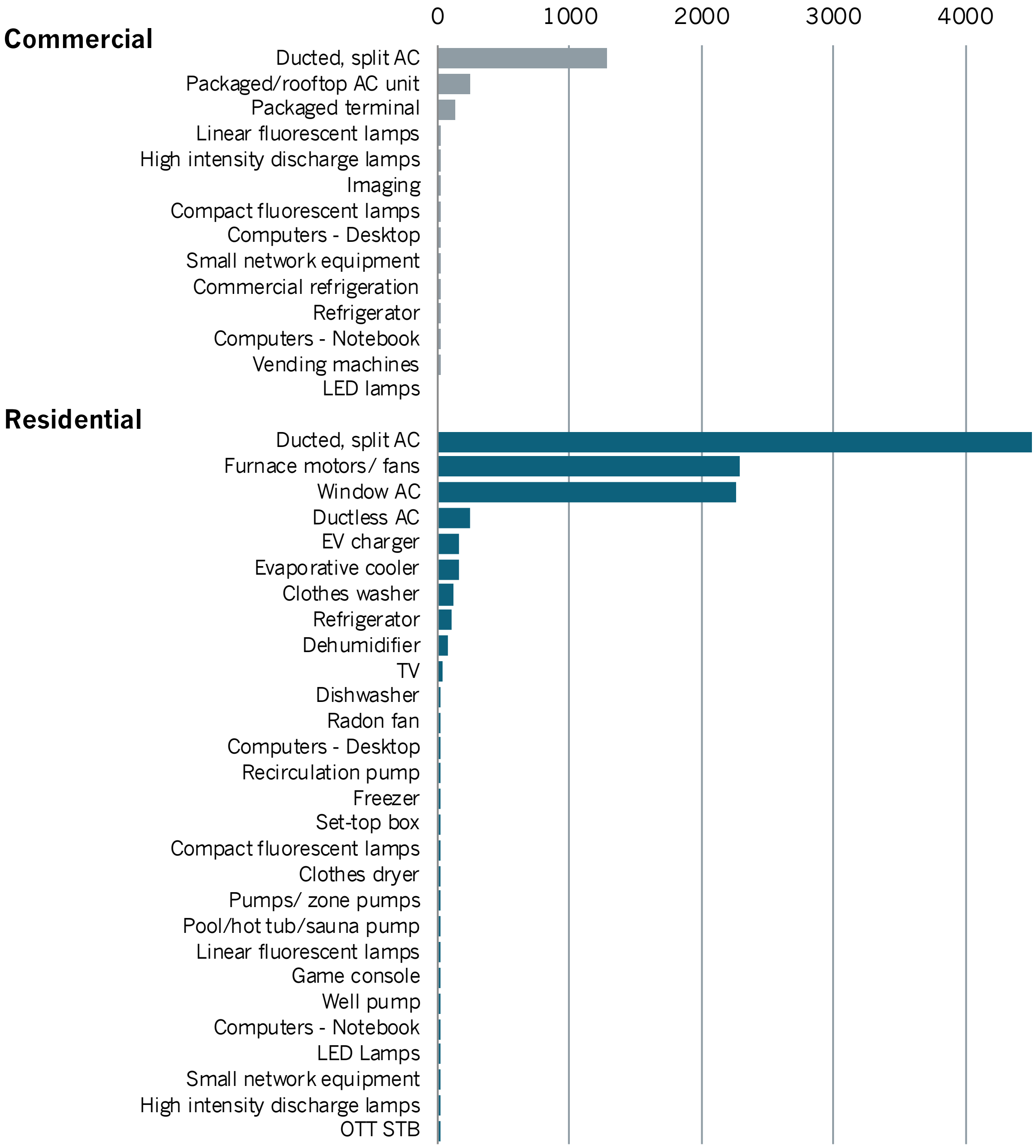


Figure 16: National building energy savings at full stock turnover Figure 13: National building energy savings at full stock turnover

Grid & Site Savings from Power Factor Correction

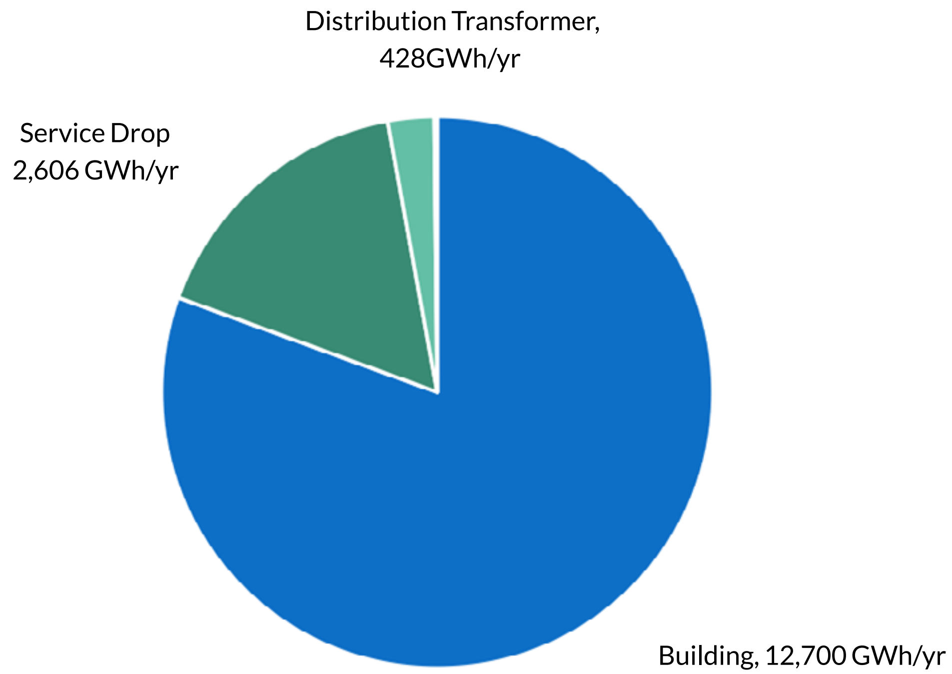
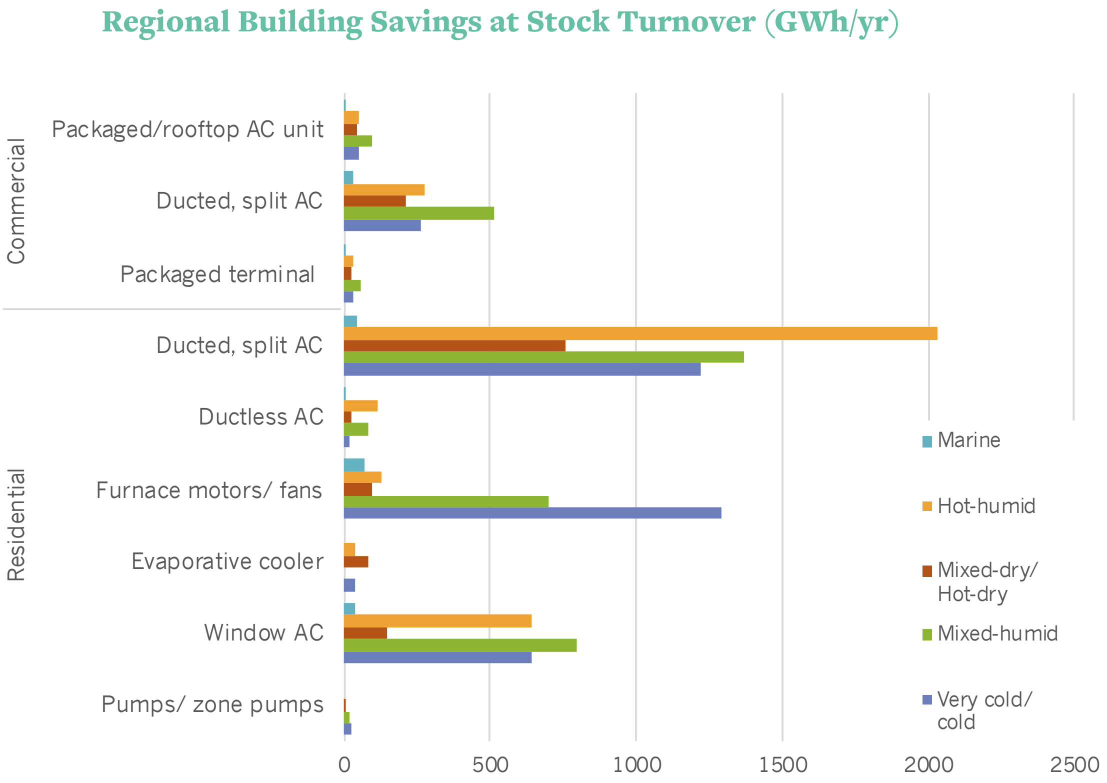


Figure 17:
National savings at stock turnover, including distribution grid impacts

Climate Sensitivities

The results above present a nationwide, aggregate view of the power factor savings opportunity, but many of the largest energy savings opportunities result from HVAC products, so savings can accrue disproportionately in regions with heating- or cooling-dominated climates. This fact becomes even more important when examining overall cost effectiveness, as certain products may only be cost-effective on a regional basis. The Statewide CASE Team conducted a separate regional analysis for eight climate-dependent loads, with regionally distinct operating hours and equipment stocks.

Figure 13 illustrates the national energy savings potential (within buildings only) across the five general climate zones used by the U.S. DOE Energy Information Administration. The geographic extents of the climate regions themselves are illustrated in Figure 14. For particular end-use equipment, a large share of the national energy savings potential may reside in one or two climate zones. The hot humid, mixed humid, and very cold/cold regions tend to fare best due to a large number of cooling degree-days and a high concentration of population. The very cold/cold and mixed humid climate zones also experiences a large number of heating degree-days, making them ideal candidates for savings in furnace fans.



Regional Building Savings at Stock Turnover (GWh/yr)

Figure 18: **Regional building-level energy savings at stock turnover for select HVAC loads with climate sensitivities**

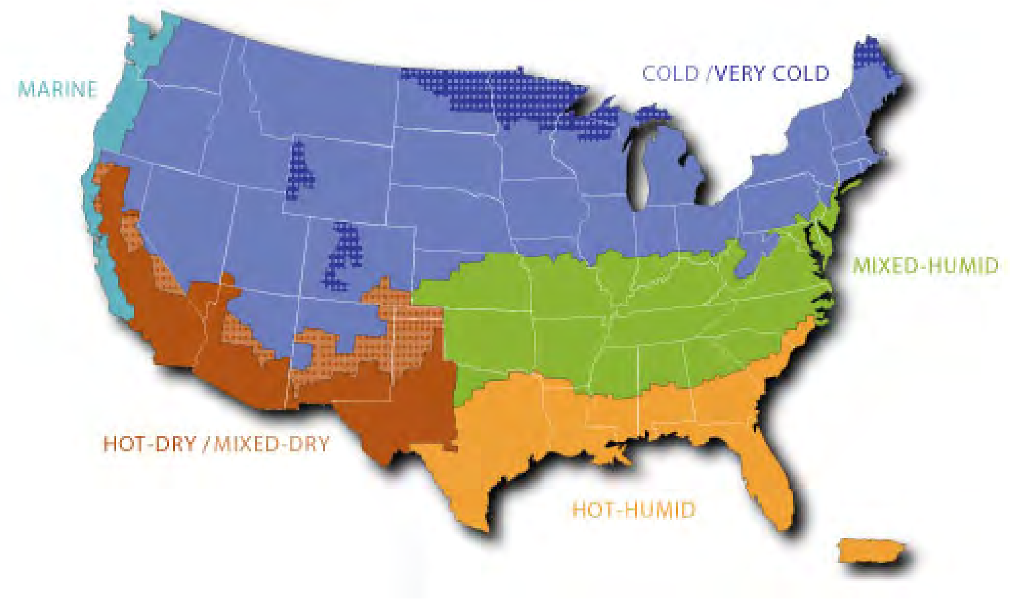


Figure 19: **US EIA climate zones. Source: U.S. EIA (2012).**

Sensitivity to Other Model Inputs

In addition to climate, the Statewide CASE Team also explored the sensitivity of savings to other key assumptions, namely the power factor and active power draw of existing products. The analysis recognized early that there is a paucity of data and resulting uncertainty around the power factor of existing loads. Although a reasonable range of power factor for HVAC equipment, appliances, and electronic equipment might only vary by a factor of 2 or less, these assumptions can have a larger impact on savings potential due to the squared relationship that drives losses in conductors. The briefly presented outcomes of this analysis underscore the need for deeper characterization of high-priority loads if stakeholders wish to further pursue the power factor savings opportunity.

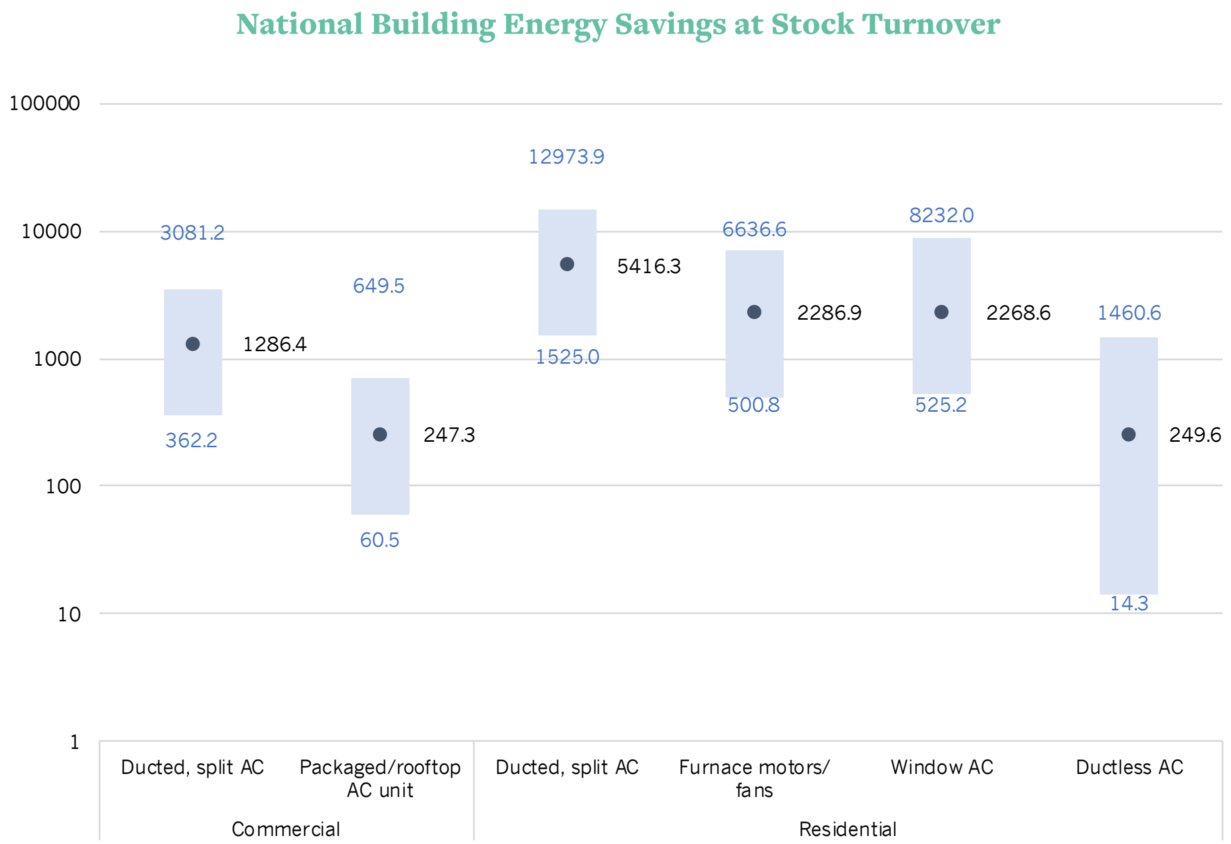


Figure 20:
Sensitivity analysis of building energy savings for top six savings opportunities, including overall savings range (blue) and typical/mid scenario (gray). Savings are presented on a logarithmic scale. The range of values results from changes to baseline power factor and active mode power draw.

Figure 15 illustrates the range of building-level savings for the top 6 loads in the analysis. Savings can vary by about an order of magnitude depending on variations in two input assumptions: baseline power factor and active power mode draw. Note that the mid savings scenario used throughout this report is actually relatively conservative. Higher current draw in the base case — resulting from lower typical power factors or higher typical operating currents — could drive savings 3 to 17 times higher depending on the load. Similarly, overly generous assumptions on power factor (assuming that existing equipment has higher power factors) could drive savings down by about 2 to 6 times. While the Statewide CASE Team is confident that the mid scenarios presented in this report reasonably approximate typical equipment and provide useful information on prioritizing future research paths, the potentially large effects observed in the sensitivity analysis underscore the need for additional data gathering in the future. Greater certainty on the state of typical equipment being sold into the market today will help to further narrow error bars and enable more robust analysis and policy recommendations.

Power Factor and Efficiency Tradeoffs for Harmonic Loads

Loads causing harmonic distortion must be addressed by incorporating active power factor correction stages in their power supplies.[21] These active power correction stages typically have a high pass-through efficiency (over 95%), but they nevertheless do incur losses that must be weighed against the potential upstream savings in the power distribution system. Generally, for power factor improvements to generate net energy benefits, the reduced conductive losses at the system level must outweigh any increased power consumption by the PFC stage itself.

The exact magnitude of the increased power consumption in the power supply is uncertain and depends on several factors. First, active power factor correction is generally incorporated in a power supply's first stage (the stage that directly interacts with AC power from grid mains). The PFC stage may increase or decrease the efficiency of this stage, depending on the existing design and the components selected for the replacement design. Secondly, even if the PFC stage introduces some additional losses into a product's power supply, those losses could be more than recouped through other improvements to the power supply's overall design, potentially resulting in overall lower power supply losses. As an example, the 80 PLUS® efficiency labeling program has for years promoted power supplies that are both highly efficient and power factor corrected. Today's computer power supplies are anywhere from 20 to 30% more efficient than mainstream products from 10 to 15 years ago and are simultaneously able to correct power factor to above 0.9 through active PFC technology. At a minimum, this demonstrates that the goals of high power supply efficiency and power factor correction are not incompatible.

Additional study, including prototyping and product measurements, will be required to examine the extent to which increased losses from PFC in electronic products might impact savings. In the meantime, however, we can look to the results of the existing analysis to provide a reasonable upper bound on PFC stage losses. Table 5 summarizes the unit and percent energy savings results across low, mid, and high scenarios for select electronic products in this study (those with highest savings). The additional savings from power factor correction are typically a fraction of a percent to a few percent of the product's unit energy consumption, so in order to maintain positive energy savings, PFC devices must themselves consume less than this amount of energy. In practice, this will mean ensuring very high pass-through efficiencies (in excess of 95%).

Table 5: **Unit and Percent Savings Ranges for Harmonic Loads**

	Unit Energy Savings (kWh/yr)			Percent Active Mode Power Savings (%)		
	Low	Mid	High	Low	Mid	High
Commercial						
High intensity discharge lamps	0.00	0.18	0.83	0.00%	0.01%	0.06%
Imaging equipment	0.00	0.05	0.25	0.01%	0.08%	0.23%
Computers - desktop	0.00	0.03	0.46	0.00%	0.02%	0.16%
Residential						
EV charger	4.4	46.4	268.0	0.13%	0.88%	3.83%
Set-top box	0.03	0.05	0.08	0.02%	0.03%	0.05%
Televisions	0.01	0.07	0.57	0.02%	0.14%	1.14%
Computers - desktop	0.01	0.03	0.11	0.02%	0.06%	0.22%

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[21] Other approaches using "passive" electronic components (capacitors, inductors, resistors, etc.) are possible, but to achieve the 0.9 power factor targets assumed in this report, active power factor correction technology must be used.

III. The Economics of Power Factor Correction

The Statewide CASE Team examined the cost effectiveness of power factor improvements as a standalone energy efficiency measure. In other words, this question is examined: "All other factors being held constant, do the economic benefits of power factor correction justify the potential costs to the consumer?" By examining power factor correction in isolation, a conservative estimate of its economically achievable energy savings potential is provided, because it is likely that power factor might be implemented alongside other energy-saving strategies in end-use products — improvements to power supply efficiency, motor efficiency, or controls — that might help improve cost effectiveness as a whole. Nevertheless, this isolated treatment is useful and appropriate to guide the reader toward product categories where power factor is likely to be most cost-effective, even if it may be possible to bundle power factor with other efficiency measures in an economical manner.

Scenarios for Economic Analysis

As with this evaluation of energy savings associated with power factor, the Statewide CASE Team examined the cost effectiveness of power factor correction at the building level, and then add grid-level impacts (Table 5). Examined first is the energy-related benefits of power factor correction on the customer side of the meter in a building (bill savings) and the incremental cost of power factor correction technology. Utility bill savings to the customer are the direct result of reduced wiring losses and can be valued at standard retail electric rates. This study used national retail electric prices from 2017 of 12.9 and 10.7 ¢/kWh for residential and commercial rates, respectively (EIA 2018a). A separate analysis was conducted based on California retail electric prices and is provided in Appendix K. Power factor tends to be economically feasible in a broader range of end uses in California due to the state's electric rates, which are higher than the national average.

The incremental costs of improving power factor at the device level can vary depending on the product and the applicable technological pathway. For reactive/displacement loads, the Statewide CASE Team developed a linear cost model to estimate typical capacitor costs based on their size (capacitors of the size appropriate to appliances and HVAC equipment are rated in microfarads). The cost model is based on retail unit sales prices for motor start capacitors of various sizes. For distortion loads, an incremental cost estimates based on input from power electronics experts[22] that scales the cost of power factor correction circuitry with the nameplate power supply rating for that product (in watts), was developed. Details of the incremental cost assumptions can be found in Appendix I.

Next this study adds the benefits that occur on the distribution grid to those in buildings. The benefits on the grid include both savings in wholesale power costs (due to reduced power losses) and one-time avoided costs (by reducing the amount of reactive power support the grid needs to provide). Assumed is that the avoided cost of providing reactive power support only applies to motorized loads. This study estimated the avoided cost wholesale power at $34.63/MWh based on an average of 2017 transactions reported by U.S. EIA (2018c). This study estimated the cost of grid-scale capacitor banks based on installed cost estimates developed by Eaton (2014).

Table 6: **Scenarios for Economic Analysis**

Scenario	Customer Benefits Monetized	Grid Benefits Monetized
1. Behind-the-Meter	Utility bill savings	None
2. Holistic	Utility bill savings	Wholesale power cost savings Reduced investment in capacitor banks for reactive power support

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[22] Based on personal correspondence with David Chen, Power Integrations.

In each of the scenarios, the Statewide CASE Team utilized mid-range energy savings estimates to value energy cost savings and sizing implications for capacitors and power factor correction filters. Reported is a combination of metrics, including simple payback period, benefit-to-cost ratios, and net present value. In valuing future savings for benefit-to-cost and net present value calculations, this study utilized a discount rate of 5%[23].

National Results

Just as the overall savings from improved power factor are concentrated into a few high-priority end uses, its cost effectiveness as a standalone measure is also limited to just a handful of products. Examining only the behind-the-meter benefits of power factor correction shows that only residential split air conditioning systems would have positive net present value (a benefit-to-cost ratio greater than one). Regardless, this single measure would capture about half of the overall behind-the-meter power factor savings opportunity (5.4 TWh/yr at stock turnover), as illustrated in Figure 16. The net present value of behind-the-meter benefits for this load alone amounts to nearly $1.5 billion over the products' lifetimes.

Behind-the-Meter Economics: National Building Energy Savings Potential from Cost-Effective Loads (5.4 TWh/yr)

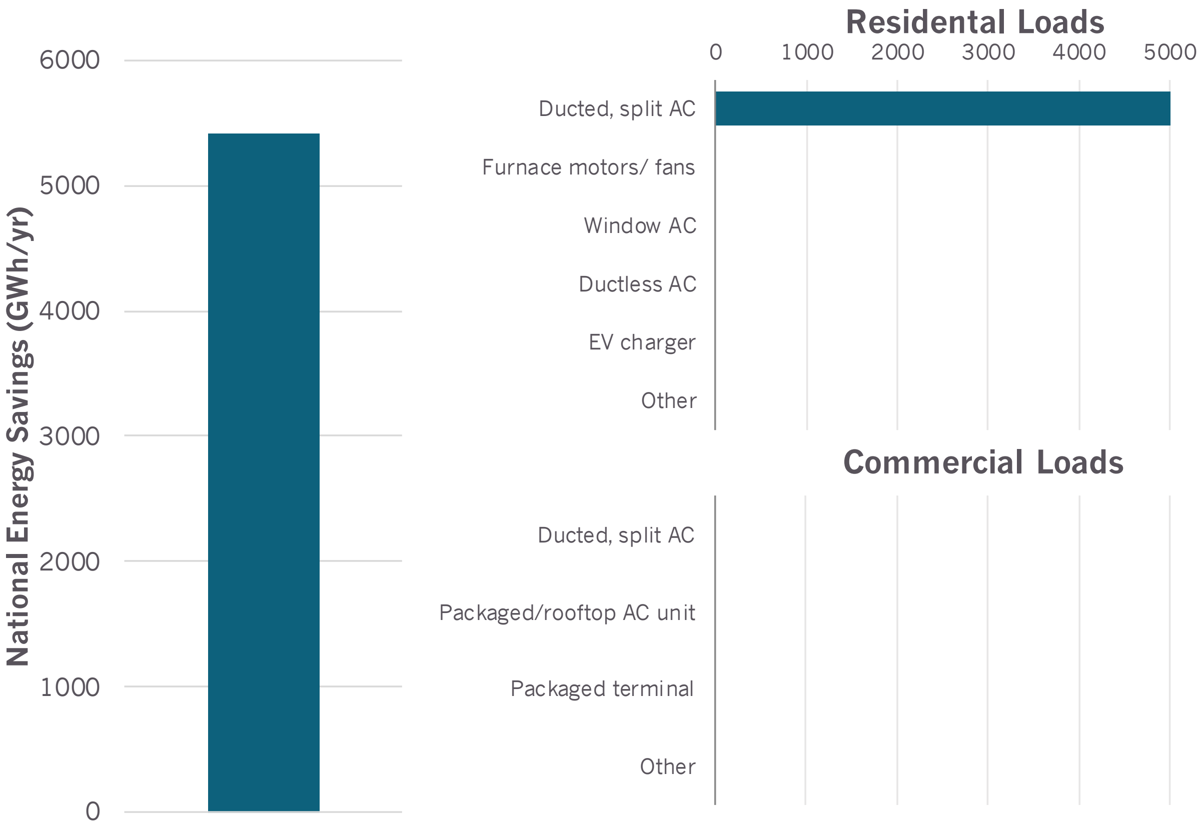

Figure 21:
National building energy savings for loads deemed cost-effective based on behind-the-meter (building-level) benefits on an aggregate (left) and device-level (right) basis. The chart is noticeably sparse because, when limited to behind-the-meter economic evaluations, residential split AC systems are the only load that proves cost-effective.

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[23] This is an average of the 2018 "real discount rate" of 3% and the 7% rate currently required in federal regulatory analyses, per guidance by the Federal Energy Management Program (FEMP) and the federal Office of Management and Budget (OMB). https://www.energy.gov/sites/prod/files/2018/04/f50/2018discountrates.pdf

The cost-effective energy savings potential increases significantly when we expand the scope of analysis to the "holistic" case and factor in grid-side benefits. As illustrated in Figure 17, two commercial (ducted, split AC systems and packaged terminal HVAC) and two additional residential loads (furnace fans and ductless AC) now become cost-effective, and the cost effectiveness of residential ducted/split AC only increases. A more holistic accounting of benefits means that two thirds of the national savings opportunity, including both building and grid savings (11.7 TWh/yr at stock turnover), would be economically achievable.[24] The net present value of the combined building and grid benefits for these five products amounts to about $5.7 billion dollars in today's dollars.

Holistic Economics: National Building + Grid Energy Savings Potential from Cost-Effective Loads (11.7 TWh/yr)

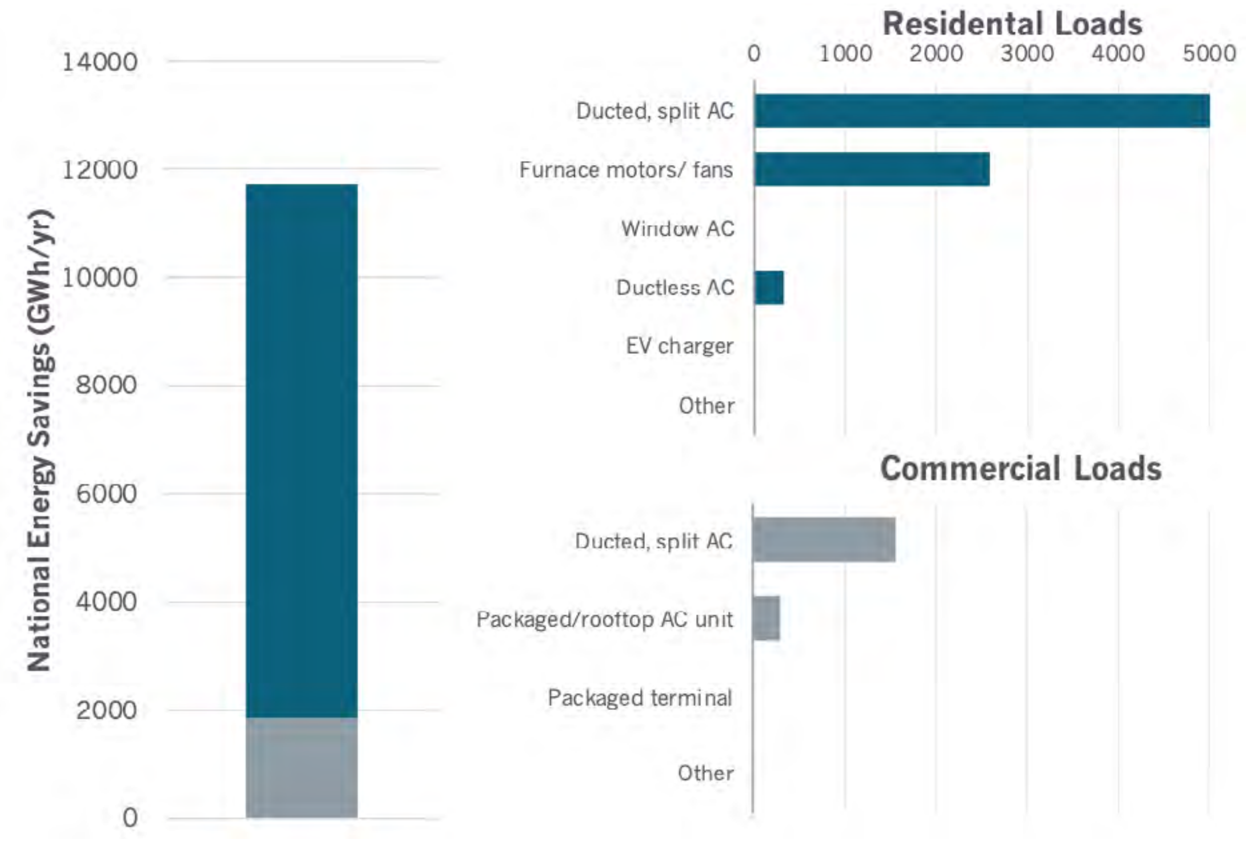

Figure 22:
National building energy savings for loads deemed cost-effective based on holistic economics (building-level) benefits on an aggregate (left) and device-level (right) basis. The additional consideration of savings beyond the customer meter allows several additional loads to become cost-effective. Savings are still dominated by residential loads.

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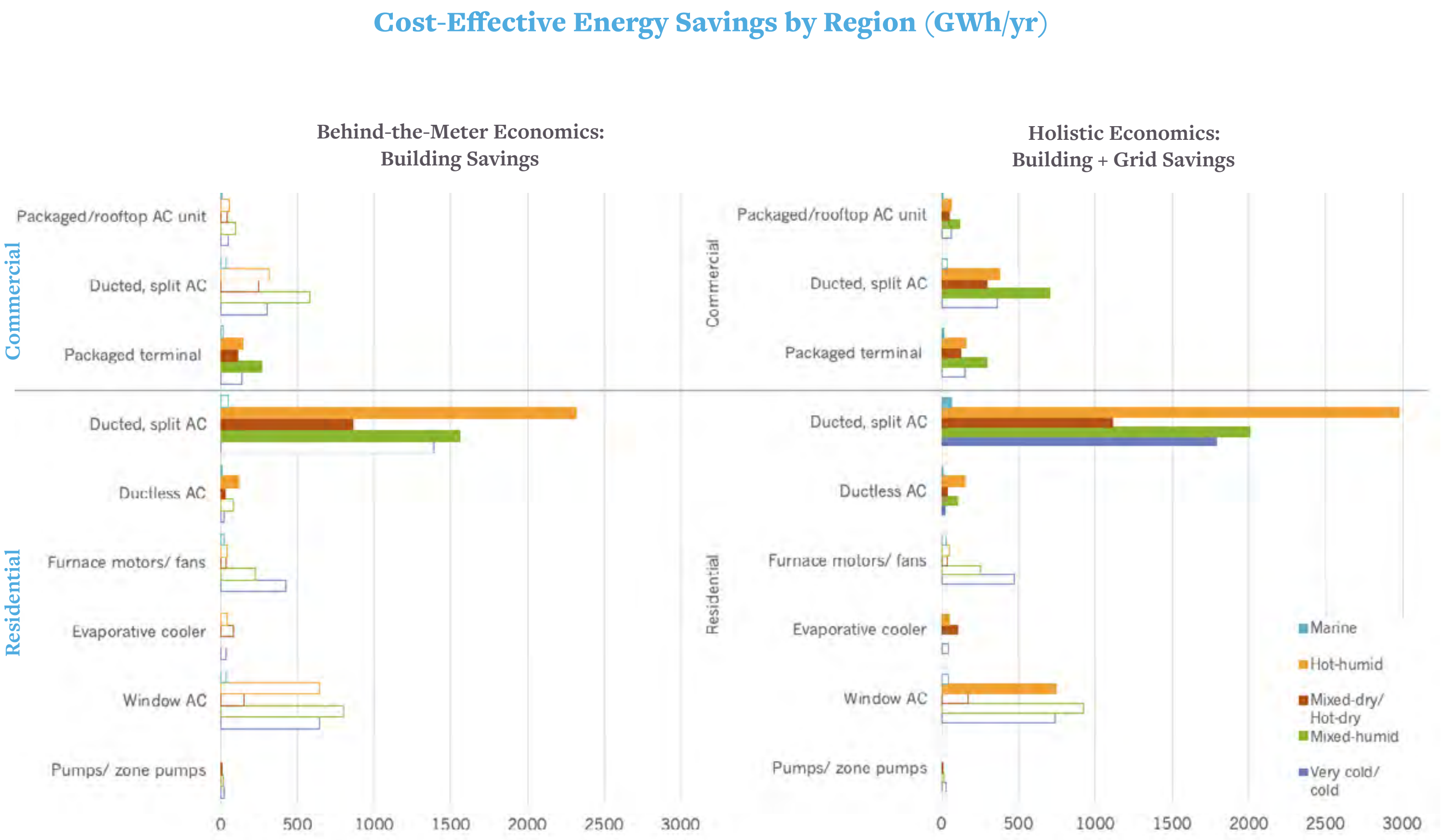
[24] Note: 9.4 TWh/yr of economically achievable savings would occur on site or behind the meter. An additional 2.2 TWh/yr of grid-level energy savings could be achieved by these loads.

Regional Results

Cost effectiveness also takes on new dimensions when examined at the regional level, where the Statewide CASE Team accounts for regional variations in product stocks, duty cycles, climate, and electricity prices (EIA 2018a). Power factor correction is only cost-effective in certain regions for various climate-sensitive loads that were examined. Results are presented in Figure 18. For residential ducted, split AC systems — the most cost-effective load with the largest energy savings across the whole analysis — energy savings are only cost-effective based on a behind-the-meter analysis for the hot-humid hot-dry/mixed-dry climate zones. Not surprisingly, these climate zones represent the vast majority of equipment stocks and achievable energy savings for central AC systems.

Regional analysis also reveals cost-effective savings opportunities in loads that might not otherwise be deemed cost-effective on a national level. For example, residential ductless AC units were only found to be cost-effective at the national level when incorporating grid benefits; however, ductless systems might be cost-effective in hot humid climate zones without the need to consider grid benefits.



Cost-Effective Energy Savings by Region (GWh/yr)

Behind-the-Meter Economics: Building Savings

Holistic Economics: Building + Grid Savings

Figure 23:
Economically achievable energy savings by load and region, based on behind-the-meter (left) and holistic benefits (right, including grid energy savings). Energy savings from cost-effective loads (those with positive net present value or a benefit-to-cost ratio greater than one) are represented by solid colored bars; empty bars are not cost-effective

IV. Conclusions and Next Steps

Although under-represented in the literature and only rarely considered as an energy-saving measure, power factor correction stands as a large and relatively untapped opportunity for energy savings in buildings. The combined savings from the suite of 42 products considered in this study could generate 12.7 TWh per year in behind-the-meter savings, with an additional 3.1 TWh per year in estimated savings on the distribution grid. When factoring in economic benefits in buildings and on the grid, over 70% of these savings could be achieved cost-effectively as a standalone measure using just a handful of loads. The economically achievable savings (11.8 TWh per year) would be enough electricity to power 1 million typical U.S. households for a year. It should be noted that power factor correction could likely be bundled with other energy efficiency pathways, making it cost-effective in a host of other loads. However, this analysis of power factor as a standalone measure already shows considerable promise. Regionally high electric rates and bundling with other energy efficiency measures would only increase its economic feasibility.

These factors notwithstanding, this study uncovered two formidable, but not insurmountable, barriers to the advancement of power factor correction as a self-standing energy efficiency measure: cost effectiveness and the need for further information to better characterize savings opportunities. Below actions are suggested to help mitigate these challenges.

Overcoming Cost Effectiveness Challenges

The Statewide CASE Team was only was able to identify a handful of loads that would pass traditional cost effectiveness tests at present. The top candidates include mostly large motor loads, such as residential central AC systems and commercial rooftop units. Public benefit dollars could be used to fund research and development efforts or efficiency design competitions that would target either the highest priority end uses or, perhaps more practically, power factor correction technologies. Lower cost motor start capacitors with capacities in the 1-100 μF range are of particular interest given the top savings opportunities identified in this study.

Cost effectiveness can be addressed not only by technology, but by improved policy processes. Many cost effectiveness analyses for mandatory appliance standards today must examine economic benefits that are directly realized by ratepayers through lower energy bills. Energy savings on the other side of the billing meter, though beneficial to society and – at least indirectly – to ratepayers, are invisible in these types of analyses. However, this study shows that incorporating a more holistic view of grid-side benefits can tip the scales on cost effectiveness in several cases. Should such benefits be permissible in rule-makings, and how might this be accomplished from a legal standpoint? These are questions the efficiency community may need to address in order to capture opportunities like power factor.

Bridging Information Gaps

Perhaps a more fundamental barrier to advancing power factor correction opportunities in priority end uses is the dearth of data, from the laboratory as well as the field, regarding the power factor of existing equipment and the associated losses in buildings and on the grid. As the brief sensitivity analysis showed, power factor modeling is particularly sensitive to input assumptions due to the non-linear nature of resistive losses in wiring. Such data will be crucial to developing more accurate savings and economic analyses on the road to policy decisions. This can be accomplished in several ways. First, power factor information can be obtained using existing energy efficiency test procedures by simply requiring true power factor as a reporting variable for portions of test procedures where real power measurements are made. The incremental burden to manufacturers and test laboratories is trivial. Current data is particularly needed for loads such as air source heat pumps, whose numbers are expected to swell as a result of building electrification efforts and for which little to no power factor data was available for this study.

Second, utilities, regional energy efficiency organizations, and public interest organizations can join forces to fund field studies of power factor in homes and businesses. The limited field trials that exist to date focus on reductions in reactive power or improvements to power factor, but tend to ignore energy savings benefits. Future studies should measure baseline power factor and wiring losses as well as the impacts of interventions, such as end-use level power factor correction, to more fully validate the opportunity. Field data are especially crucial to validate the benefits that may be achievable, as very few studies to date have done so.

Additional market research and characterization is essential for motorized products. Motors can exhibit either displacement or a distortion power factor depending on whether they are outfitted with electronic controls such as variable-speed drives (VSD). VSD-controlled motors will exhibit distortion power factor rather than displacement and would, therefore, require different technological pathways to improve power factor. Since motor-driven loads present the largest energy savings opportunities, future research must better characterize the share of VSDs within individual product categories.

Finally, as test procedures, voluntary labeling requirements, and mandatory standards for key end-use equipment like HVAC are updated, stakeholders interested in power factor correction should request reporting and disclosure of true power factor, as has recently been done for televisions and computers under California's Title 20 regulations. (See California Code of Regulations, Title 20. § 1604. "Test Methods for Specific Appliances" for examples). Power factor should generally be examined as part of overall cost-effective energy efficiency paths when examining minimum efficiency requirements for most products, but especially the high-priority loads identified in this report.

Analytical Refinements

As the first broad, cross-sector investigation of end-use power factor correction, this study adopted a set of simplified calculations for estimating the energy savings potential in individual loads and highlighting those loads that might be most promising for additional study. All told, of the 42 original loads, only a small number were shown to be cost-effective when power factor was considered as a standalone measure. For the subset of loads identified, the Statewide CASE Team recommends not only additional lab and field data gathering, but also more detailed and rigorous analysis to inform future policy decisions. Such modeling would discard many of the simplifications adopted for the purposes of this study and more thoroughly investigate the impacts of operational patterns, load coincidence, and typical wiring topology[25] for individual loads of interest.

For other loads, the Statewide CASE Team still strongly urges consideration of power factor improvements as part of overall energy efficiency pathways. Even if power factor correction may not be cost-effective in isolation for these loads, it may prove economical when combined with other energy efficiency strategies, such as improved controls, power supply efficiency, motor efficiency, and other product features.

Power factor correction is unique, because it mainly affects the power delivery to a product rather than the service or amenity provided by the product itself. In this way, it is most similar to power supply and battery charger efficiency efforts enacted over the past 15 years. As with these earlier efforts, the most viable path for implementing power factor requirements may be simultaneous with the development of voluntary efficiency specifications or mandatory standards. The savings opportunity is diffuse enough that it is unlikely power factor could be successfully implemented as a standalone utility efficiency program.[26]

Power factor is a complex electrical systems concept that transcends individual loads and invokes concepts often ignored in energy efficiency measures. As a strategy for saving energy, it is certainly not the simplest of propositions, as its benefits span traditional boundaries for evaluating energy savings, particularly the billing meter. Despite its complexities, the power factor savings opportunity merits deeper investigation for jurisdictions looking to extend energy efficiency and decarbonization in buildings.

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[25] Wiring topology could include choices on the location of loads in relation to the service panel, common circuit lengths, as well as whether the device is placed on its own home-run circuit.

[26] Many large utilities do already provide power factor mitigation services to large commercial and industrial customers, who also fall into rate classes with power factor or reactive power provisions.

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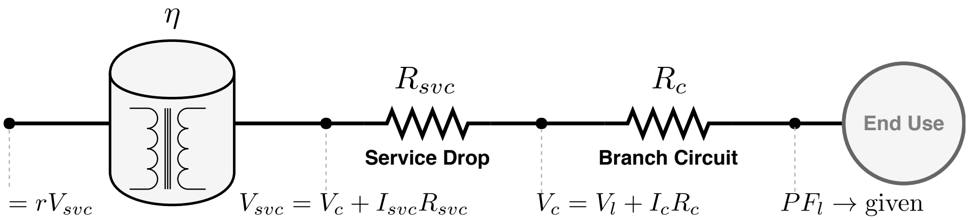
VI. Appendix

A. Basic Mathematical Formulation

The Statewide CASE Team used simplified, steady-state power flow calculations to demonstrate order-of-magnitude savings associated with improved power factor. At its core, this study tracks power flow on a hypothetical feeder through distribution transformers, service lines to a facility, and through the building's wiring itself down to the end load. Calculations proceed in a reverse fashion, starting with assumptions about the end load and working back toward the grid. Power quantities — voltage (V), current (I), and real (P), apparent (S), and reactive power (Q) — are tracked for several nodes in the system: the point of load, the branch circuit level, the service drop (secondary side of the transformer), the primary side of the transformer, and the feeder circuit. The power factor of the load (PFl), efficiency of the transformer (h), resistance of the branch circuit (Rc), resistance of the service drop (Rsvc), voltage serving the load (Vl), and turns ratio for the distribution transformer (r) are all provided as inputs.

Figure 19 illustrates the physical model and the formulas used to calculate various power flow quantities.



$$V_f = rV_{svc} \qquad I_{svc} = I_c \qquad P_{svc} = P_c + I_{svc}^2 R_{svc} \qquad S_{svc} = \sqrt{P_{svc}^2 + Q_{svc}^2} \qquad Q_{svc} = Q_c$$

$$V_{svc} = V_c + I_{svc}R_{svc} \qquad I_{svc} = I_c \qquad P_{svc} = P_c + I_{svc}^2 R_{svc} \qquad S_{svc} = \sqrt{P_{svc}^2 + Q_{svc}^2} \qquad Q_{svc} = Q_c$$

$$V_c = V_l + I_c R_c \qquad I_c = I_l \qquad P_c = P_l + I_c^2 R_c \qquad S_c = \sqrt{P_c^2 + Q_c^2} \qquad Q_c = Q_l$$

$$PF_l \rightarrow \text{given} \qquad V_l \rightarrow \text{given} \qquad I_l = \frac{S_l}{V_l} \qquad P_l \rightarrow \text{given} \qquad S_l = \frac{P_l}{PF_l} \qquad Q_l = \sqrt{S_l^2 - P_l^2}$$

Figure 24: Single line diagram of simplified power flow and accompanying equations

B. Simplifying Assumptions and Implications

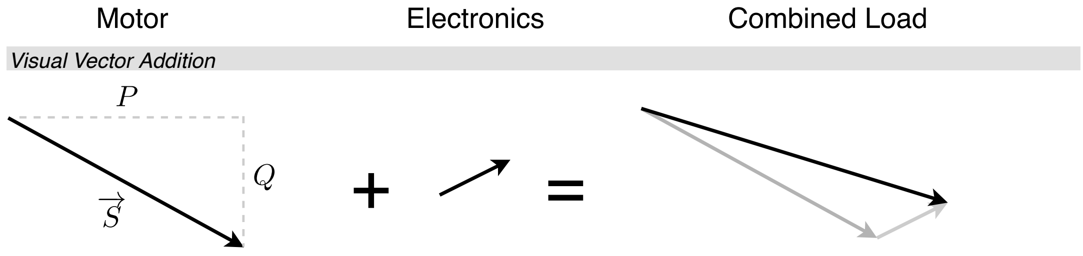
The Statewide CASE Team calculation methodology is useful for analyzing some of the order-of-magnitude impacts of power factor on wiring but ignores some realities of power transfer, including:

- Flow of reactive power between loads
- Load coincidence
- Capacitive properties of paired conductors
- Frequency domain effects that can impact flow of harmonic currents

Below are examples of some of the errors introduced through these simplifications.

Interactions Between Reactive Loads

The first and largest simplification in this analysis is that this study generally ignores the interactive effects between reactive loads on the power system. The approach in Figure 19 treats each load individually, isolating that load's contribution to overall power flows and ignoring the power flowing to and between other devices. This step significantly simplifies calculations especially when scaling results up to the level of the national installed base; however, it also introduces several sources of error. By treating loads this way, this study ignores the interactive effects between reactive loads on the power system. When reactive loads combine and interact, one must use vector addition to account for the flow of real and reactive power. Figure 20 illustrates the vector addition of an inductive (lagging) and capacitive (leading) load, which is influenced by both the magnitude and direction of the load represented on a coordinate plane with axes of real power and reactive power. The presence of the capacitive load ultimately helps to improve the power factor of the inductive load, and the power factor of the combined load is slightly higher (i.e. improved) than either load operating on its own.



Mathematical Vector Addition

$$\begin{aligned} P_{\text{motor}} &= 2\text{ kW} \\ Q_{\text{motor}} &= -1\text{ kVAR} \\ S_{\text{motor}} &= 2.2\text{ kVA} \\ PF_{\text{motor}} &= 0.91 \end{aligned}$$

$$\begin{aligned} P_{\text{elec}} &= 0.2\text{ kW} \\ Q_{\text{elec}} &= 0.1\text{ kVAR} \\ S_{\text{elec}} &= 0.22\text{ kVA} \\ PF_{\text{elec}} &= 0.91 \end{aligned}$$

$$\begin{aligned} P_{\text{combined}} &= P_{\text{motor}} + P_{\text{elec}} \rightarrow 2.2\text{ kW} \\ Q_{\text{combined}} &= Q_{\text{motor}} + Q_{\text{elec}} \rightarrow -0.9\text{ kVAR} \\ S_{\text{combined}} &= \sqrt{P_{\text{combined}}^2 + Q_{\text{combined}}^2} \rightarrow 2.4\text{ kVA} \\ PF_{\text{combined}} &= \frac{P_{\text{combined}}}{S_{\text{combined}}} \rightarrow 0.92 \end{aligned}$$

Figure 25: Vector addition of two reactive loads

While the loads with the largest overall demand contributions and the largest energy savings potential in this study are inductive in nature, a variety of electronic and lighting devices are known to have slightly capacitive (leading) power factor. Per the example above, these loads would help to mitigate some of the impacts of the inductive loads. The Statewide CASE Team analysis ignores this effect.

Load Coincidence Effects

By examining building loads in isolation, this study also ignores the fact that products operate coincidently on a given branch circuit, within buildings, and in the broader grid context. This assumption results in an underestimation in the overall losses in the wiring; that is, the losses that the Statewide CASE Team estimates by treating the loads independently and summing effects are actually lower than if the loads were evaluated together. This arises because resistive losses vary with the square of current. If we have two loads – to simplify further, two resistive loads – operating on a branch circuit, and each load draws current I (Figure 21), the common conductor that serves the two loads will see an overall load of 2I and overall losses of 4I2R ("Coincident Analysis").[27] If the Statewide CASE Team had evaluated the loads independently and examined their losses, each would have drawn the current I through the common conductor, resulting in losses of I2R for each product or 2I2R when summed together ("Non-Coincident Analysis"). Thus, the overall losses estimated through the branch circuit would have been underestimated by a factor of 2 by treating them independently.

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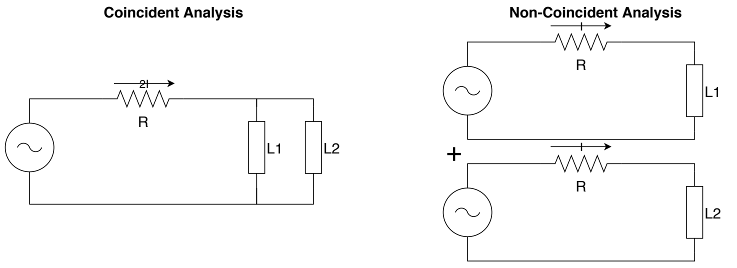
[27] For the purposes of this example, this study ignores the portions of the circuit serving the individual loads/receptacles and focus instead on the common conductor upstream of these loads that must deliver the aggregate current. Also assumed is that both loads are either inductive or capacitive.



Loss Calculations

$$\begin{aligned} P_{\text{loss,base}} &= (2I)^2R \rightarrow 4I^2R \\ P_{\text{loss,new}} &= (1.5I)^2R \rightarrow 2.25I^2R \\ P_{\text{savings}} &= P_{\text{loss,base}} - P_{\text{loss,new}} \rightarrow 1.75I^2R \end{aligned}$$

$$\begin{aligned} P_{\text{loss,base}} &= I^2R + I^2R \rightarrow 2I^2R \\ P_{\text{loss,new}} &= (0.5I)^2R + I^2R \rightarrow 0.25I^2R + I^2R \rightarrow 1.25I^2R \\ P_{\text{savings}} &= P_{\text{loss,base}} - P_{\text{loss,new}} \rightarrow 0.75I^2R \end{aligned}$$

Figure 26: Coincident and non-coincident treatment of two resistive loads

In this study, the overall objective is to estimate savings potential for a given product given an improved power factor. In the example above, assume that this study reduced the current drawn in one of the loads from I to 0.5I. The common current to both loads will be reduced to 1.5I and the losses reduced to about 2.25I2R. Had this study treated the loads independently, the estimated combined losses would be at 1.25I2R. In the combined calculation, the overall savings – the difference in losses – is 1.75I2R, whereas when treated independently, the savings would be 0.75I2R, a factor of 2.3 lower than when examining the combined case. The exact magnitude of this underestimation of savings will vary depending on size of loads involved and coincidence with other loads (here, it is assumed 100% coincidence, which is a worst case), but suffice it to say, independent treatment of loads or an assumption of no load coincidence will tend to underestimate energy savings potential.

The Statewide CASE Team stresses that the combined effect of these two sources of error has not been rigorously quantified. More sophisticated power flow models that account for reactive power flows and coincidence will be required in the future to more accurately quantify the combined energy savings potential for select pairings of power factor measures. Such models might also incorporate more accurate assumptions regarding the capacitance presented by paired conductors.

C. Product Stock Assumptions

Building Sector	Product Category	Product	National Installed Base	Sources & Notes
Commercial	Appliances	Refrigerator	554,000	13
		Vending machines	145,000	13
	Electronics &Office	Computers - Desktop	69,000,000	17
		Computers - Notebook	77,000,000	17
		Imaging	52,800,000	4
		Small network equipment	642,000,000	17
	HVAC	Ducted, split AC	31,105,000	1,11,13
		Packaged terminal	4,186,000	10,13
		Packaged/rooftop AC unit	5,721,000	6,9
	Lighting	Compact fluorescent lamps	165,255,000	17
		High intensity discharge lamps	24,662,000	17
		LED lamps	217,639,000	17
		Linear fluorescent lamps	1,622,321,000	17
	Process	Commercial refrigeration	89,000	8

C. Product Stock Assumptions, continued

Building Sector	Product Category	Product	National Installed Base	Sources & Notes
Residential	Appliances	Clothes dryer	96,753,000	a
		Clothes washer	103,809,000	a
		Dishwasher	104,080,000	a
		Freezer	21,983,000	a
		Refrigerator	172,336,000	15
	Electronics and Office	Computers - Desktop	106,000,000	17
		Computers - Notebook	240,000,000	17
		Game console	87,142,000	3
		OTT STB	21,440,000	a
		Set-top box	170,979,000	a
		Small network equipment	200,642,000	3
		TV	278,724,000	a
	HVAC	Dehumidifier	3,935,000	a
		Ducted, split AC	83,623,000	a
		Ductless AC	6,106,000	a
		Evaporative cooler	2,800,000	a
		Furnace motors/ fans	76,207,000	a
		Pumps/ zone pumps	32,568,000	5,14
		Radon fan	1,244,000	18
		Recirculation pump	6,785,000	a
		Well pump	678,000	a
		Window AC	54,900,000	a
	Lighting	Compact fluorescent lamps	2,067,668,000	a
		High intensity discharge lamps	755,000	17
		LED Lamps	417,779,000	a
		Linear fluorescent lamps	512,315,000	a
	Miscellaneous	EV charger	3,603,000	a
		Pool/hot tub/sauna pump	271,000	a

Notes

a. Based on a 2018 survey of California residences conducted by Pacific Gas and Electric Company. Results have been scaled to a national basis using a GDP ratio between California and the entire United States (approximately 0.13).

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D. Product Power Factor Assumptions

				Baseline Power Factor			
Building Sector	**Product Category**	**Product**	**Predominant Mode of Power Factor Disturbance**	**Low**	**Mid**	**High**	**Data Sources and Notes**
Commercial	Appliances	Refrigerator	Displacement	0.65	0.73	0.8	1,7,9,15
		Vending machines	Displacement	0.75	0.75	0.75	5
	Electronics and Office	Computers - Desktop	Harmonics	0.8	0.85	0.9	7,9
		Computers - Notebook	Harmonics	0.55	0.68	0.8	7,9
		Imaging	Harmonics	0.58	0.69	0.8	12,a
		Small network equipment	Harmonics	0.44	0.62	0.8	a
	HVAC	Ducted, split AC	Displacement	0.5	0.65	0.8	b
		Packaged terminal	Displacement	0.62	0.71	0.8	1.5.15
		Packaged/rooftop AC unit	Displacement	0.3	0.55	0.8	b
	Lighting	Compact fluorescent lamps	Harmonics	0.5	0.65	0.8	12,c,d
		High intensity discharge lamps	Harmonics	0.8	0.87	0.94	12
		LED lamps	Harmonics	0.5	0.98	1	e
		Linear fluorescent lamps	Harmonics	0.7	0.75	0.8	9.12
	Process	Commercial refrigeration	Displacement	0.8	0.80	0.8	5
Residential	Appliances	Clothes dryer	Displacement	0.45	0.48	0.5	15
		Clothes washer	Displacement	0.5	0.60	0.7	7,9,11,15
		Dishwasher	Displacement	0.6	0.70	0.8	8,15
		Freezer	Displacement	0.7	0.70	0.7	1,9
		Refrigerator	Displacement	0.65	0.73	0.8	1,7,9,15
	Electronics and Office	Computers - Desktop	Harmonics	0.55	0.68	0.8	7,9
		Computers - Notebook	Harmonics	0.55	0.68	0.8	7,9
		Game console	Harmonics	0.75	0.78	0.8	7,18
		OTT STB	Harmonics	0.3	0.45	0.6	7,11
		Set-top box	Harmonics	0.3	0.45	0.6	7,11
		Small network equipment	Harmonics	0.44	0.62	0.8	a
		TV	Harmonics	0.4	0.55	0.7	7,9,f
	HVAC	Dehumidifier	Displacement	0.3	0.55	0.8	b
		Ducted, split AC	Displacement	0.5	0.65	0.8	b
		Ductless AC	Displacement	0.5	0.65	0.8	16,b
		Evaporative cooler	Displacement	0.3	0.55	0.8	b
		Furnace motors/ fans	Displacement	0.5	0.65	0.8	17
		Pumps/ zone pumps	Displacement	0.3	0.55	0.8	2,b
		Radon fan	Displacement	0.5	0.65	0.8	b
		Recirculation pump	Displacement	0.3	0.55	0.8	b
		Well pump	Displacement	0.3	0.55	0.8	b
		Window AC	Displacement	0.62	0.71	0.8	1,5,15
	Lighting	Compact fluorescent lamps	Harmonics	0.5	0.65	0.8	c,d
		High intensity discharge lamps	Harmonics	0.8	0.87	0.94	12
		LED Lamps	Harmonics	0.7	0.75	0.8	6
		Linear fluorescent lamps	Harmonics	0.7	0.75	0.8	9,12
	Misc.	EV charger	Harmonics	0.4	0.60	0.8	10,13
		Pool/hot tub/sauna pump	Displacement	0.35	0.58	0.8	3,4,14

Notes

a. Estimate based on analysis of office plug load field data collected by Moorefield, L., B. Frazer, and P. Bendt, 2011. "Office Plug Load Field Monitoring Report." California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2011-010. http://www.energy.ca.gov/2011publications/CEC-500-2011-010/CEC-500-2011-010.pdf

b. Estimate derived from analysis of Washington State University MotorMaster+4.0. http://www.energy.wsu.edu/ComputerServices/SoftwareDevelopment/SM-MPAMotorMaster4.aspx

c. Estimate based on sources cited and power factor requirements in DOE standard.

d. Estimate based on ENERGY STAR qualified residential lighting fixtures as of 2017.

e. Estimate based on ENERGY STAR qualified commerical lighting fixtures as of 2017.

f. Estimate based on cited sources and analysis of TVs registered as of November 30, 2017 on the California Energy Commission Modernized Appliance Efficiency Database System (MAEDBS) https://cacertappliances.energy.ca.gov/Pages/ApplianceSearch.aspx.

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E. Product Active Power and Duty Cycle Assumptions

Building Sector	Product Category	Product	Active Power (W)			Climate-Driven Duty Cycle?	Active Hours per Year	Data Sources & Notes
			Low	Mid	High			
Commercial	Appliances	Refrigerator	100	150	200	N	3,504	12,a
		Vending machines	200	270	340	N	3,504	12
	Electronics and Office	Computers - Desktop	12	31	50	N	5,751	18,b
		Computers - Notebook	12	18	24	N	1,078	18,c
		Imaging	26	57	87	N	1,226	8
		Small network equipment	3	3	3	N	8,760	18
	HVAC	Ducted, split AC	2,200	3,200	4,200	Y	4,019	d,e,v
		Packaged terminal	800	1,100	1,600	Y	4,019	e,f,v
		Packaged/rooftop AC unit	2,096	3,272	4,447	Y	4,019	16,e,f,v
	Lighting	Compact fluorescent lamps	19	22	24	N	4,490	17
		High intensity discharge lamps	289	325	361	N	3,760	17
		LED lamps	15	17	19	N	4,052	17
		Linear fluorescent lamps	27	31	34	N	2,957	17
	Process	Commercial refrigeration	284	609	934	N	8,760	13,g
Residential	HVAC	Dehumidifier	200	475	750	N	2,160	6
		Ducted, split AC	2,200	3,200	4,200	Y	3,582	6,d,o
		Ductless AC	1,000	2,250	3,500	Y	3,582	o
		Evaporative cooler	600	900	1,200	Y	3,582	o,t
		Furnace motors/ fans	500	575	650	Y	4,413	19,o
		Pumps/ zone pumps	60	80	100	Y	4,413	9,o
		Radon fan	50	185	320	N	8,760	11
		Recirculation pump	28	60	92	N	8,760	9
		Well pump	600	700	800	N	183	q
		Window AC	800	1,100	1,600	Y	3,582	d,o,r,t
	Lighting	Compact fluorescent lamps	13	14	16	N	804	17
		High intensity discharge lamps	138	156	173	N	1,205	17
		LED Lamps	8	9	10	N	694	17
		Linear fluorescent lamps	30	34	38	N	731	17
	Misc.	EV charger	3,500	5,250	7,000	N	1,000	r
		Pool/hot tub/sauna pump	900	1,600	2,300	N	2,500	2,u

Notes:

a. This study applies annual total energy consumption (TEC) over 8760 hours to achieve average on mode power estimates.

b. Power range based on power values for desktop computers that would comply with California Energy Commission 2019 desktop computer efficiency standards.

c. Using U.S. EIA (2017) value for low estimate, doubling for high scenario to account for power scaling during active mode.

d. Power estimates based on values reported on the California Energy Commission Modernized Appliance Efficiency Database System (MAEDBS) https://cacertappliances.energy.ca.gov/Pages/ApplianceSearch.aspx.

e. Duty cycle based on Xergy Consulting's analysis of the U.S. Department of Energy (U.S. DOE) commercial benchmark buildings for medium office (available at: https://www.energy.gov/eere/buildings/commercial-reference-buildings)

f. Low estimate based on a highly efficient unit, equivalent to DOE's Efficiency Level (EL) 5 from the 2015 standard analysis; high estimate based on an inefficient unit, equivalent to EL0 from DOE's 2015 standards analysis.

g. Low estimate assumed to be an efficient 5-foot unit; high estimate assumed to be an inefficient 10-foot unit. For both estimates, operating in self-contained fashion, i.e. on-board compressor is assumed.

h. Power draw estimates includes motor only. The operation of heating coils is exlcuded.

i. Duty cycle based on the number of loads reported in the U.S. Department of Energy (DOE) 10 CFR part 430, subpart B - test procedures (available at: https://www.ecfr.gov/cgi-bin/text-idx?SID=def2ccd87bf072bf54ea289aee4fb-f42&mc=true&node=ap10.3.430_127.d1&rgn=div9). Also, assumed is that each cycle has a duration of one hour based on the following reports: 1) NEEA, 2014. "Dryer Field Study". Prepared by Benjamin Hannas and Lucinda Gilman (Ecotope Inc). Available at: https://neea.org/img/uploads/neea-clothes-dryer-field-study.pdf 2) Meyers, Steve, Victor Franco, Alex Lekov, Lisa Thompson, and Andy Sturges. 2010."Do Heat Pump Clothes Dryers Make Sense for the U.S. Market?". Available at: http://aceee.org/files/proceedings/2010/data/papers/2224.pdf .

g. Duty cycle based on the number of cycles specified in the U.S. Department of Energy (DOE)'s 10 CFR 430, Subpart B, Appendix D1 (available at: https://www.ecfr.gov/cgi-bin/text-idx?SID=def2ccd87bf072bf54ea289aee4fb-f42&mc=true&node=ap10.3.430_127.d1&rgn=div9). Inferred is a cycle time of 1 hour from the number of cycles per year and the number of hours in standby in the current U.S. regulation available at: http://www.regulations.gov/#!documentDetail;D=EERE-2013-BT-TP-0009-0001.

k. Power estimates based on the motor operation only. Heating element operations is excluded.

l. Power estimates based on ENERGY STAR certified freezers.

m. This study uses the same power estimate assumptions as for small network equipment.

n. Power estimates based on true median of on mode power values of TVs with on mode power values <100 W registered on the California Energy Commission Modernized Appliance Efficiency Database System (MAEDBS). Available at: https://cacertappliances.energy.ca.gov/Pages/ApplianceSearch.aspx

o. Duty cycle estimated based on analysis of runtime hours for IECC 2006 code compliance reference models, developed by Pacific Northwest National Laboratory (PNNL) and available at: https://www.energycodes.gov/development/residential/iecc_models

p. For active power low estimate, a low-end for ECM pump is assumed from: Arena, L., and O. Faakye, 2013. "Optimizing Hydronic System Performance in Residential Applications." Prepared for NREL by the Consortium forAdvanced Residential Buildings. DOE/GO-102013-4108. https://www.nrel.gov/docs/fy14osti/60200.pdf

q. A 1/2 hour usage/day is assumed.

r. Power estimates based on the assumption that given 10,000 miles/yr driving, current vehicle efficiencies from fueleconomy.gov, and required kWh charging, annual energy use for passenger vehicle should be 2,500 - 5,000 kWh/yr.

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F. Regional Stock and Duty Cycle Assumptions

Sector	Product	CBECS/Building America Climate Zone	Installed Base (a)	Annual Operating Hours (e,f)	Data Sources and Notes	Heating or Cooling Season Duty Cycle
Commercial	Packaged/rooftop AC unit	National	5,721,022	4,019	3,b	Cooling
		Very cold/cold	2,095,337	2,100		
		Mixed-humid	1,830,940	4,676		
		Mixed-dry/Hot-dry	790,694	4,518		
		Hot-humid	842,851	5,448		
		Marine	161,200	2,900		
	Ducted, split AC	National	31,105,000	4,019	1,7,c	Cooling
		Very cold/cold	11,392,274	2,100		
		Mixed-humid	9,954,757	4,676		
		Mixed-dry/Hot-dry	4,298,978	4,518		
		Hot-humid	4,582,553	5,448		
		Marine	876,439	2,900		
	Packaged terminal	National	4,185,617	4,019	6	Cooling
		Very cold/cold	1,532,991	2,100		
		Mixed-humid	1,339,553	4,676		
		Mixed-dry/Hot-dry	578,488	4,518		
		Hot-humid	616,647	5,448		
		Marine	117,937	2,900		
Residential	Ducted, split AC	National	83,623,000	3,582	4	Cooling
		Very cold/cold	31,245,417	2,212		
		Mixed-humid	22,792,551	3,401		
		Mixed-dry/Hot-dry	9,811,363	4,375		
		Hot-humid	18,264,229	6,304		
		Marine	1,509,440	1,621		
	Ductless AC	National	6,106,407	3,582	d	Cooling
		Very cold/cold	825,987	2,212		
		Mixed-humid	2,448,463	3,401		
		Mixed-dry/Hot-dry	619,491	4,375		
		Hot-humid	1,858,472	6,304		
		Marine	324,495	1,621		
	Furnace motors/ fans	National	76,207,000	4,413	4	Heating
		Very cold/cold	33,489,083	5,886		
		Mixed-humid	23,234,621	4,567		
		Mixed-dry/Hot-dry	4,146,774	3,582		
		Hot-humid	11,211,754	1,748		
		Marine	1,693,319	6,325		

F. Regional Stock and Duty Cycle Assumptions, continued

Sector	Product	CBECS/Building America Climate Zone	Installed Base (a)	Annual Operating Hours (e,f)	Data Sources and Notes	Heating or Cooling Season Duty Cycle
Residential	Evaporative cooler	National	2,800,000	3,582	8	Cooling
		Very cold/cold	1,000,000	2,212		
		Mixed-humid	0	3,401		
		Mixed-dry/Hot-dry	1,200,000	4,375		
		Hot-humid	400,000	6,304		
		Marine	0	1,621		
	Window AC	National	54,900,000	3,582	9	Cooling
		Very cold/cold	23,000,000	2,212		
		Mixed-humid	18,600,000	3,401		
		Mixed-dry/Hot-dry	2,700,000	4,375		
		Hot-humid	8,100,000	6,304		
		Marine	1,800,000	1,621		
	Pumps/ zone pumps	National	32,567,502	4,413	2,8	Heating
		Very cold/cold	16,762,685	5,886		
		Mixed-humid	14,817,923	4,567		
		Mixed-dry/Hot-dry	740,171	3,582		
		Hot-humid	0	1,748		
		Marine	0	6,325		

Notes

a. All regional estimates are calculated by applying regional saturation values from U.S. EIA's CBECS and RECS surveys. The Statewide CASE Team avoids using the CBECS and RECS numbers directly in several cases, because this does not always capture the number of installed units (particularly in CBECS).

b. NEEP report provides an estimate of stock for the northeast region and estimates that this represents approximately 18% of the national installed base. This study uses these combined pieces of information to estimate national stock.

c. Shipments pre-2010 are included in DOE's technical support document for residential central air conditioners and heat pumps [7]. Shipments between 2010 - 2017 are from [1]. This study assumes that the share of split AC and HP remains the same before and after 2010. Based on [7], this study assumes a lifetime expectancy of 24 years for very cold/cold and mixed-dry regions. For mixed-humid, hot-humid and marine regions, this study assumes 18 years. Using shipments from [1] and lifetime expectancy, this study calculates the total stock. This study subtracts the residential stock of ducted, split AC from the total stock of ducted, split AC to determine the commercial stock.

d. Based on a 2018 survey of California residences conducted by Pacific Gas and Electric Company. Results have been scaled to a national basis using a GDP ratio between California and the entire United States (approximately 0.13).

e. Commercial duty cycles estimated based on analysis of runtime hours for U.S. DOE's commercial reference building models for the climates and seasons listed. Commercial reference buildings models are available at: https://www.energy.gov/eere/buildings/commercial-reference-buildings.

f. Residential duty cycles estimated based on analysis of runtime hours for IECC 2006 code compliance reference models, developed by Pacific Northwest National Laboratory (PNNL) and available at: https://www.energycodes.gov/development/residential/iecc_models.

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G. Building Wiring Assumptions

Building Sector	Product Category	Product	Number of AC Power Phases	AC Voltage (Vrms)	Wire Gage (AWG) (a)	Wire Resistivity (ohms per 1,000 ft)	Round-Trip Circuit Length (ft)	Round Trip Circuit Resistance (ohms)
Residential	Appliances	Clothes dryer	1	240	10	1.0	50	0.100
		Clothes washer	1	120	12	1.6	50	0.159
		Dishwasher	1	120	12	1.6	50	0.159
		Freezer	1	120	12	1.6	50	0.159
		Refrigerator	1	120	12	1.6	50	0.159
	Electronics and Office	Computers - Desktop	1	120	13	2.0	50	0.200
		Computers - Notebook	1	120	13	2.0	50	0.200
		Game console	1	120	13	2.0	50	0.200
		OTT STB	1	120	13	2.0	50	0.200–
		Set-top box	1	120	13	2.0	50	0.200
		Small network equipment	1	120	13	2.0	50	0.200
		TV	1	120	13	2.0	50	0.200
	HVAC	Dehumidifier	1	120	13	2.0	50	0.200
		Ducted, split AC	1	240	10	1.0	50	0.100
		Ductless AC	1	240	10	1.0	50	0.100
		Evaporative cooler	1	120	10	1.0	50	0.100
		Furnace motors/ fans	1	120	14	2.5	50	0.253
		Pumps/ zone pumps	1	120	14	2.5	50	0.253
		Radon fan	1	120	13	2.0	50	0.200
		Recirculation pump	1	120	14	2.5	50	0.253
		Well pump	1	120	10	1.0	50	0.100
		Window AC	1	120	13	2.0	50	0.200
	Lighting	Compact fluorescent lamps	1	120	13	2.0	50	0.200
		High intensity discharge lamps	1	120	13	2.0	50	0.200
		LED Lamps	1	120	13	2.0	50	0.200
		Linear fluorescent lamps	1	120	13	2.0	50	0.200
	Misc.	EV charger	1	240	8	0.6	50	0.063
		Pool/hot tub/sauna pump	1	240	8	0.6	50	0.063

Notes

a. A value of 13 AWG is used for products that might be placed on either a 15 or 20A circuit.

H. Grid Infrastructure Assumptions

Assumption	Value	Units	Source
Distribution feeder voltage	12,000	V	Consultation with PG&E system engineers.
Distribution feeder circuit length	10,000	ft	
Distribution feeder AWG	4/0 aluminum		
Feeder resistivity	0.077	ohms/1,000 ft	https://www.engineeringtoolbox.com/copper-aluminum-conductor-resistance-d_1877.html and https://www.solaris-shop.com/content/American%20Wire%20Gauge %20Conductor%20Size%20Table.pdf
Service drop length	50	ft	Consultation with PG&E system engineers.
Service drop AWG	4 aluminum		
Service drop resistivity	0.2485	ohms/1,000 ft	https://www.engineeringtoolbox.com/copper-aluminum-conductor-resistance-d_1877.html and https://www.solaris-shop.com/content/American%20Wire%20Gauge %20Conductor%20Size%20Table.pdf

I. Incremental Cost Assumptions

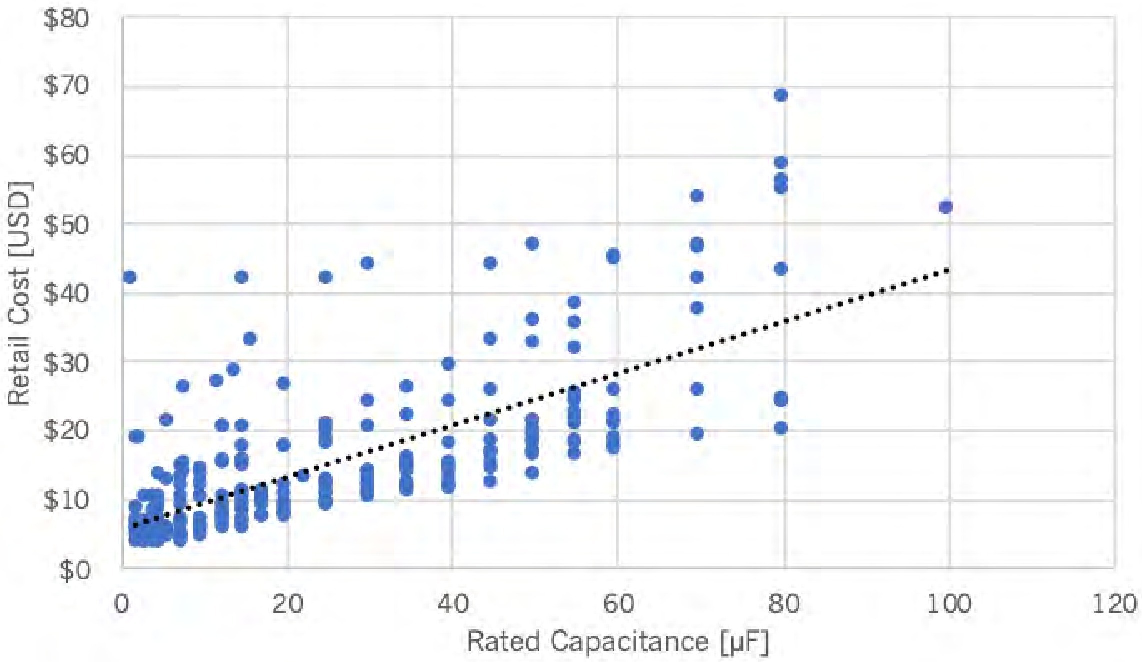
Incremental price assumptions for active power factor correction products have been informed through consultation with Power Integrations. The Statewide Case Team assumes that any power factor correction stage will add a minimum of $0.30 to the bill of materials. This study further assumes that costs will scale according to the nameplate rating of the product's power supply, with an average incremental cost of ¢0.6/W. The Statewide CASE Team's overall equation for active PFC bill of materials cost is, therefore:

$$\text{BOM cost} = \max\left(\$0.30,\ W_{\text{PSU}} * \$0.006\right)$$

Equation 6: Incremental Cost of PFC

where WPSU is the power supply nameplate rating. This study assumes an additional retail markup of 200% will be added to these costs and passed on to the consumer to arrive at an incremental retail cost to the consumer.

For capacitors, the Statewide CASE Team developed assumptions of typical price directly from capacitor retail cost data. In this case, this study analyzed data from Granger.com, an online electronic component retailer, to estimate cost based on the rated capacitance (in microfarads or µF) of various motor-start capacitors. A fairly linear relationship exists between capacitance and retail cost (Figure 22). As a result of this analysis, this study employed an incremental retail cost to the consumer of ¢38/µF for capacitors.



Cost-Capacitance Relationship for Motor-Start Capacitors on Granger.com

Figure 27: analysis of cost vs. capacitance relationship for motor-start capacitors suitable to be integrated into motorized appliances, based on data from Granger.com.

J. Sensitivity Analysis Detailed Results

			National Building Energy Savings (GWh/yr)			National Distribution Grid Energy Savings (GWh/yr)		
Building Sector	**Product Category**	**Product**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Commercial	Appliances	Refrigerator	0.1	0.5	1.4	0.0	0.1	0.2
		Vending machines	0.2	0.3	0.5	4.1	18.7	56.4
	Electronics and Office	Computers - Desktop	0.3	0.9	0.0	0.2	0.8	2.5
		Computers - Notebook	0.1	0.4	1.5	0.1	0.1	0.1
		Imaging	0.2	2.8	13.2	0.0	0.2	1.5
		Small network equipment	0.3	1.1	3.1	0.0	0.0	0.1
	HVAC	Ducted, split AC	200.8	1,044.3	6,170.6	42.4	220.5	1,302.7
		Packaged terminal	64.6	144.5	1,076.5	7.6	17.0	126.4
		Packaged/rooftop AC unit	33.5	384.3	4,543.9	7.1	81.1	959.1
	Lighting	Compact fluorescent lamps	0.5	2.0	6.1	0.8	1.2	1.7
		High intensity discharge lamps	13.0	4.4	0.0	0.0	0.0	0.6
		LED lamps	0.0	0.0	4.5	0.0	0.2	0.7
		Linear fluorescent lamps	6.0	12.5	23.0	0.0	0.1	0.0
	Process	Commercial refrigeration	0.1	0.7	1.5	0.7	5.8	48.6

J. Sensitivity Analysis Detailed Results, continued

			National Building Energy Savings (GWh/yr)			National Distribution Grid Energy Savings (GWh/yr)		
Building Sector	**Product Category**	**Product**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Residential	Appliances	Clothes dryer	3.0	4.3	6.0	9.0	22.0	48.9
		Clothes washer	48.3	117.6	261.3	0.4	1.8	4.2
		Dishwasher	6.9	20.6	47.0	0.0	0.0	0.0
		Freezer	2.2	9.6	22.2	0.0	0.4	1.9
		Refrigerator	21.8	100.1	301.6	0.0	0.0	0.1
	Electronics and Office	Computers - Desktop	1.9	10.9	38.9	0.3	1.7	6.0
		Computers - Notebook	0.2	1.1	4.3	0.1	0.3	0.9
		Game console	0.7	1.4	2.4	0.1	0.2	0.4
		OTT STB	0.0	0.1	0.2	0.0	0.2	0.4
		Set-top box	11.6	30.9	90.7	1.8	4.7	13.9
		Small network equipment	0.1	0.3	0.9	0.0	0.0	0.0
		TV	4.6	37.9	316.1	0.0	0.2	0.4
	HVAC	Dehumidifier	1.6	55.3	656.9	0.2	8.5	100.9
		Ducted, split AC	845.4	4,397.2	25,982.0	242.0	1,258.9	7,437.1
		Ductless AC	14.3	177.7	1,474.9	4.1	50.9	422.2
		Evaporative cooler	8.2	86.6	984.9	2.3	24.5	279.0
		Furnace motors/ fans	500.8	1,628.4	7,137.4	63.9	207.7	910.5
		Pumps/ zone pumps	0.3	2.6	25.8	0.4	3.7	37.3
		Radon fan	0.1	5.9	42.9	0.0	0.9	6.6
		Recirculation pump	0.3	7.8	87.1	0.0	1.0	11.1
		Well pump	0.1	0.9	5.4	1.8	0.6	0.0
		Window AC	525.2	1,175.6	8,757.2	81.0	181.2	1,349.7
	Lighting	Compact fluorescent lamps	1.2	5.4	16.4	0.8	1.8	3.2
		High intensity discharge lamps	0.1	0.0	0.0	0.0	0.1	0.2
		LED Lamps	0.4	0.5	0.6	1.3	3.9	8.8
		Linear fluorescent lamps	1.6	3.3	6.1	0.2	0.5	0.9
	Misc.	EV charger	15.8	167.2	965.8	44.7	326.4	1,373.3
		Pool/hot tub/sauna pump	0.2	3.4	27.1	2.3	33.0	279.4

K. California Statewide Power Factor Energy and Economic Analysis

The following tables present the results of a California statewide power factor cost effectiveness analysis using estimated device stocks at the state level and California average retail electric rates by sector for the year 2017 (EIA 2018a). Cells highlighted in green and with bold text indicate end uses where power factor correction could be economical. Due to California's higher retail electric rates, a total of seven products would be cost-effective based on behind-the-meter energy savings (behind-the-meter economics columns), and eight would achieve cost effectiveness when considering building and grid savings (holistic economics column).

			Statewide Building Energy Savings (GWh/yr)			Statewide Distribution Grid Energy Savings (GWh/yr)			Statewide Economics - Behind-the-Meter Economics, Mid Scenario		Statewide Economics - Holistic Economics, Mid Scenario	
Building Sector	**Product Category**	**Product**	**Low Scenario**	**Mid Scenario**	**High Scenario**	**Low Scenario**	**Mid Scenario**	**High Scenario**	**Benefit-Cost Ratio, CA Rates**	**CA NPV Savings (Millions USD)**	**Benefit-Cost Ratio, CA Rates**	**CA NPV Savings (Millions USD)**
Commercial	Appliances	Refrigerator	0.0	0.1	0.2	0.0	0.0	0.0	0.1	-$1.1	0.1	-$1.0
		Vending machines	0.0	0.0	0.1	0.0	0.0	0.0	0.1	-$0.4	0.1	-$0.3
	Electronics and Office	Computers - Desktop	0.0	0.3	4.3	0.0	0.0	0.1	0.0	-$5.4	0.0	-$5.4
		Computers - Notebook	0.0	0.1	0.2	0.0	0.0	0.0	0.0	-$6.2	0.0	-$6.2
		Imaging	0.0	0.4	1.8	0.0	0.0	0.0	0.1	-$4.8	0.1	-$4.8
		Small network equipment	0.0	0.1	0.4	0.0	0.0	0.1	0.0	$0.0	0.0	$0.0
	HVAC	Ducted, split AC	52.1	185.0	495.2	32.1	0.0	0.0	0.9	-$27.3	1.7	$145.3
		Packaged terminal	9.3	19.7	154.8	1.1	2.3	18.1	0.7	-$9.8	0.9	-$3.5
		Packaged/rooftop AC unit	8.7	35.6	102.1	1.8	7.4	21.3	0.9	-$3.6	1.9	$31.5
	Lighting	Compact fluorescent lamps	0.1	0.3	0.8	0.0	0.0	0.0	0.0	-$13.3	0.0	-$13.3
		High intensity discharge lamps	0.0	0.6	2.8	0.0	0.0	0.0	0.0	-$12.4	0.0	-$12.4
		LED lamps	0.0	0.0	0.6	0.0	0.0	0.3	0.0	-$17.6	0.0	-$17.6
		Linear fluorescent lamps	0.8	3.5	10.6	0.0	0.4	7.3	0.0	-$127.7	0.0	-$127.6
	Process	Commercial refrigeration	0.0	0.1	0.2	0.0	0.0	0.0	0.3	-$0.3	0.3	-$0.3

			Statewide Building Energy Savings (GWh/yr)			Statewide Distribution Grid Energy Savings (GWh/yr)			Statewide Economics - Behind-the-Meter Economics, Mid Scenario		Statewide Economics - Holistic Economics, Mid Scenario	
Building Sector	**Product Category**	**Product**	**Low Scenario**	**Mid Scenario**	**High Scenario**	**Low Scenario**	**Mid Scenario**	**High Scenario**	**Benefit-Cost Ratio, CA Rates**	**CA NPV Savings (Millions USD)**	**Benefit-Cost Ratio, CA Rates**	**CA NPV Savings (Millions USD)**
Residential	Appliances	Clothes dryer	0.3	0.4	0.6	0.0	0.0	0.0	0.0	-$110.3	0.0	-$74.3
		Clothes washer	5.0	12.2	27.1	0.0	0.1	0.2	0.0	-$525.0	0.0	-$444.3
		Dishwasher	0.7	2.1	4.9	0.0	0.0	0.1	0.0	-$268.2	0.0	-$233.2
		Freezer	0.2	1.0	2.3	0.0	0.0	0.2	0.1	-$30.1	0.1	-$26.9
		Refrigerator	2.3	10.4	31.3	0.0	5.4	8.6	0.1	-$259.7	0.1	-$228.4
	Electronics and Office	Computers - Desktop	0.3	1.5	5.2	0.0	0.2	0.8	0.1	-$7.6	0.1	-$7.6
		Computers - Notebook	0.0	0.2	0.6	0.0	0.0	0.0	0.0	-$19.4	0.0	-$19.3
		Game console	0.1	0.2	0.3	0.0	0.0	0.0	0.0	-$9.7	0.0	-$9.7
		OTT STB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	$0.0	0.0	$0.0
		Set-top box	0.5	0.9	1.4	0.1	0.1	0.2	0.1	-$9.8	0.1	-$9.8
		Small network equipment	0.0	0.0	0.1	0.0	0.0	0.0	0.0	$0.0	0.0	$0.0
		TV	0.5	3.9	32.8	0.0	0.0	32.5	0.2	-$14.2	0.2	-$14.2
	HVAC	Dehumidifier	1.0	7.6	27.1	0.1	1.2	4.2	0.4	-$16.6	0.4	-$12.4
		Ducted, split AC	114.8	407.7	1,091.3	32.4	115.1	308.2	1.8	$340.4	4.8	$647.0
		Ductless AC	1.3	22.5	133.1	0.4	6.4	37.6	1.3	$10.3	3.4	$31.9
		Evaporative cooler	11.1	35.2	89.0	0.3	4.9	39.3	0.9	-$5.2	1.1	$8.0
		Furnace motors/ fans	59.0	269.6	841.6	7.5	34.3	107.0	1.2	$89.2	1.4	$175.6
		Pumps/ zone pumps	0.3	3.5	25.8	0.0	0.4	3.3	0.1	-$42.8	0.1	-$37.9
		Radon fan	0.1	1.9	8.2	0.0	0.3	1.3	0.8	-$1.0	0.9	-$0.3
		Recirculation pump	0.2	1.1	3.6	0.0	0.1	0.5	0.2	-$7.6	0.2	-$6.7
		Well pump	0.1	0.1	0.2	0.0	0.0	0.0	0.0	-$6.1	0.1	-$5.1
		Window AC	6.8	29.2	112.8	1.0	4.5	17.3	0.8	-$11.4	1.0	-$2.1
	Lighting	Compact fluorescent lamps	0.1	0.2	0.7	0.0	0.1	0.2	0.0	-$55.3	0.0	-$55.3
		High intensity discharge lamps	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-$0.2	0.0	-$0.2
		LED Lamps	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-$14.6	0.0	-$14.6
		Linear fluorescent lamps	0.1	0.1	0.2	0.0	0.0	0.0	0.0	-$11.5	0.0	-$11.5
	Misc.	EV charger	2.1	22.6	130.4	0.3	1.1	3.0	1.0	$1.3	1.1	$1.6
		Pool/hot tub/sauna pump	0.0	0.4	2.8	0.0	0.3	0.8	0.4	-$0.8	1.1	$0.05