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RESEARCH

Cross-cutting strategies to lower electricity use of miscellaneous electric loads in the domestic sector

Alan Meier · Joshua Butzbaugh · Wyatt Merrill

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Abstract Miscellaneous Electric Loads (MELs) account for roughly one quarter of building electricity use in most developed countries. A product-specific approach to lowering MELs electricity use in this category takes too long and costs too much because there are so many MELs, each providing unique services. An alternative approach focusing on key functionalities was therefore explored. These functionalities include: (1) power management, (2) power scaling, and (3) power conversion. Cross-cutting efficiency improvements to these functionalities can be incorporated into broad categories of MELs, thus saving electricity and lowering costs. Even though the population of MELs is diverse and rapidly evolving, major technical opportunities exist to improve their efficiency in these functionalities. Research into energy-saving solutions within the cross-cutting technologies will probably have larger savings than focusing on single products.

Keywords ; Energy efficiency · Power conversion · Power management · Power scaling · Part-load

The combined contribution of miscellaneous electrical loads is large

While definitions of miscellaneous electric loads (MELs) vary, here we consider any electric load that does not fulfill a core building service of HVAC, lighting, water heating, cooking, or major appliances to be a MEL. No perfect definition of MELs exists since any definition relying on exclusion is likely to have some ambiguity. This definitional ambiguity related to consumption does not interfere with the methodology to investigate savings from individual improvements in technologies proposed here.

In the United States, MELs are forecasted to increase in both share and magnitude of total building electricity consumption through 2050 (Butzbaugh et al., 2021). MELs in residential and commercial buildings accounted for approximately 44% of delivered electricity for those sectors in 2021. By 2050, MELs are forecasted to increase to nearly 52% of delivered electricity in residential and commercial buildings. The U.S. Energy Information Administration developed these estimates using a combination of nameplate information, engineering approximations,

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and field measurements. The sum of the estimates from the bottom-up approach were cross-checked with the energy consumption remaining after subtracting major end uses. (U.S. Energy Information Administration. 2018) In spite of the high degree of detail displayed, the values are nevertheless quite uncertain.

The substantial and growing share of MELs' electricity consumption underscores the importance of characterizing their electricity usage and identifying effective energy efficiency measures to decrease it. This has been difficult because MELs comprise a wide range of end uses. Some MELs are present at very high saturations and have low per-unit electricity consumption (e.g., mobile phone chargers), whereas other MELs are present at low saturations but have high per-unit electricity consumption (e.g., home spas, home elevators, commercial kitchen ventilation systems). In addition, the electricity consumption of certain MELs depends on occupant behavior (e.g., microwaves), while other MELs have consumption that is mostly independent (e.g., network equipment). To complicate matters, the composition of MELs is continuously changing as new products (e.g., smart speakers) emerge and new features (e.g., connectivity and cloud communications) alter modes of consumption. At the same time, other formerly popular MELs (e.g., VCRs, water beds) are disappearing. Figure 1 depicts the wide variety of end uses that contribute to MELs and magnitude of their aggregate energy consumption. The "unspecified" portion represents residual energy consumption between the bottom-up and top-down methodologies. We attribute the overwhelming fraction of this energy use to MELs.

Energy consumption and usage patterns of MELs are sparse because they are difficult to monitor. Most

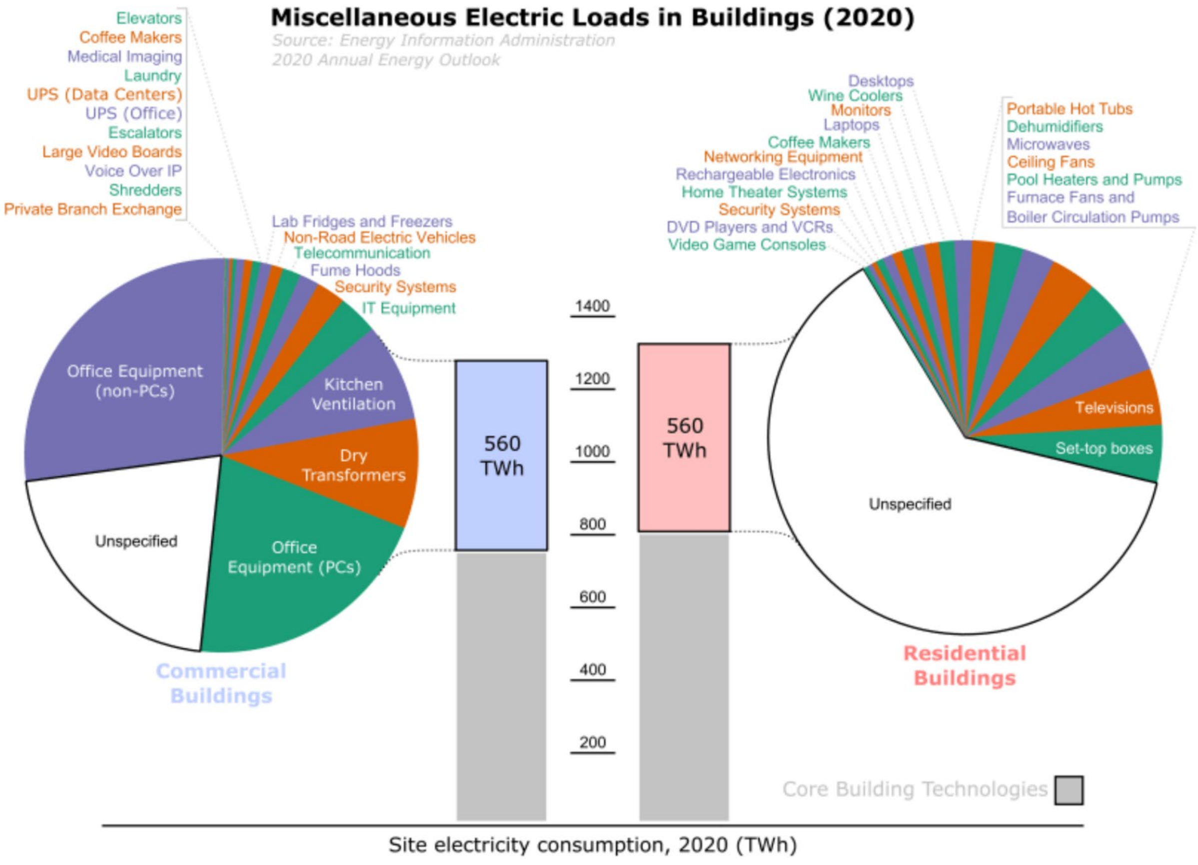


Fig. 1 Approximate 2020 MELs share of residential and commercial buildings electricity consumption in TWh/year. Core building technologies (in gray) refer to HVAC, water heating, lighting, refrigerators, freezers, clothes washers and dryers, and dishwashers. (Adapted from U.S. Energy Information Administration. 2021)

MELs (e.g., home electronics) use shared circuits in a building so they cannot be monitored at the electrical panel. MELs can also be monitored using some smart plug monitors but these are more intrusive. Some MELs are hardwired, making them less amenable to submetering. Portable MELs (e.g., re-chargeable bikes, garden equipment) may also consume energy in different buildings throughout a week or day. Energy modeling therefore struggles to accurately capture consumption from MELs. Together, these challenges suggest that any strategy for decreasing the energy consumption of MELs should be cross-cutting in nature to achieve energy savings across a wide range of MELs.

A technical approach to energy savings in mels based on cross-cutting functionality

The traditional approach to reducing the energy consumption of a device is to carefully examine the service it provides and the interactions between subcomponents that provide that service, and in turn, determine losses inherent to design and componentry. This paper focuses on R&D measures that avoid a product-by-product approach, which would be particularly challenging for MELs given that:

There are too many MELs, each providing unique services, to evaluate each individually;
New MELs are constantly introduced to the market and existing ones are updated and modified;
MELs often interact with each other in ways that affect their energy use (e.g., computer and monitor);
The energy consumption and/or stock of many individual MELs is relatively small, so that device-specific approaches may not be a priority.

A product-by-product approach to lowering MELs'energy consumption with a unique solution for each product will take too long, cost too much, and waste resources. It is also wasteful because researchers, designers, and manufacturers will devote considerable time re-inventing solutions that have already been applied in other products.

We propose instead to explore improvements in cross-cutting functionalities that are present in numerous MELs. Researchers and manufacturers can realize efficiency gains to these cross-cutting functionalities through development or integration of components, controls, protocols, or other ubiquitous features. By finding more energy-efficient solutions to those functionalities, whole categories of MELs will benefit by increasing energy efficiency or lowering costs (or both). The following cross-cutting functionalities for initial investigation:

Power management
Power scaling
Power conversion
Measurement and estimation
Interfaces/displays
Communications/networking

We describe in detail the first three (in bold font) to illustrate the approach. The cross-cutting functionalities described below illustrate broad applicability and highlight significant opportunities for energy savings.

Power management

Power management is the method by which a device reduces the power levels of its components when they are not needed. Engineers use this term somewhat differently depending on the technology. The term originated in computers, where it applies to mechanisms managed by the operating system including sleep and deep-sleep modes. Figure 2 illustrates the concept.

Today, computers perform power management through various Operating System-directed configuration and Power Management (OSPM) frameworks. One such framework is Advanced Configuration and Power Interface (ACPI), an open standard for operating systems to configure the power modes of various hardware modules. Various other emerging protocols provide an energy-focused hardware description for analyzing, designing, and managing the energy features of a device.

For MELs, the most straightforward application of power management is in microprocessor-controlled devices, such as printers, set-top boxes, and routers. Relays or solid-state methods can disable electronic and mechanical modules, and microprocessors themselves often offer a range of sleep and deep-sleep modes. Power management also applies to devices with distinct subsystems such as an elevator, which

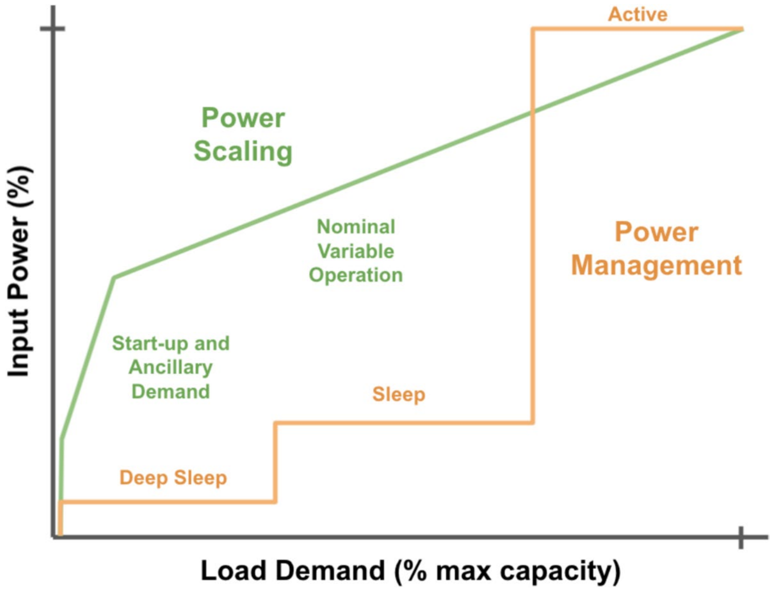


Fig. 2 An example device with power management (orange) and another with power scaling (green). Power management appears as a discrete change in input power with operating mode, whereas power scaling implies a continuous change in operation

could reduce energy for lighting and ventilation systems while unoccupied. In general, power management techniques are relevant to any MEL with internal modules that are separable by functionality or discretized based on user demands (such as staged power supplies).

Designers of device-level power management systems must begin with an assessment of possible low-power modes and the controls that specify modes of operation. MELs may have many low-power modes ranging from idle to various levels of sleep. Deep sleep modes save more energy but may take longer to wake the various systems and modules that were deactivated. Innovative design may employ intermediate low-power modes that save power by foregoing certain unused modules while preserving latency. The power-management controller is responsible for deciding when to transition to a low-power mode. These controllers typically track the elapsed time since a component or subsystem last required a resource; if the designated interval has been exceeded, then it is switched off or placed in a low power mode. Power-management controllers can also make decisions based on the time of day or an internal signal from another module. Sophisticated systems may even receive an external signal from another device or sensor; an elevator, for example, could receive a signal from a building management system that was based on a schedule or security system.

A concept known as “shrinking the staircase” (Meier et al., 2020) visually demonstrates the basis of many opportunities for improving power management. The staircase-like histogram in Fig. 3 plots the power requirements and daily hours of operation of the various power modes in a generic device. Various improvements to power management can create new low-power modes, reduce the consumption of existing low-power modes, or shift the device’s operation such that it spends more time in low-power modes.

Shrinking the staircase can substantially reduce the overall consumption for MELs. A typical entry-level desktop computer, shown in Fig. 4, may consume as much as 83 kWh per day (Mills et al., 2019). Shrinking the consumption of the computer’s idle, sleep, and off modes, could approximately save up to a third of the daily consumption (based on data from Fig. 4). It is more difficult (but possible) to also reduce the consumption during active modes such as browsing and streaming. In general, engineers have started to study how the energy-first designs widely used in mobile applications can be repurposed for plug-loads. A recent study (Davorin et al., 2019) analyzed the consumption in major components for several types of plug-load MELs. It developed reference designs that leveraged mobile design principles and found the savings to range from 2.4 kWh/year for smart TVs up to 70 kWh/year for set-top boxes.

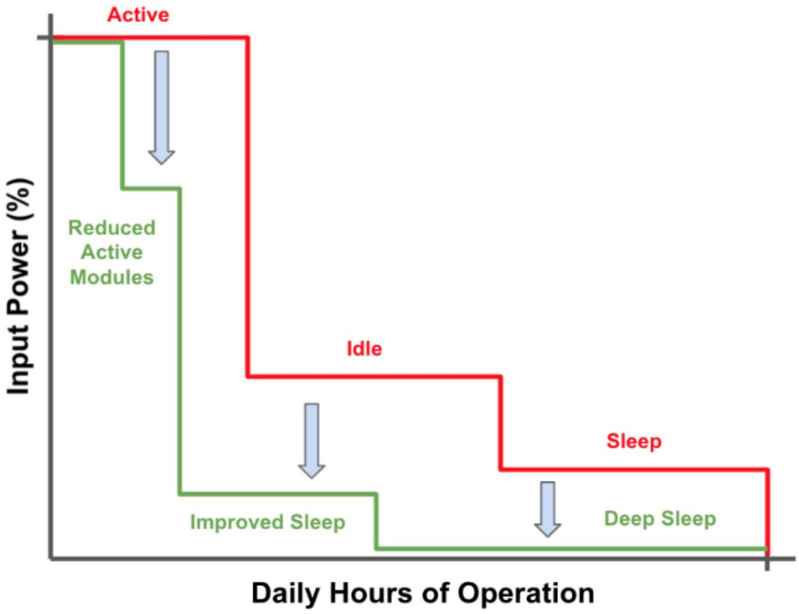


Fig. 3 An example histogram of the various low-power modes and the proportion of the day the device spends in each mode. "Shrinking the staircase" is the methodical improvement of the consumption and frequency of the various low-power modes

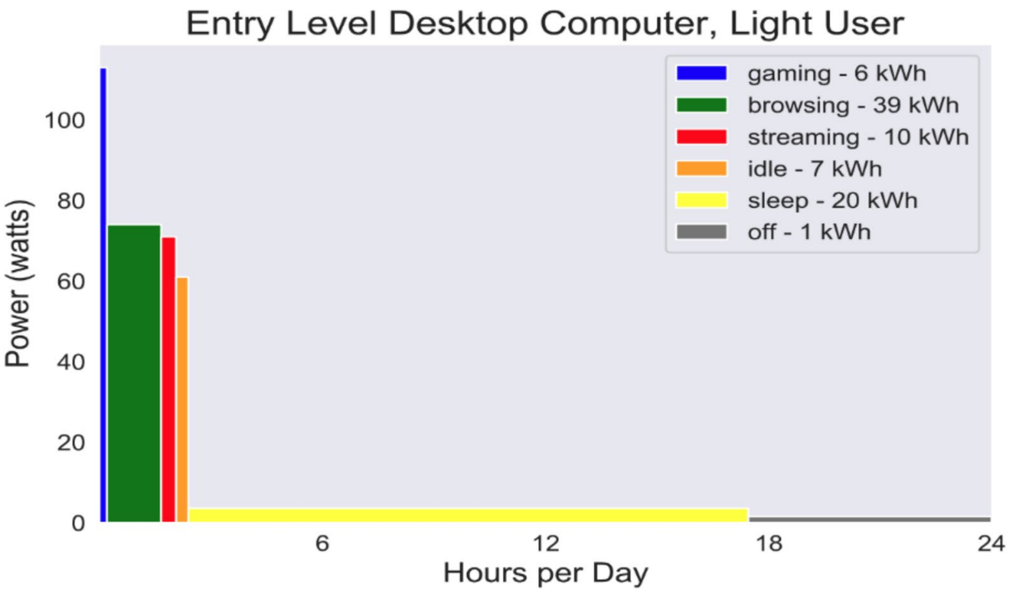


Fig. 4 Power use distribution of an entry-level desktop computer with light use. The box height is the power level, and the box area is the energy use of each mode. Idle, sleep, and off modes can all benefit from standby reduction techniques. (Adapted from Meier et al. (2020))

Power management research opportunities are inherently cross-cutting when targeting low-power modes that apply to a family of devices. One such opportunity would investigate how to increase the use of deep sleep modes, whose consumption is commonly in the milli-watt range. Deep sleep modes can reduce a significant amount of power (thus energy) but may require a prohibitively long wake-up process. Sensors or predictive algorithms applied to connected devices could provide a role in controlling how and when to wake a device from deep sleep in anticipation of user interactions. Such predictive control protocols are sensible target for emerging training approaches utilizing machine learning.

Finally, there are also many promising system-level solutions that can help shrink the staircase, including networked occupancy sensing, autonomous software update scheduling, and the use of direct current (DC) power servers.

Other research opportunities could focus on eliminating standby and sleep modes altogether (Gerber et al., 2019). Standby-reduction techniques often use a mechanical, solid-state, or micro-electro mechanical (MEM) relay to cut power to the device's main electronics. One of the more promising standby-reduction solutions is the wake-up radio, a type of extremely low power RF (i.e., radio frequency) receiver designed explicitly to wake a device from sleep or standby. Other solutions include harvesting energy from the ambient environment and storing it, which becomes more feasible as new circuit designs and components reduce power requirements.

Power scaling

The capacity of a MEL is typically expressed in its provision of services such as data rate, illumination, audio volume, heat, electric power, or air flow. Energy-efficient design, engineering, and certification often studies or optimizes around delivering this maximum output with minimal power draw. In practice, however, typical use of MELs does not demand maximum output all the time, and indeed, doing so could lead to overheating, over-illumination, or excessive power draw. The MEL must therefore modulate its output to avoid over-supplying the service. For complex MELs, components inside the devices must also modulate their outputs. Power scaling is the process of adjusting the level of delivered service according to the needs of the user at any moment. "Ideal" power scaling is delivering the service over a wide range of needs with the minimum input energy in a continuous fashion (as opposed to the step-wise approach of power management). Figure 5 shows an ideal power scaling schematically contrasted with power scaling behavior for a typical device. Figure 2 also shows one implementation of power scaling by employing different operating modes.

At any level of service, the typical device will draw more power than an ideal device. An important distinction between typical and ideal occurs at zero level of service. An ideal system will draw no power at zero service, but typical systems draw some power, the standby power of the device.

Specific industries or applications may use other methods to achieve power scaling. For example, Load Following and Output Modulation refer to the ability for a device to modulate its power output to match demand. Impedance Matching refers to the design of a power interface between two devices such that the impedances are closely matched, thereby minimizing reflections and maximizing the power transfer. Dynamic Voltage Scaling and Clock Rate Control are techniques processors use to reduce switching loss and average power consumption by selectively scaling the clock frequency and supply voltage when processing demand is low. In addition, the difference

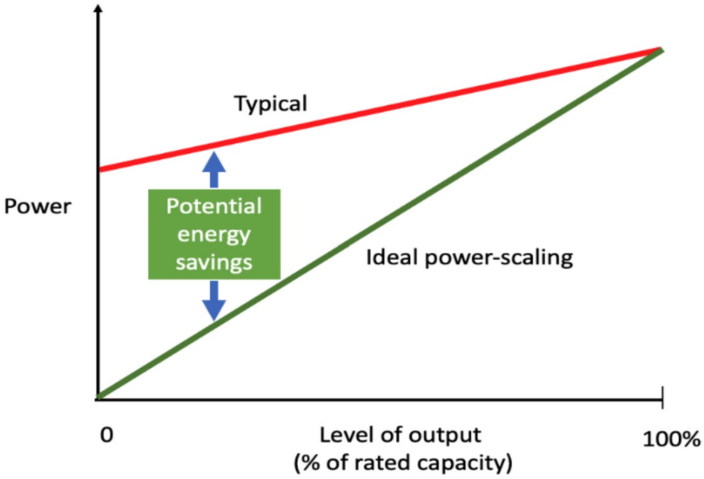


Fig. 5 Relationship between a device's level of output and power input, showing typical and ideal power scaling

between power scaling (continuous) and power management (discrete) is gradually becoming less clear-cut in some products; for example, some computers have many barely differentiable modes so that their power curves appear less discrete and more continuous.

Minimizing deviation in power scaling from the ideal curve, shown in Fig. 5, reduces energy use. The deviations from ideal are collectively known as the device's part-load losses. Besides increased consumption, part-load losses can cause important secondary problems, such as excess heat, electrical output, or noise. Appliance designers have adopted a range of strategies to modulate output and, at the same time, to achieve performance closer to ideal power scaling. A common solution is cycling. In this situation, a device with a single level of output must match a fluctuating demand for that output. For instance, microwave ovens use cycling to provide less than full output or to cook food more uniformly. However, cycling can still cause part-load losses in many applications, because pulsed on–off operation is almost always less efficient than continuous operation. For example, variable-frequency drives (VFDs) allow motor loads to operate with a continuous variable output and have been shown to save up to 50% of the motor's part-load energy consumption compared to those operated with on/off duty cycles (Greenberg et al., 1988).

For very low power requirements, designers have staged multiple power supplies and stored energy in batteries or thermally conductive materials. Some of these strategies can minimize standby power losses for devices that would otherwise require considerable power even when delivering no useful output. For example, many TVs employ auxiliary power supplies to energize only the controls until a signal is received from a remote controller. This allows the primary power supply to shut down completely when output is not required.

Energy savings from improved power scaling

An estimate of potential energy savings from improved power scaling requires two calculations. First, the power savings at each level of output must be measured (or estimated). Second, the corresponding time in which the device operates at each level of output must be measured, typically stated in hours/year. The annual savings from improved power-scaling technology is the product of power savings and hours at each level of service.

The Wi-Fi router profiled in Fig. 6 draws a relatively large standby power of 4-5W, even when there is no network traffic. As shown in Fig. 7, a typical Wi-Fi router operates nearly all of the time below 1% of capacity. This performance is far from ideal power scaling.

There is surprisingly little published data on MELs'power scaling behavior. Manufacturers are principally concerned about the device's behavior near full capacity, where overheating may occur or other components stressed. Despite the general lack of published data, power scaling is relevant to many

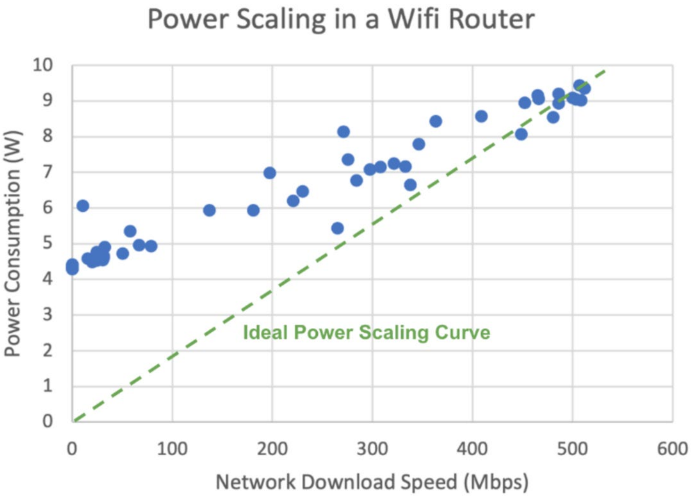
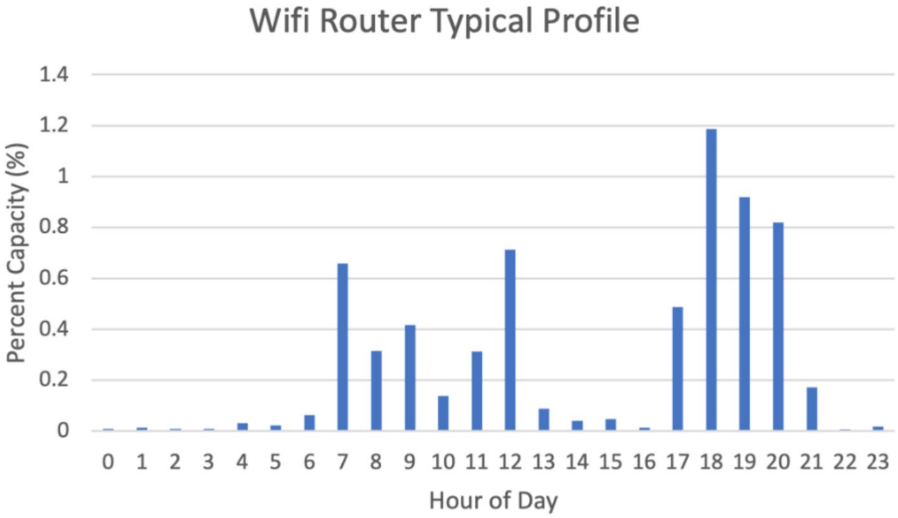


Fig. 6 The relationship between a Wi-Fi router's output (measured in data throughput, megabits/second or Mbps) and power draw. (Source: LBNL measurements)

Fig. 7 Capacity utilization of a typical Wi-Fi router over a day. (Source: LBNL measurements)



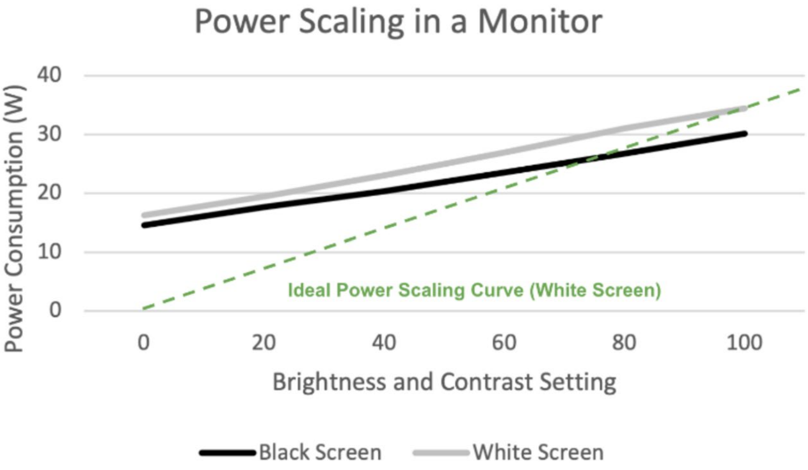
types of MELs, and such data can easily be measured in a lab. For example, Fig. 8 shows the measured power-scaling profile of an LCD monitor, which like the Wi-Fi router, also has a linear characteristic with a significant no-load power. The power-scaling profile of a sound bar, shown in Fig. 9, has a nonlinear relationship between volume setting and power, which may be a result of magnetic saturation at high current.

Information is also scanty about the time MELs reside at different utilization levels. New scoping studies and data are necessary to fully characterize the opportunity for power-scaling improvement in MELs. These studies would categorize MELs by their functional output, and conduct lab measurements or access manufacturer data to analyze how the consumption varies with this output. In addition, it is important to discuss how power scaling can be improved for each category of MELs and whether such improvements are feasible.

Power conversion

Power conversion is the process in which one form of energy is transformed into another form with different physical properties. The initial power conversion in MELs is electrical and ranges from milliwatts to kilowatts (six orders of magnitude). The most frequent forms of power conversion involve electrical, chemical (batteries), and mechanical energy; however, they can also include thermal energy and electromagnetic radiation (illumination,

Fig. 8 The relationship between an LCD monitor's brightness and power draw for a black screen and a white screen. The brightness and contrast are increased together. (Source: LBNL measurements)



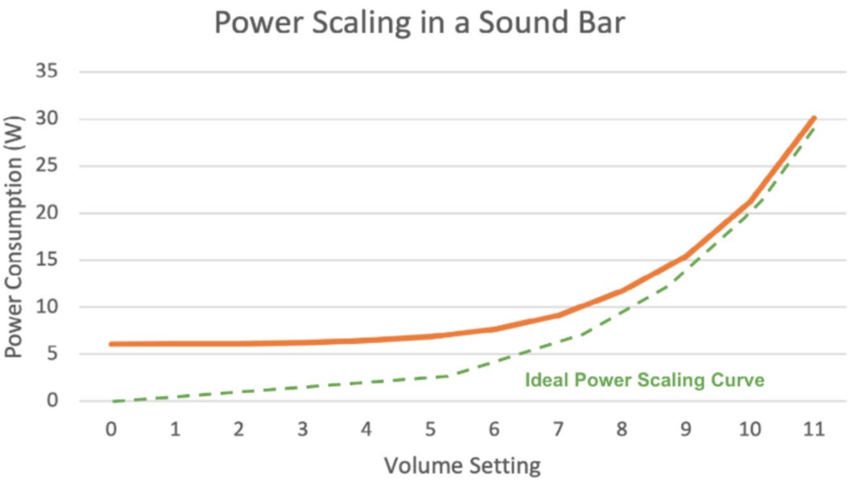


Fig. 9 The relationship between a sound bar's volume setting and its power draw. The test was conducted with a 440 Hz pure-sine tone. (Source: LBNL measurements)

Table 1 Commonly occurring Power Conversions in MELs

Input	Output
Electricity (Alternating Current)	AC DC
Electricity (Direct Current)	DC AC DC Wireless
Electricity	Mechanical (e.g., motors, actuators)
Electricity	Heat
Electricity	Radiation (e.g., illumination, radio frequency)
Mechanical	Mass Movement (e.g., fans, fans on heat sinks, pumps, compressors, generators)
Environmental (e.g., light, motion)	Electricity
Heat (source)	Heat (sink)

RF, etc.) as shown in Table 1. Opportunities to improve power conversion are cross-cutting because many MELs leverage the same small set of standardized components, and nearly all MELs undergo conversion from alternating current (AC) to direct current (DC) either internally or via an external power supply.

Multiple power conversions within a single MEL are common. Figure 10 shows an example of the many types of power conversion that take place in a laptop. Most types of conversions suffer from inefficiency in the form of heat loss, causing the useful output power to be less than the input power. Energy storage (in batteries, capacitors, and inductors) is a special case of power conversion in which either direction of conversion results in energy loss and a smaller energy leakage occurs constantly (known as standing loss). Batteries play an ever-growing role in MELs operations—from uninterruptible power supplies to electric bikes to robot vacuums.

In general, saving energy is not a major driver for more efficient power conversion in MELs. However, manufacturers of MELs have incentives to make power conversion more efficient, including reduced waste heat and weight, extended range and operating time, and reduced parts count. These can improve the product's performance, reduce manufacturing costs, or improve reliability.

While many specific technologies can improve power conversion efficiency, most exploit one or more of the following principles:

Avoid multiple conversions – Many devices have multiple stages of power conversion. For example, light-emitting diode drivers step-down and convert alternating current to direct current (AC/

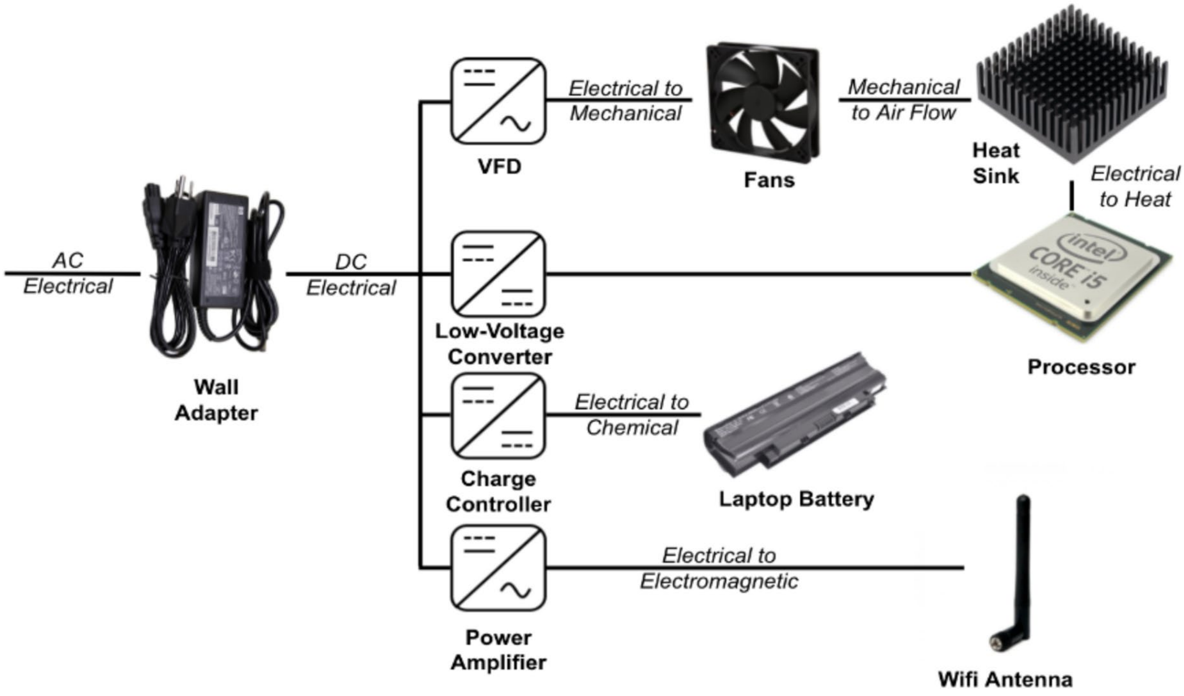


Fig. 10 A computer has many types of power conversion, many of which are sequential, resulting in multiplicative losses. For MELs, electrical power conversion is the first conversion, followed by other types. All power losses are heat

DC) before the dimming stage. Sometimes, clever design can consolidate or avoid these stages.

Improve existing conversions – Where the design cannot avoid conversion stages, individual stages can be improved through enhanced technology that improves their efficiency. For example, the transition to gallium nitride semiconductors has shown promise to reduce device losses in many types of power converters.

Integration and spinoffs – MELs design may repurpose highly-efficient technology from other end uses or combine the functionalities of several components into a single specialized component. For example, some power switches now have an integrated gate driver, which eases design and reduces circuit-board losses.

While these principles may have a positive impact on efficiency, cost, and performance, component modularity may suffer. For example, consolidating conversions may require the use of specialized converters that perform multiple functions specific to a single device. This loss of modularity may incumber design processes and supply chains.

Other cross-cutting technologies in MELs

Other technologies and characteristics are present in many MELs. These are listed in Table 1 (along with those already discussed earlier) (Table 2).

These technologies appear in a wide range of products, sometimes using the same component or solution. In this way, an innovation in the underlying technology can lead to energy savings in many, diverse products.

Cross-cutting MELs research opportunities

We led a series of workshops in collaboration with industry and research institutions on MELs energy consumption. Research opportunities emerged based on the cross-cutting approach outlined above. A general theme of the activities is that they target system-level or design solutions that confront multiple inefficiencies across many MELs with similar componentry or behavior. We list some research opportunities and recommendations.

Table 2 Cross-cutting technologies present in MELs

Cross-cutting Technology	Notes
Power management	Discussed above
Power scaling	Discussed above
Power conversion, power electronics, and DC distribution	Discussed above and includes any type of semiconductor-based power conversion electronics and can perform any type of electrical conversion to or from AC to DC). DC distribution avoids power conversions between AC and DC through building- (power distribution) and device-level design
Communications/Networking	Maintaining a connection to a network in wait of external commands requires additional computation by a device's central processor
Interfaces/Displays	Many MELs require information to be conveyed visually to the user. Commonly, displays will operate with a backlight that illuminates the entire screen at once and block unneeded light rather than control individual pixels
Measurement/Estimation	Measuring or estimating energy use of the device, and reporting energy use to users and vendors is a prerequisite for a number of energy-saving intervention strategies

1. Develop low-latency recovery strategies. Fast response times to recover from sleep modes and other automated responses should ideally make energy efficiency measures unnoticeable to users. If customers see/feel the impacts of energy management solutions, they may be inclined to disable them.
2. Improve mechanical power scaling over a wider range of output with variable-capacity drives and minimize cycling to the greatest extent possible. At the same time, it is important to collect more primary data on power scaling.
3. Consolidate power conversion stages. Many MELs contain multiple stages of power conversion that can be combined or avoided through clever design topologies and techniques.
4. Match internal voltages in MELs. Voltages for many components have emerged organically rather than optimized for performance. This results in multiple DC-DC conversions and losses.
5. Treat power and communications in conjunction as building systems. More and more, these two services are delivered in the same medium and are interdependent.

Ultimately, each device must be designed and optimized to meet its specific requirements. However, the availability of components, methodologies, and protocols that have already been optimized for energy efficiency makes efficient design easier and likely to be more successful. These recommendations can direct future research investments in MELs most effectively. Other studies have shown that research is often distributed widely to many companies, reducing duplicative efforts, which can lead to the commercialization of products with unique functionality, applied across multiple industries over many years. (Fleming et al., 2019).

Conclusions

At about one quarter of electrical consumption in buildings, MELs have a significant and growing portion of building electric use. Conventional approaches to reducing equipment energy consumption are less effective for MELs because of their diversity and the relatively small consumption of each device. Research and development can instead focus on technological functionalities common to many devices. We recommend that researchers pursue energy savings opportunities through cross-cutting functionalities, such as power scaling, power management, and power conversion. These improvements will both improve efficiency and lower costs, which can apply to a wide range of products.

We investigated several cross-cutting opportunities for improving the energy efficiency of MELs, three of which are discussed in this paper. This investigation highlights the diversity of expertise required to reduce electricity consumption of MELs, which include: electronics, communications/networks, mechanical engineering, and human factors. Researchers, engineers, and manufacturers can together draw upon these insights to reduce the steady growth of MELs energy consumption in buildings.

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Author contributions WM proposed and led the overall MELs project. AM and JB developed the conceptional approach proposed in the manuscript. AM, JB, and WM obtained data and contributed to the analysis. WM and AM conceived and prepared the illustrations. AM and JB prepared the manuscript, but with critical contributions from WM.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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