Low Power but High Energy:
The Looming Costs of Billions of Smart Devices

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Abstract

Individually, wall-powered Internet of Things devices are small: in form factor, in complexity, in function, and in power draw. However, at scale, and certainly at the scale optimistic forecasters project, these small devices add up to be a big energy problem. Just adding a single two watt sensor to each US building would add to more annual energy consumption than some small countries. Wall-powered IoT devices are also easier to create than their energy-constrained (i.e. battery-powered) counterparts, and marketed as more convenient (no hub required!), leading to their continued growth. Yet, unlike other energy consuming devices, there are no Energy Star (or equivalent) standards for smart devices. Despite having very infrequent active times, they draw power for functions like AC-DC conversion, wireless communication, and wakeup word detection continuously. Further, the discrete nature of devices and siloed nature of IoT ecosystems leads to significant redundancy in IoT devices.

We posit that new techniques are needed to reverse this trend. This includes new techniques for auditing devices, systems that leverage existing devices rather than requiring new ones, and architectures that have less reliance on the cloud (and the energy overhead of network usage and cloud compute). The IoT is pitched to improve energy efficiency and reduce users' carbon footprints, but we need a new research agenda to ensure the devices themselves are not the next problem.

1 Introduction

Decades of research into low power wireless embedded systems has made ubiquitous battery-powered devices possible. Recognizing the negative impacts of disposable batteries [13], research continues to lower power requirements further, making devices low power enough to operate on scavenged energy [11]. The underlying motivating intellectual challenge has been how to make increasingly interesting and useful computers operate with increasingly less energy. When energy is *not* constrained, however, even for Internet of Things (IoT) and other embedded devices, the research questions shift as managing limited energy is no longer the pressing concern. Mains-powered devices do not have to fret over every last joule, instead relying on stable power from the grid. And, as even carelessly implemented mains-powered devices still likely only draw a handful of watts, individually they pale in comparison to the energy consumption of other common loads. This has kept wall powered IoT devices under the radar from an energy consumption perspective.

But, the Internet of Things is plural for a reason, and the key value proposition has always been its purported scale. This has unfortunate implications for sustainability: while an individual mains-powered device may consume a relatively insignificant handful of kilowatt-hours of electricity per year, at national or global scale, the consumption adds up. Consider: a popular commercially available air quality sensor draws just 1.76 watts in normal operation [3]. As the COVID-19 pandemic has highlighted, monitoring indoor air quality is a pressing need, but deploying just one of these sensors per building in the US's 5.6 million commercial buildings [1] would add 237 MWh of energy consumption, *per day*. Annually, this is more energy consumption than some small countries [2].

Additionally, the IoT revolution has reversed the continuously improving power trend for certain appliances by making them "smart". For example, energy star requirements and technology advances dramatically lowered the power draw of televisions, but adding connectivity and additional features has increased their standby consumption [14]. Similarly, traditional light bulbs are physically disconnected when turned off, whereas smart bulbs constantly draw a trickle of energy to remain networked whether used or not [26]. Introducing always-on voice assistants is another new source of continuous energy consumption in an IoT-enabled world.

Using an AC-DC converter to power IoT devices provides simplicity and reliability, but it comes at the cost of adding an additional, albeit small, load to the electrical grid. Reducing energy consumption of buildings is a key national priority [4], and while additional sensing is an invaluable asset in that goal, it is critical that the solution does not exacerbate the problem. New research is needed to enable IoT devices to leverage the benefits of reliable mains power while being energy frugal in line with existing sustainability efforts.

How can future IoT devices and systems, particularly mains-powered devices, reduce their energy consumption? We identify three general strategies. First, is a traditional approach: reduce the energy consumption of individual devices. Existing work in this area has addressed this as a matter of necessity when using constrained power sources such as batteries. However, the lack of a fundamental technical limit introduces new challenges. Second, reducing the number of devices would reduce overall energy use. One approach to accomplish this while not diminishing the IoT's potential is by extending the longevity of devices. But, many devices are developed for a relatively short time horizon (e.g. 3-5 years). And third, leveraging existing devices rather than adding additional ones would permit increased functionality with less or no additional energy consumption. However, existing devices typically target a specific function and are not equipped to adapt over time.

To further analyze this issue we explore and describe a range of challenges limiting progress in this domain, despite a major traditional obstacle (i.e. operating energy) not being a limitation. We also identify potential opportunities and developments that could have a positive impact and support a more energy optimized Internet of Things. Finally, we describe several research questions this area raises that could potentially be the starting point for new research into addressing the growing energy consumption of IoT devices.

2 Challenges and Opportunities

We identify several challenges that lead to or exacerbate the growing energy consumption of mains-powered IoT devices.

2.1 Development Impediments

Despite significant progress on low power computing, developing robust systems with energy constraints remains challenging. Ensuring hardware and software is functionally correct itself is difficult, and simultaneously ensuring that a device is correctly energy optimized adds additional complexity. Even smartphones backed by large companies often struggle with battery usage issues [7]. Low power and energy optimized compute frameworks are not ubiquitous and commonplace where low power development is as simple as traditional embedded computing. When energy is not constrained (i.e. a device has mains power), the development cost to use energy frugally is typically too high.

Similarly, low power wireless protocols have not kept pace with Wi-Fi's ubiquity and ease of use for both developers and users. Wi-Fi in IoT is often a selling point, as users already have Wi-Fi infrastructure and do not require an additional hub. Wi-Fi is also generally reliable and interoperable. Low power alternatives, such as Bluetooth Low Energy, ZigBee, EnOcean, or ANT, are typically siloed and do not provide the same general purpose connectivity that Wi-Fi does. When energy is not constrained, the advantages to using a lower power wireless radio are virtually non-existent.

Additionally, energy unconstrained devices generally do not incur runtime tradeoffs, and developers can be conservative when configuring the device's operation to handle a variety of potential use cases. For example, when selecting a sample rate for a sensor without energy constraints and a clear understanding of the required sample rate, the developer can choose a relatively high sample rate to support use cases which may need the higher rate. A major challenge for developers is clearly understanding the utility of various device operations, and configuring operation to balance utility and energy consumption. However, the utility may be context and use-case specific, suggesting that devices need to adapt at runtime, and not be fixed at design time, to select the correct operating point.

2.2 Network Redundancy

Many energy challenges emerge when many devices are deployed in quantity. One such challenge is the redundancy of many IoT devices which are designed to operate as a single device or in collaboration with many other devices. When in a network, these devices are often individually overprovisioned, each equipped to perform their most complex task which in practice happens infrequently. Consider as an example a hypothetical voice assistant capable of running a speech recognition model on its local hardware. When a single assistant is on the network, it must have the compute resources to run the model. However, voice assistants are typically used at most a handful of times per day [24] meaning the compute resources are generally idle. A second voice assistant then does not need to duplicate the compute resources and instead could leverage the existing device. However, as devices in the standalone case must be self-sufficient, they remain independent even in larger deployments. This incurs a larger energy cost as compute energy cost generally positively correlates with increased compute capability. This same issue occurs with wireless radios, as all devices are capable of communicating with the central network, even if they could coordinate locally to save energy and have a single device connect to the main network.

2.3 Lifecycle Issues

IoT devices are generally designed to be fixed-function and fixed-purpose, and their capabilities remain generally fixed during their entire lifespan. This then necessitates adding additional devices to increase functionality, and incurring the additional energy cost. As IoT devices are typically closed, non-programmable platforms, there is little opportunity for ongoing development and user-guided customization after the device is manufactured which would permit the device to upgrade and change as the user's requirements change. This stands in stark contrast to the modern smartphone platform, which has a rich programming environment and a constantly updating suite of user-selectable programs available. If IoT devices had a similarly expressive platform for customization, devices could potentially perform multiple tasks and reduce the total number of required hardware devices.

2.4 Limited Regulation and Market Pressure

Larger electronic appliances, such as televisions and refrigerators, are in many regions subject to specific regulations on energy consumption and energy use disclosure. However, these regulations do not extend to general IoT devices. Further, as the impact of IoT devices on a single consumer's overall energy consumption is relatively minimal, consumers have little incentive to consider energy when purchasing IoT devices. This void generates little pressure on manufacturers to consider and prioritize energy efficiency. Developing regulations is difficult, however, as unlike appliances such as refrigerators which have a very clear and specific goal, IoT devices are much more diverse and deciding what is acceptable energy use is challenging.

2.5 Context-Based Optimizations

IoT devices are often over-provisioned, whether for energy availability, sample rate, communication capacity, compute capability, or other parameters, when there is uncertainty about how the device will operate and how it will be used. New techniques that distil contextual information about a device's operating environment (e.g. how critical the device is, whether the device is likely to be used, or how its data is being processed) can then inform how the device should operate to increase efficiency. For example, a smart voice assistant will never be activated when no one is present. If that contextual information was available, then when there are no users nearby the device could enter a very low power mode. Despite its potential for improvement, acquiring the context remains challenging.

2.6 New Embedded Operating Systems

Many operating systems and software libraries for embedded systems have sacrificed flexibility in exchange for resource optimization and small memory/code footprints. However, new OS designs for resource constrained embedded devices, such as modern FreeRTOS [6] and TockOS [16], provide more capable multiprogramming capabilities. This opens the possibility for more flexible devices going forward which can be customized and reprogrammed after deployment. Yet, while the on-device foundations are beginning to emerge, the broader ecosystem for usable reprogramming and customization is still lacking.

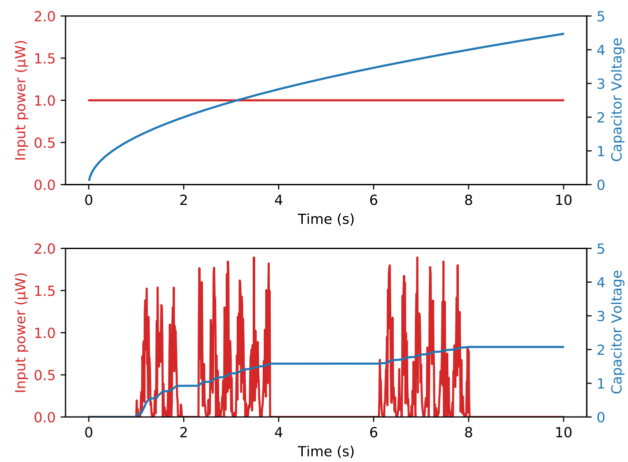

Figure 1: Comparison of reliable versus unpredictable input power. The top figure shows a low harvesting rate (1 µW), but a capacitor charges in a predictable fashion. On bottom, the input power is intermittently higher, but the time when the capacitor reaches a threshold voltage is less deterministic.

2.7 Leveraging Proximal Compute Resources

Hardware redundancy leads to unnecessary energy consumption, but as the Internet of Things continues to scale, the opportunity for resource sharing and specialization also increases. That is, future devices may not need be self-sufficient, and instead expect to operate collaboratively with the network, and only include hardware uniquely necessary for its overall goal (for example a specific sensor modality). Leveraging existing compute resources leads to a more efficient use of resources, and separating concerns reduces optimization effort. Further, a more locally centralized architecture is easier to upgrade, as replacing a single device with newer hardware can benefit many nearby devices.

3 Research Questions

Ensuring the Internet of Things itself is sustainable prompts several new research opportunities and underlying research questions (RQ).

3.1 Reliable but Meager Power

Mains-powered devices enjoy reliable *and* essentially unlimited power, which simplifies many embedded systems and networking challenges, including communication, reliability, and security. However, requiring a physical connection to power stands as a major deployment impediment. Opposite on the energy spectrum are small energy-harvesting devices which are tasked with operating on the intermittent and unpredictable energy they can scavenge nearby. Being self-powered increases deployment flexibility, but complicates device software and operation. Numerous techniques exist to help mask intermittency [17], but the unpredictable nature of harvesting energy is a constant concern.

Is it possible to merge these two extremes to achieve both reliability and ultra low power operation? Traditionally, rectifying and regulating AC to usable DC for a digital system incurs efficiency losses and results in bulky devices. To a first order, AC-DC output power scales with converter size, so shrinking the supply power not only reduces the overall power draw but also reduces the physical form factor. The challenge is then supply power is then too low to run typically microcontrollers and radios continuously. Leveraging intermittent computing techniques, however, may enable devices to operate while "charging" from the meager input power. Unlike typical energy-harvesting systems, however, the input power is constant and predictable, as shown in Figure 1. *RQ*: How do intermittent computing approaches function when incoming energy is predictable? What optimizations can exploit the predictability of energy?

3.1.1 Realizing Meager Power

Another challenge of ultra-low power but reliable IoT devices is accessing reliable sources of energy with low or no energy overhead. Commercially available AC-DC power supplies target multiple watts of output power, and focus on efficiency at expected output power levels. Optimized and ultra-low power output converters (less than 100 µW output) are needed to provide reliable power at very low levels.

Energy-harvesting from constant sources is another potential opportunity. New magnetic field energy harvesters capture energy in the proximity of a magnetic field [15, 23] and could potentially provide constant power sources to IoT devices. Other harvesting sources such as microbial fuel cells [18] may similarly be able to provide constant power. *RQ*: What energy sources are available in IoT application locations that can supply a constant trickle of power? What new circuits and system architectures are needed to integrate these into IoT devices?

3.2 NILM for Devices

Energy Star [5] and similar regulations have led to significant energy reductions for covered appliances as attention and monitoring made energy use an important consideration for appliances. However, there is currently no comparable regulation for IoT devices. In part, this is due to the complexity and diversity of IoT devices, and the difficulty in benchmarking what an expected or typical level of power draw is given the type of the IoT device. Measuring the power draw of a device is straightforward, but contextualizing that consumption is more difficult.

Larger systems, such as buildings, face the same issue where measuring total power is straightforward, but detailed insights are more difficult to obtain. Non intrusive load monitoring (NILM) [10] is one technique for disaggregating electricity consumption into individual loads. Extending NILM techniques to a single device may permit analyzing the detailed operation of the device using just measurements of its total power draw and without the ability to modify or inspect the device's code. This breakdown can then provide understanding on how the device is using energy for different operations. This effectively disaggregates the device's operation, making it more feasible to compare various devices and define standard consumption profiles. This transparency can lead to more competition and provide the basis for fair regulation. *RQ*: How can NILM techniques extend to single devices?

3.3 Sharing Resources

IoT devices are often designed to operate both individually and as part of a collective, and the actual function depends on individual deployments. For example, a voice-based assistant device can operate as the only IoT device in a home. It can also operate as part of a network either controlling other IoT devices or coordinating with other voice assistants (for example to play music). This flexibility leads to unnecessary redundancy, as each device must include the compute capability as if its the only deployed device. From an energy perspective, the marginal cost of running additional instructions is fairly low, whereas the cost of running an entirely new microcontroller and all of the supporting circuitry is much higher. Thus, sharing compute resources that are already powered rather than requiring each IoT device to be self sufficient could lead to overall energy savings.

Many IoT devices are used infrequently, but today must be provisioned with the hardware required for the most complex task it must execute (and likely the most complex task the designers intend to execute in the future). The result is that at any given time there is likely significant spare compute available within an IoT network. If devices had the capability to leverage these spare resources they could reduce their own compute requirements and instead leverage the spare cycles from other devices. Devices could then downsize their onboard compute to reduce their own energy consumption. *RQ*: What network and system-level architectures are needed to enable device-to-device compute cooperation? How can IoT software be designed to scale with available nearby compute without needing to over-provision the IoT device's CPU?

3.4 Net Negative IoT

One key application-level goal for the Internet of Things is to improve sustainability, and reduce energy use. The common paradigm is that consistent, real-time sensing and control leads to more optimized systems and less energy waste. However, these types of deployments typically do not consider the energy cost of the sensing and actuation devices themselves. In general, for the IoT to be successful in many applications it as a whole must not increase energy use or create additional sustainability issues. What would IoT devices look like if they were all net energy negative? That is, if every IoT device was designed to reduce more energy than it consumes?

At an individual device level this is likely not possible. However, as a network, the data generated from each device or the actuation capability of each device provides another resource for that network to optimize the house, building, factory, or environment where the devices are deployed. Future networks may expect that devices can offset their own energy consumption by increasing the efficiency of the overall network. This may require new abstractions and API design, where perhaps energy credits are required for devices to join and participate. Devices may only get access to local services (e.g. storage or Internet connectivity) if they demonstrate energy reduction capabilities. For consumers this would effectively reduce the cost of smart devices, as their initial cost would be offset by ongoing energy savings. *RQ*: How can a network of IoT devices ensure they generate energy savings greater than their cumulative energy consumption? What new software abstractions are needed to enable heterogeneous devices to collaborate towards overall energy reductions?

4 Ancillary Challenges

We primarily focus on the energy challenge of devices themselves in the context of a specific deployment. However, the Internet of Things more broadly includes large-scale data collection and processing. From a device design perspective, the energy costs of transmitting, collecting, storing, and processing data are ignored. However, there is a real energy cost in terms of the networks and routers used to transport data, and the data centers where data are stored and processed. These costs are nearly entirely hidden from developers and users.

From an energy consumption perspective, new tools are needed to be able to consider these costs both when designing new systems and at runtime. At runtime, devices could make a decision based on the energy cost and expected utility of using the network or the cloud. At design time, developers could compare different architectures (including edge-focused designs) not just in terms of performance or privacy, but also in terms of energy.

5 Related Work

One general technique for addressing IoT device energy consumption is reducing the energy use of devices themselves, and this has been a major research focus. Various works targets a range optimizations, from ultra-low power radios [8] to improving microcontrollers [20, 25], as well as addressing leakage and configuring voltage [19,21]. These improvements benefit mains-powered and battery powered devices, but must be easily integrated or incentivized for traditionally energy-unconstrained devices.

Others have examined the impact various loads and IoT devices can have on overall energy consumption in various contexts. For example, devices in standby mode can similarly add up to significant consumption [12] and various techniques may be able to help. IoT devices specifically with always-on connectivity can use excessive energy [26], and potential solutions exist but are not widely implemented. The connectivity of IoT devices and their use of the cloud also contributes to energy consumption, which can be quantified [22]. Various networking architectures also have direct impacts on energy [9].

6 Conclusion

Left unchecked, the convenience of implementing IoT devices with mains power can lead to a new energy disaster where IoT devices are a significant consumer of energy on a national scale. While rigid energy constraints (i.e. batteries or energy-harvesting) have so far driven research in low power computing, an opportunity—and need—is arising to not ignore mains-powered devices. We identify a range of potential opportunities for new research focused on increasing the utility of IoT devices, while simultaneously reducing their own energy footprint. This is critical to prevent the Internet of Things from becoming its own sustainability problem—ironically counteracting one of its own purported benefits.

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