Electronic Devices & Networks Annex
EDNA

Getting to Zero: An Evaluation of Zero Network Standby Power

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International Energy Agency

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Electronic Devices & Networks Annex
EDNA

The EDNA Annex (Electronic Devices and Networks Annex) of the 4E TCP is focussed on a horizontal subset of energy using equipment and systems - those which are able to be connected via a communications network. The objective of EDNA is to provide technical analysis and policy guidance to members and other governments aimed at improving the energy efficiency of connected devices and the systems in which they operate.

EDNA is focussed on the energy consumption of network connected devices, on the increased energy consumption that results from devices becoming network connected, and on system energy efficiency: the optimal operation of systems of devices to save energy (aka intelligent efficiency) including providing other energy benefits such as demand response.

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GETTING TO ZERO:
AN EVALUATION OF ZERO NETWORK STANDBY POWER

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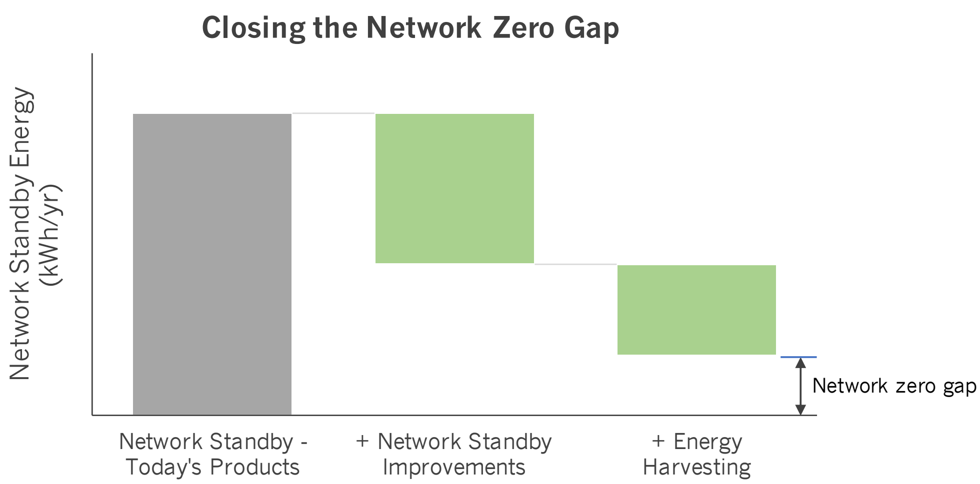
EXECUTIVE SUMMARY

As the number of networked products rapidly proliferate, the energy efficiency policy community has stepped up efforts to mitigate the energy impacts of network standby (network standby is a function that allows a product to maintain a network connection and await a network "trigger" or message to be woken as needed). One strategy takes the concept of net zero energy, now used commonly to address energy use in buildings, and applies it to the network standby function itself. A zero network standby or network zero device, therefore, is that use a combination of deep power management of network standby components, energy harvesting technologies, and energy storage to generate (and potentially store) enough energy over the course of a year to meet the needs of the network standby function. As with zero net energy buildings, a zero network standby or network zero device would first employ the maximum amount of efficiency improvements, followed by energy harvesting, in an attempt to achieve the net zero goal. In reality, some devices may fall short depending on the degree of power management capable or the amount of energy that can feasibly be harvested. We call this remaining balance of energy the "network zero gap." (figure below).



The path toward network zero and the network zero gap

This report examines the feasibility and economics of achieving network zero in three different products: mini-split HVAC systems, smart speakers, and connected light bulbs. We investigate the range of network standby efficiencies that may be achievable under different degrees of power management, based on the findings of the Electronic Devices and Networks Alliance's (EDNA) *Network Standby Power Basics* report (EDNA 2018a). We then examine the amount of energy that could feasibly be harvested using today's energy harvesting technologies (EHT) and assuming a range of environmental conditions. Our analysis also identifies the gap that may still remain. The report also briefly compares the economics and e-waste impacts of network zero devices to building-scale energy harvesting and storage solutions to offer a point of comparison.

We find that with sufficiently aggressive power management of network interfaces and attention to power conversion efficiencies, it should be feasible to achieve network zero in today's devices. Reducing network standby power requirements is the single largest factor determining the feasibility of the network zero concept. Indoor environmental conditions (ambient light levels, temperature, etc.)

also play an important role once EHT is employed, but network zero is all but impossible without first cutting the power draw of network standby functionality to the tens of milliwatts. The network zero gap for indoor products that we investigated can be on the order of 1 to 10 kilowatt-hours per year — basically insurmountable by current EHT — unless network interfaces are allowed to enter their lowest power states. Products with direct access to solar radiation, such as HVAC equipment, can achieve network zero more easily, although reductions in network standby power requirements are still a key piece of the strategy.

The complete network zero solution, including EHT, is still cost-prohibitive in most cases due to the high cost and low efficiency of most EHT today. Although this may change as the market for various EHT matures, it bears repeating that the first step on the path to network zero will be to reduce network standby power. EHT should be added only after designers have maximized cost-effective energy efficiency improvements, if anything to reduce costs.

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1. INTRODUCTION

The International Energy Agency's One Watt Standby initiative from the early 2000s achieved great success in reducing standby energy consumption of consumer products. These gains may be overwhelmed, however, by steady increases in the number of network-connected devices unless efforts are made to reduce network standby power. The number of network-connected devices is forecast to grow from 8.4 billion in 2017 to over 20 billion by 2020 (Gartner 2017). Although network-connected devices and appliances may enable substantial energy savings at the system level, for example in a building or transportation system, the fact that more devices are connected within the system and potentially drawing significant additional power for that connectivity means that their incremental power partially offsets potential savings (IEA 2017). In fact, inefficient networked standby could waste about 740 TWh per year by 2025 (IEA 2014, 2017).

Continued advances in low-power network technologies coupled with new energy harvesting technologies have led a variety of IEA stakeholders to investigate whether "zero energy" (Ellis, Siderius and Lane 2015) or "zero watt standby" (Meier and Siderius 2017) could become the next frontier for appliance energy efficiency policy. This concept may take various forms in practice. Meier and Siderius (2017), for example, introduce "standby zero" or "standzero" applied to electrical products that operate for short periods without relying on mains-supplied electricity. More broadly, Ellis et al. (2015) use the term "zero energy" appliances to indicate a stand-alone appliance that derives its energy from non-grid renewable sources or, if grid-connected, exports an equal amount of energy as it consumes over a given period. In this work, we apply the concept of "standzero" specifically to network standby.

For the purposes of this report, we apply the concept of standby zero down to the network standby function itself. Network standby is a function that allows a product to maintain a network connection and await a network "trigger" or message to be woken as needed. It follows that in this report, we examine zero network standby devices. These are products that use a combination of deep power management of network standby components, energy harvesting technologies, and energy storage to generate (and potentially store) enough energy over the course of a year to meet the needs of the network standby function. As with zero net energy buildings, a zero network standby or network zero device would first employ the maximum amount of cost-effective efficiency improvements, followed by energy harvesting, in an attempt to achieve the net zero goal. In reality, some devices may fall short depending on the degree of power management capable or the amount of energy that can feasibly be harvested. We call this remaining balance of energy the "network zero gap." (Figure 1)

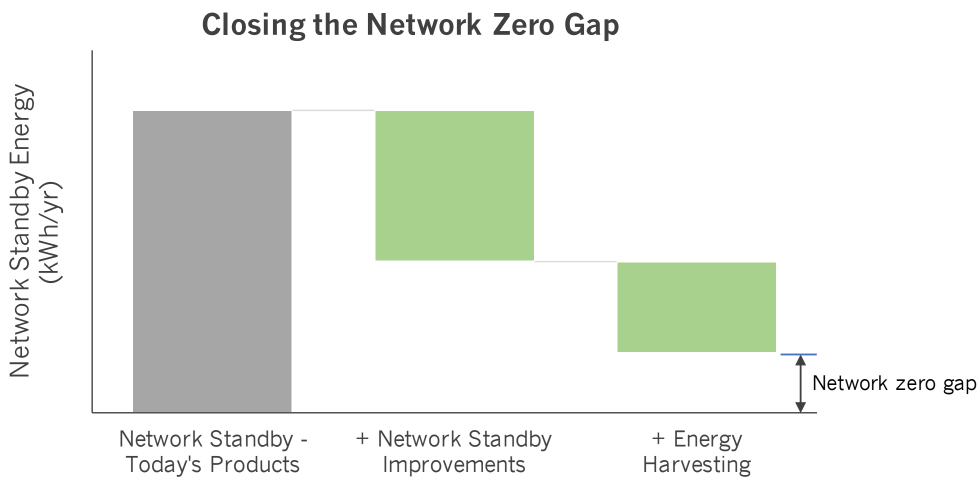

Figure 1: The path toward network zero and the network zero gap

Although one can conceive of several compelling use cases for zero network standby devices, several important questions remain unanswered to date, namely:

- Given the state of current enabling technologies (including efficient network standby components, energy harvesting, and storage), under what use cases and conditions is network zero technically feasible?
- In cases where network zero is not yet feasible, what is the size of the network zero gap that needs to be overcome?
- Is network zero currently cost-effective or at least cost-neutral?
- What are the non-energy impacts, such as material disposal, of network zero devices?
- How do cost and non-energy impacts compare to building-scale electricity generation and storage alternatives?

In this report, we address the research questions above by examining three potential applications for zero network standby concepts: connected mini-split air conditioners (ACs) and heat pumps (HPs), smart speakers and connected light bulbs. For each use case, we determine the technical feasibility, economic, and non-energy (such as material and disposal) impacts of the energy harvesting and storage required to provide the needed power for the network standby functionality. We find that in some cases, today's energy harvesting and storage technology can indeed meet a product's network standby power requirements.

We then qualitatively compare the cost and non-energy impact of device-level energy production and storage to building-scale photovoltaic (PV). This broader context is important to convey the merits of zero network standby to policymakers alongside other energy efficiency strategies.

Finally, we examine emerging and innovative means of achieving network zero that may help close the current gap between technically feasible solutions and fully network zero. We then provide policy recommendations and a near-term roadmap of suggested activities for this topic.

2. NETWORK ZERO DEVICES – DEFINITIONS AND OVERALL APPROACH

In this report, we apply the concept of standby zero specifically to network standby by examining whether network-connected loads may be capable of consuming zero network standby energy over the course of the year through a combination of strategies, including: reductions in network standby energy itself, energy harvesting technologies, and device-level energy storage (if necessary). For the purposes of this discussion, we define the network standby function as a state in which a product maintains a network connection and awaits a network "trigger" or message to be woken as needed (EDNA 2018a).

Based on the work of Meier, Siderius, and others, we foresee three potential use cases for network zero products (Meier and Siderius 2017, Ellis, Siderius and Lane 2015):

1. **Load shifting and deferred consumption** – devices employ energy storage such as supercapacitors or batteries protect against grid failures and provide network standby functionality for a limited period of time (on the order of hours) in the absence of grid power. These solutions may consume slightly *more* energy than products without storage given the losses inherent in battery charger systems, unless designers significantly improve efficiency associated with network standby functions. The primary motivation behind such use cases would be resiliency and reliability, which is already highly valued in network or telecommunications applications, for example.

2. **Net zero network standby** – devices employ a combination of energy efficiency improvements and energy harvesting technology (EHT) to eliminate a significant portion of total network standby power requirements on balance over the course of a year. For certain devices, it may be possible to meet or exceed network standby energy requirements, in which case these would be considered net zero or net positive. These scenarios are analogous to zero net energy (ZNE) buildings, only the system boundary is set at the device level and only for the portion of annual energy consumption associated with network standby. The primary motivation behind such use cases would be optimal efficiency and minimal network standby energy use.

3. **Grid resilient network standby** – a resilient network standby device would have sufficient energy harvesting and energy storage to provide for all of its network standby energy consumption, regardless of the presence of the grid (it would still require grid power for primary functionality). This use case is essentially a hybrid of cases 1 and 2 above and would result in net energy savings.

In this work, we focus on use cases 2 and 3, as these relate most directly to energy efficiency. Case 1 is potentially of interest from a resiliency or load flexibility standpoint, but is not expected to generate energy savings, so has been excluded from our analysis.

3. NETWORK ZERO AT THE DEVICE LEVEL

3.1. GENERAL METHODOLOGY

In this section, we examine the technical and economic feasibility of achieving zero network standby for three mains-connected product types: mini-split ACs and HPs, smart speakers, and connected light bulbs. These products were selected due to their network connectivity, increasing popularity and market growth, and based on preferences of project steering committee members. For each of these use cases, we examine the range of achievable network standby power that can be achieved based on prior research, select an EHT that is best suited for the product, estimate how much energy that EHT can provide (with and without storage), and compare to the product's required network standby energy. From these estimates, we can determine which applications of net zero network standby and grid resilient network standby may currently be feasible and identify the remaining network zero gap that may remain. We then conduct an economic analysis of these use cases to provide an order-of-magnitude estimate of economic feasibility.

3.1.1. Network Standby Component Assumptions

All of our use cases incorporate one or more network interfaces. To assess the overall power requirements for network standby, we rely on EDNA's 2018 *Network Standby Power Basics* report (EDNA 2018a), which provides a range of component-level power consumption values for various interfaces when those interfaces are providing network standby functionality (i.e. they are in an idle or non-transmitting state and are waiting to be reactivated with a network trigger or signal). The report provides a very wide range of component power estimates. For a given interface, the range from low to high may span two orders of magnitude. As stated in EDNA (2018a) this range represents "the extent to which component-level power management is deployed and optimized" in these products. Devices that are aggressively power-managed may achieve the low end of the range; devices with minimal power management will tend toward the high end. The degree of power management optimization will vary by product and use case, depending on the manufacturer's capabilities, their customers' tolerance for latency associated with waking devices from a network standby state, and related factors.[1] This report does not delve extensively into these issues; however, we assume that any device designed for network zero will need to be robustly power-managed and -optimized. Therefore, in this report, we assume worst-case component power consumption is the *middle* of the range presented in EDNA (2018a) (Table 1).

[1] "Network Standby Basics" provides a more comprehensive discussion of the various factors that influence the power requirements of the network standby function.

Table 1: Network Interface Power for Network Standby Functionality (Source: EDNA 2018a)

Network Interface	DC Component Power (mWdc)		
	Low	*Mid*	*High*
Fast Ethernet port	252	615	977
Gigabit Ethernet Port @ 10 Mbps	30	414	798
Gigabit Ethernet Port @ 100 Mbps	107	449	790
Gigabit Ethernet Port @100 Mbps (EEE)	40	415	790
Gigabit Ethernet Port @ 1000 Mbps	256	643	1029
Gigabit Ethernet Port @ 1000 Mbps (EEE)	41	535	1029
IEEE 802.11n radio Wi-Fi	3	741	1478
IEEE 802.15.4 Zigbee	0.2	81	161
IEEE 802.15.4 Bluetooth LE	0.2	43	86
IEEE 802.15.1 Bluetooth	0.9	228	455

Component-level power is typically delivered at direct current (DC) voltages below 3V and must go through several conversion stages prior to use by integrated circuits. Therefore, we adopt several power conversion efficiency ranges as well, based on input from industry stakeholders. We assume that power from the grid must first be converted and rectified from high-voltage alternative current (AC) in the range of 120 to 230Vac down to a lower DC voltage in the range of 12Vdc. This can occur with an efficiency of approximately 70% for the power levels required in network standby. We also assume an additional 10 to 50 mW of fixed losses through the AC-DC power supply. This DC voltage must be further down-converted to lower voltages by a DC-DC power supply, and these are assumed to have efficiencies of 75 to 90%. For the purposes of this report, we further assume that any power generated by EHT must be down-converted before it can be used by electronic components. Therefore, we take DC-DC conversion losses into account when establishing DC power budgets that must be met by EHT. For grid resilient network standby cases in which we include energy storage, we account for 80% roundtrip efficiencies for the collective battery and charge control circuitry (Homer Energy 2018). Figure 2 illustrates the simplified power conversion topology adopted for this report and the assumed efficiency ranges for power conversion processes.

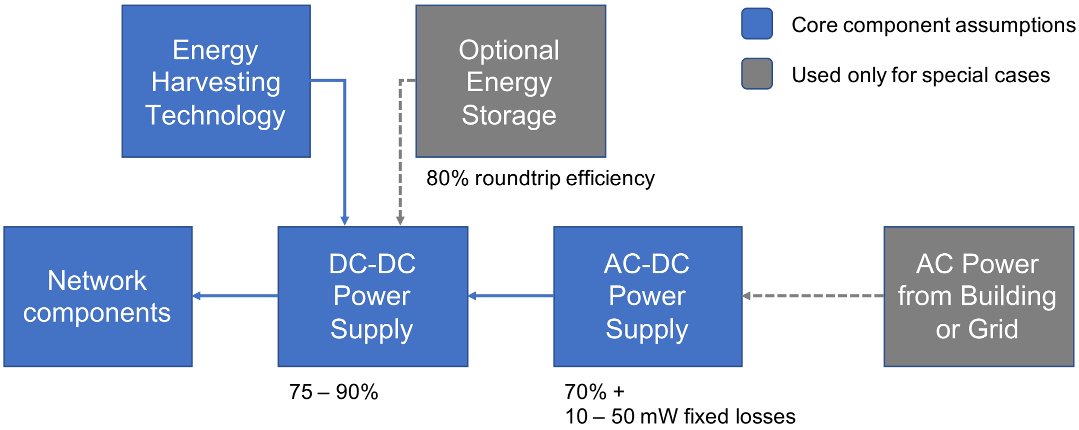

Figure 2: Power flow and conversion efficiencies

3.1.2. Zero Network Standby Assumptions

Several EHT can generate significant energy under favorable conditions, including:

- **Photovoltaic (PV) –** Converts solar energy into usable electricity. PV systems are found from the megawatt to the milliwatt range producing electricity for a wide range of applications from wristwatches to grid-connected PV systems.
- **Electromechanical generators –** Convert rotational motion (e.g. from clothes dryers or clothes washers) into electricity.
- **Thermoelectric generators (TEGs) –** Convert temperature differences into usable electricity. The larger the difference in temperature across the two sides of a TEG module, the larger the amount of energy generated.
- **Piezoelectric transducers –** Convert mechanical vibrations into electricity. When force is applied on a piezoelectric crystal or fiber, the static structure is deformed, shifting charge carriers and generating electrical current (EDNA 2018b).

Detailed assumptions for each use case are presented in Appendix 1. For each use case, we assess the cost effectiveness of a *net zero network standby* configuration and a *grid-resilient network standby* configuration compared to the standard mains-powered configuration. For net zero network standby, we examine the EHT requirements needed to achieve net zero network standby energy over the course of a year under a range of component power budget scenarios. This may not be feasible in all cases, due to space constraints in or on the device itself. In other cases, it may be possible to generate significantly more energy than what the network standby function alone requires (i.e. net positive). For the grid-resilient network standby case, we include device-level energy storage as well to store sufficient self-generated energy to maintain network standby functionality for a full day, even in the absence of grid power.

Table 2: Scenario Descriptions for Device-Level Analysis

Net Zero Network Standby Scenario	Grid-Resilient Network Standby Scenario
• Power assumptions for network-related components built up from EDNA (2018a) and industry comments on power delivery efficiency • Include appropriate EHT and evaluate ability to meet some or all of the power budget for network standby	• Power assumptions for network-related components built up from EDNA (2018a) and industry comments on power delivery efficiency • Include appropriate EHT and evaluate ability to meet some or all of the power budget for network standby • Include Li-Ion battery at device level to store enough self-generated energy to support network standby functionality for one day

3.2. DUCTLESS MINI-SPLIT ACS AND HPS

Mini-split ACs and HPs have been widely adopted in the residential sector and are one of the fastest growing HVAC products (Research and Markets 2018). Mini-split ACs and HPs are installed in two parts: an outdoor unit provides heat rejection and absorption capabilities outside the building envelope, and one or more indoor units distribute heat via fans to individual zones (Figure 3).

Figure 3: Ductless Mini-Split Systems (Image source: https://d-airconditioning.com/blogs/news/44790533-introduction-to-ductless-minisplit-systems)

3.2.1. Network Standby Power and EHT Assumptions

Connected mini-split ACs and HPs have internal wireless network circuitry or can be augmented with external wireless network modules. Through the use of mobile phone applications, users can power the units on or off and manage temperature setpoints. Because they are controlled remotely, connected mini-split ACs and HPs must be able to receive instructions from the user via the network at all times. We assume that connected mini-split ACs and HPs will typically be connected wirelessly via a Wi-Fi (802.11) network interface. Based on the estimates of *Network Standby Power Basics*, we can assume that this will require anywhere from 3.3 to about 750 mW of DC power or 0.015 to 1.4 W of AC power once power conversion steps are accounted for. For reference, ENERGY STARcertified connected mini-split ACs and HPs commonly achieve about 0.5 Wac in a connected state (ENERGY STAR 2018).

Because they have an outdoor unit with significant surface area, mini-split ACs and HPs are well suited for outdoor PV, provided they are installed in a location with direct access to sunlight. Outdoor PV has by far the highest energy harvesting density of any EHT, with a power output of up to 100 mW/cm^2 (EDNA 2018b).[2] To capture regional variability in solar radiation, we examined two scenarios: high insolation (>5.75 kWh/m^2/day) and low insolation (<4.00 kWh/m^2/day).

3.2.2. Technical and economic feasibility

We investigate the potential of PV thin-film modules to provide the energy required for network standby functionality for mini-split ACs and HPs. Using NREL's PVWatts calculator, we estimate that thin-film modules mounted on a horizontal surface (i.e. the top of the mini-split's housing) would have an average capacity factor of 12.7 and 17.7 percent for our low and high insolation scenarios, respectively (NREL 2018). To calculate the PV capacity needed to offset the energy used by the network standby function for mini-split ACs and HPs, we divide the network standby energy budget by the capacity factor in each solar radiation scenario.

We find that connected mini-split ACs and HPs with thin-film modules could offset and even exceed network standby energy requirements for both insolation scenarios, due to the ample available surface area of the outdoor unit housing. Assuming unimpeded access to sunlight, this use case could even be highly net positive (at least from the standpoint of network standby), even in less sunny locations. Using the total available surface area on top of the outdoor unit could yield in the range of 110 to 140 kWh of DC power per year, more than sufficient to supply DC energy power budgets in the range of 0.03 to 8.6 kWh per year.

We use simple payback to evaluate the economic feasibility to achieve net zero network standby and grid-resilient network standby (incorporating energy storage). Assuming that thin-film modules cost about $0.77 per watt (€0.65 per watt) of rated output (Fu et al. 2017), we estimate payback periods of about 0.5 to 2, depending the level of insolation, to achieve net zero network standby. For grid-resilient network standby, the added cost of device-level battery storage increases the payback period to about 5 and 9 years under high and the low insolation, respectively, because of the added cost of the battery. According to the most recent market trends, we assume that the cost of Li-ion batteries is currently about $0.20/Wh (€0.17/Wh) (QNovo 2016; Battery University 2018), but acknowledge that costs are decreasing rapidly.

[2] In fact, this year LG launched a solar hybrid air conditioner with PV modules attached to the top of the outdoor unit. See: https://www.designboom.com/technology/lg-electronics-solar-hybrid-air-conditioner/

3.3. SMART SPEAKERS

The market for smart speakers is growing rapidly, with rapid mass-market adoption of various voice assistant devices. The worldwide smart speaker market grew 187% in the second quarter of 2018. Collectively, Apple, Google, Xiaomi, Amazon, and others shipped 16.8 million units, up from nine million in the first quarter (Wiggers 2018).

3.3.1. Network Standby Power and EHT Assumptions

Smart speakers connect to the user's smartphone, tablet or computer via wireless network interfaces, such as Wi-Fi and Bluetooth (Figure 4), although some premium models also offer Zigbee connectivity to control smart home products. For the purposes of our analysis, we assume the presence of both a Wi-Fi and Bluetooth interface, often integrated onto a single system on chip (SoC) component. Based on estimates from EDNA (2018a), the combined interfaces would require from 3.4 to 782 mW DC power or about 0.015 to 1.5 W AC power once all power conversion is taken into account. Note that these estimates account only for network standby functionality and do not include energy requirements for other secondary functions that likely operate in connected modes, such as voice recognition. This is borne out by recent measurements of three smart speakers, which range between 0.9 to 5.2 Wac (4E EDNA 2017). In the measurements, the test state was limited to a low power state with network standby functionality.

Indoor PV would be the best suited EHT for smart speakers. Depending on the room illuminance, indoor PV modules can generate between 3 to 36 μW per square centimeter have found applications in room thermostats and sensors (EDNA 2018b). We examine two room illuminance scenarios: low illuminance of 150 lux, representing a dimly lit office, and high illuminance of 1,000 lux representing a bright sun-lit room.

Figure 4: Examples of Smart Speakers (from: PCMag.com)

3.3.2. Technical and economic feasibility

The total number of PV modules is limited by the physical constraints of the device and the module size. With a surface area of about 574 cm^2 (roughly the surface of an Amazon Echo speaker), we can accommodate 20 indoor PV modules at most. Assuming typical module efficiencies (EDNA 2018b) and about 8 hours per day of useful production, total generation ranges from 0.006 kWh to 0.058 kWh of DC energy per year, depending on indoor light conditions. Although these values may seem small compared to whole-device energy consumption, they are enough to provide for 0.1 to 17 percent of the network standby power budget under low lighting conditions and 0.6 to 175 percent under brightly lit conditions. This leaves a network zero gap of up to 9.1 kWh of DC energy per year, depending on the extent of power optimization and the environmental conditions under which the device is operated.

Researchers report that they have created solar cells that work at a record efficiency for making electricity from the low-intensity diffuse light that is present inside buildings and outside on cloudy days. These solar cells may one day cover the network standby energy budget for smart speakers (Service 2018).

Although potentially feasible with access to sufficiently bright lighting and with robust power management of network components, the cost of indoor PV cells will need to decrease to make this technology economically viable. Today, we assume that each indoor PV module costs about €2.99.[3] Given the relatively low power densities achievable under indoor lighting conditions, this means that achieving network zero is an expensive proposition for this use case. Installing the maximum feasible 20 modules on the surface of a smart speaker would add over €55 to the cost of the product. In some cases, this investment would address less than half of the network standby energy needs, producing only pennies worth of electricity. In the grid-resilient case, in which we incorporate a battery to store self-generated energy, the economics fare slightly worse (Table 4).

3.4. CONNECTED LIGHT BULBS

The global market for networked lighting is expanding rapidly (MarketsandMarkets 2018). By 2020, analysts estimate there will be 100 million smart light bulbs and lamps worldwide (ONWorld 2014), each with its own wireless network connection operating around the clock.

3.4.1. Network Standby Power and EHT Assumptions

When the connected lamp is not emitting light, the lamp still draws power as it switches to a low power mode and waits for a signal from the end-user, via the network, to switch on again. For this analysis, we assume that smart lamps will incorporate a Zigbee wireless network interface. Based on estimates from EDNA (2018), such an interface should require between 0.2 and 80 mW of DC power to maintain a network standby state, or from 0.010 to 0.18W of AC power when factoring in power

[3] Price for typical indoor solar cells from: https://www.digikey.com/product-detail/en/panasonic-bsg/AM-1815CA/869-1004-ND/2165189

conversion losses. Recent power measurements collected from laboratories in the countries participating in the SSL Annex show a very large variation in the network standby power from 0.15 to 2.70 W (SSL Annex 2016).

Although LED lamps have made significant efficacy gains in recent years, diodes themselves are still not fully efficient and do produce substantial heat during the course of operation. Thermoelectric generators (TEGs) can be used to recover this waste heat, turning it into usable electricity through the thermoelectric effect.

3.4.2. Technical and economic feasibility

We evaluated the feasibility of using TEGs by utilizing the thermal gradient of a household connected LED light bulb with ambient air as a viable source of energy. We assume that thermoelectric generators could be mounted on the backside of the circuit board to which LEDs are currently attached as well as along the sides of the metal shielding often found in the lamp's base (Figure 5). We assume each TEG module produces 100 µW per 7°C temperature gradient (EnOcean 2018). The number of modules is limited by the physical constraints of the lamp itself. Given the geometries of typical, general service, screw-base lamps, such as the Philips Hue, we estimate that it would be feasible to install about 27 TEGs in a product.

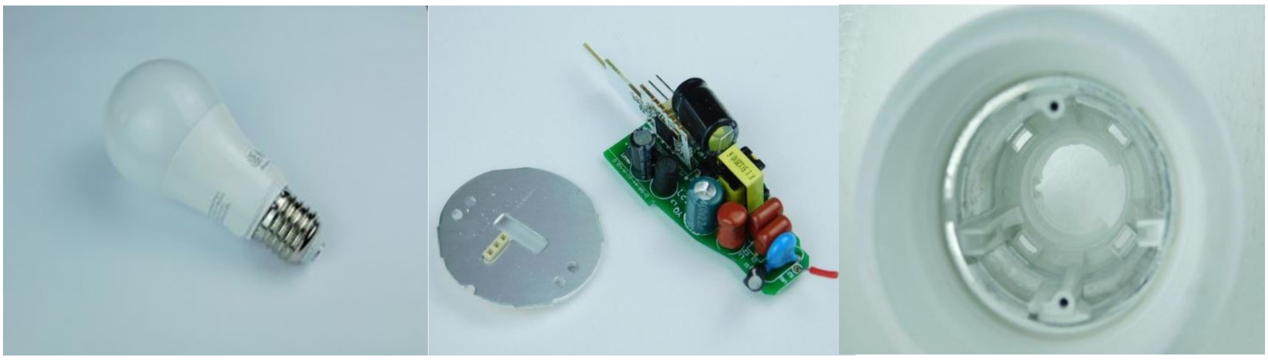

Figure 5: Hive smart light bulb (left), backside of LED circuit board (middle) and interior of bulb base (right). (Image source: Digikey.com, 2018)

We estimate that using TEGs with a LED light bulb could generate approximately 12 mW of DC power while the lamp is operating, or about 0.008 kWh of DC energy per year, if operated 2 hours per day. This would be a sufficient amount of energy to power the network standby function, provided that device manufacturers can leverage lower device power states through power management (Table 3); however, insufficient attention to power optimization of network standby components could lead to a network zero gap of up to 0.9 kWh of DC energy per year.

Efficiencies for commercial TEGs are only estimated to be in the 5 to 8 percent range.[4] This is lower than solar panels, which average about 15 to 17 percent efficiency (Aggarwal 2018). Research is necessary to further improve the efficiencies of TEGs with new thermoelectric materials. In addition, cheaper TEGs are necessary to allow for wide-scale deployments in a cost-effective manner. A

4 See: https://en.wikipedia.org/wiki/Thermoelectric_generator#Efficiency

single TEG module currently retails at about $8 (€6.80) and could only generate pennies worth of power in this particular use case (Future Electronics 2018). Given the value of harvested energy at typical grid prices, it would currently take tens of thousands of years to recoup the initial TEG module cost investment (Table 4).

3.5. SUMMARY OF DEVICE-LEVEL FINDINGS

Table 3 provides estimates of the component-level power budget required for network standby functionality, as well as the amount of power that can be feasibly harvested with the EHTs investigated. The range in component power depends on the extent to which manufacturers optimize and power manage their products. The power reductions achieved at the component level have a significant impact on the overall feasibility of achieving net zero network standby in these products, so large, in fact, that they can drive the energy harvesting requirements up by orders of magnitude.

Table 3: Device-Level Feasibility Analysis Results

Product Use Cases	Energy Harvesting Technology	Total Network Standby Energy Budget (dc kWh/yr)	Total Energy Harvested (dc kWh/yr)	Percent Network Standby Energy Harvested (%)	Network Zero Gap (dc kWh/yr)	Notes
Mini-Split ACs and HPs	Outdoor PV	0.032 - 8.6	134 - 243	1272 - 1619	0	1, 3
Smart Speakers	Indoor PV	0.033 - 9.2	0.006 - 0.058	0.1 - 175	0 - 9.1	2, 3
Connected Light Bulbs	Thermoelectric	0.002 - 0.9	0.008	0.9 - 452	0 - 0.9	2

1. We calculate the total energy harvested per year for mini-split ACs and HPs by dividing the device network standby energy budget by the capacity factor in each solar radiation scenario. NREL's PVWatts Calculator provides the capacity factor for each solar radiation scenario (NREL 2018). The lower bound estimate is for the low insolation scenario and the upper bound is for the high insolation scenario.
2. We calculate the total energy harvested per year for the smart speakers and connected light bulbs by multiplying the total potential number of modules by the power harvested by each module and the duty cycle of the ETH. See Appendix 1 for more details.
3. Ranges in the network standby energy budget reflect a range of assumptions about component power draw and the degree of power management of those components. Ranges in total energy harvested reflect assumptions on different operating conditions for EHTs. Specifically, the outdoor and indoor insolation/illuminance levels vary for the mini-split AC and smart speaker user cases, respectively.

Given sufficiently aggressive power management of network interfaces, it should be possible to achieve net zero network standby in the use cases analyzed in this report, even using today's energy harvesting technology. End uses with easy access to outdoor solar resources, like mini-split HVAC equipment, should be able to achieve net zero network standby even with modest effort toward power optimization. Indoor products like smart speakers and smart lamps may be more challenging. Robust power management of network components will be required to close the network zero gap, and actual attainment of net zero could be highly dependent on operating conditions, particularly availability of light or temperature differentials. Locating devices in a dimly lit or excessively warm space[5] would hamper the device's ability to harvest the energy it needs.

Table 4 details results from the economic analysis. Again, the power budget for network standby and the extent to which these components are power-managed drives the outcome, oftentimes with results spanning several orders of magnitude. In the smart speaker and connected light bulb cases, these differences ultimately have no impact on cost effectiveness; these cases are far from cost-effective today due to the high cost of EHT. However, for mini-split HVAC, the power optimization of network standby functions could be the difference between a relatively quick, months-long payback or a multi-year payback.

In all cases, the addition of device-level storage to achieve grid resilient network standby further detracts from cost effectiveness. The inclusion of a battery does not increase the value or benefit of the energy harvested, but it introduces additional, round-trip efficiency losses that effectively increase the amount of energy that must be harvested to achieve net zero. However, the grid resilient case provides other sources of value that we cannot fully quantify in our economic analysis. As the name states, by including energy storage, the grid resilient case could provide a measure of resilience against grid failures and maintain the most basic of network standby services in the case of a grid outage.[6] Our analysis specifically excludes valuation of resilience as it is notoriously difficult to quantify and, ultimately, highly subjective.

[5] A warm space would lessen the temperature differential between the smart lamp and ambient air. As this is the driving force of thermoelectric generation, it would reduce generation potential.

[6] This would only have value if the building's other network equipment were able to maintain power during such an outage.

Table 4: Economic Results - Maximum Feasibility Offset Scenario

	Net Zero Network Standby				Grid-Resilient Network Standby			
Product Use Cases	Incremental Cost - Energy Harvesting (EUR)	Cost per kWh of Harvested Energy (EUR/kWh) [2]	Value of Harvested Energy at Typical Grid Prices (EUR/Year)	Simple Payback Period for Energy Harvesting Upgrades (Years)	Cost of Energy Harvesting + Storage (EUR) [3]	Cost per kWh of Harvested Energy (EUR/kWh)	Simple Payback Period for Energy Harvesting Upgrades (years)	Notes
Mini-split AC	0.01 – 5.11	0.42 – 0.59	0.027 - 2.58	0.5 - 1	0.12 – 34	3.93 – 4.10	5 - 14	1
Wireless Bluetooth speakers	32 - 56	545 - 9538	0.002 - 0.009	4657 - 32599	32 - 66	550 - 11400	4663 - 38863	4
Light bulb	41 - 184	4824 - 21806	0.001 - 0.002	74533 - 74533	41 - 187	4820 - 22130	74543 - 123885	5

1. We assume the PV module cost to be $0.77/W (€0.65/W) (Fu et al. 2017)
2. Average European grid electricity price is €0.2048 per kWh. Source: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_household_consumers
3. We assume that the cost of lithium ion batteries is $0.20/Wh (€0.17/Wh) (QNovo 2016; Battery University 2018).
4. The cost of the indoor PV module is based on the following module: Panasonic AM - 1815 CA (EDNA 2018b) (https://www.digikey.com/product-detail/en/panasonic-bsg/AM-1815CA/869-1004-ND/2165189)
5. The cost of the TEG module is based on the following module : Ocean ECT-310-perpetuum (http://www.futureelectronics.com/en/technologies/semiconductors/semi-energy/harvesting-receivers/Pages/1020036-S3004-P310.aspx?IM=0)

4. COMPARISON TO BUILDING-SCALE ENERGY HARVESTING AND STORAGE

Device level energy harvesting and storage are not the only paths to offset the network standby footprint of today's products. In this section, we provide a broader policy context by comparing device-level costs and non-energy impacts against current building-scale generation and storage technologies to answer key questions, such as:

- How do the economics of zero network standby compare when applied at device- versus building-scale?
- How do non-energy impacts, specifically e-waste, compare when providing zero network standby capability at these different scales?

4.1. METHODOLOGY

In the device level analysis, we analyzed a range of network standby power budget values to illustrate the impact that robust power management and low power device states could have on attainment of net zero network standby. To simplify and compare with building level systems, we adopted the upper end of the power budget range from the device level analysis. We assume that building level generation systems will provide AC power, so PV and storage must be sized to offset the device's AC network standby energy, accounting for power conversion losses. We calculate the additional PV and storage capacity needed to provide *complete* offset of network standby energy at the building level, even though certain devices may only be able to provide a partial offset at the device level. We use the same low and high insolation scenarios to account for the variability in PV generation by region. We then compare the associated economic and non-energy impacts of these building-level systems to maximum feasible standby power offset systems at the device level.

To examine the non-energy impacts of the three product use cases at the building and device level, we analyze the mass of electronic waste (e-waste) produced over a 30-year time horizon. We estimate e-waste for the generation technologies in the net zero network standby scenario, and the sum of the e-waste from generation and energy storage technologies in the grid resilient network standby scenario. The analysis examines incremental differences in e-waste from the energy harvesting and energy storage technologies only; waste associated with end-of-life device disposal is assumed to be the same across scenarios, and therefore ignored.

For the grid resilient network standby scenario, we assume the devices use lithium cobalt oxide ($LiCoO_2$) battery technology. Given that the lifetime of these batteries is currently much shorter than the product lifetimes in the three product use cases, we assume that batteries would need to be replaced roughly every three years, a common battery lifetime for consumer electronic products (Battery University 2017). A summary of the differences in assumptions between device and building level technologies and performance is presented in

Table ***8*** in the appendix, along with a table of key assumptions used in the non-energy impacts analysis (*Table 9*).

To contextualize the results from this analysis, we calculate the percentage increase in the overall product waste stream created by the additional e-waste from EHT and battery storage at the device level.

4.2. BUILDING-LEVEL FINDINGS

4.2.1. Economic Results

Results from an economic analysis of device- and building-level network standby offsets are presented below in Table 5. Ranges in the mini-split ACs and HPs and building level results are reflections of the low and high insolation scenarios; ranges in device-level results for the connected light bulb use case stem from a sensitivity analysis of indoor lighting conditions. We compare the costs of employing the maximum feasible EHT at the device level (even if this only results in a partial network standby energy offset) to a building-scale system sized to *fully* offset network standby energy (thus achieving zero network standby). Although this might be construed as an unfair comparison, we present our results in this manner to show what is possible when utilizing device and building level approaches to their fullest extent.

Table 5: Economic Comparison of Maximum Feasible Network Standby Power Offset at the Device Level with Full Offset at the Building Level

	Net Zero Network Standby - Incremental Costs of EHT (EUR)		Grid Resilient Network Standby - Incremental Costs of EHT + Storage (EUR)	
	Device Level	Building Level (full offset)	Device Level	Building Level (full offset)
Mini-split ACs and HPs	4 - 5 (100% offset)	2 – 3	34 - 35 (100% offset)	12 - 13
Smart speakers	56 (0.1 – 100+% offset)	2 – 3	66 (0.1 – 100+% offset)	12 - 13
Connected light bulbs	184 (0.9 – 100+% offset)	0.28 - 0.36	187 (0.9 – 100+% offset)	1.40 - 1.50

To achieve net zero network standby in mini-split ACs and HPs, building level technologies are significantly cheaper. Even though a building-level solution might require slightly more PV than at the device scale because of additional AC-DC and DC-DC power conversion losses, we assume building-level PV to be obtainable at lower prices and therefore at lower incremental cost. For grid resilient network standby, the results show a similar gap in cost, exacerbated by the fact that consumer-grade batteries that might be used at the device level would need to be replaced six times over the assumed 20-year life of the product.

For the smart speakers, it is significantly cheaper to offset full standby power at the building level than to offset even a fraction of this energy at the device level. In the net zero scenario, costs at the building level are approximately 20 times cheaper, and in the grid resilient scenario costs at the building level are approximately four to five times cheaper.

The economic disparities are most pronounced for the connected light bulb due to the high cost of thermoelectric generation. It is 500 to 600 times cheaper to achieve net zero network standby at the building level than with a device-level solution and 130 times cheaper for a grid resilient solution with storage.

These results imply that, at least today, generating and storing the energy for network standby at the building level is eminently more affordable than providing the same services at smaller device scales. These findings also underscore the importance of first driving down network standby energy use through low-energy designs as a strategy to approach network zero rather than simply trying to solve the problem from the supply side.

4.2.2. Non-energy Impacts

Results comparing e-waste produced over 30 years at the building and device level are presented below in Table 6. For the grid resilient scenario, we assume that batteries incorporated at the device level will require replacement every three years. All other ranges are driven by the same variability of generation conditions discussed in the Economic Results section above.

Table 6: 30 Year E-waste comparison of Maximum Feasible Network Standby Power Offset at the Device Level with Full Offset at the Building Level

	Net Zero Network Standby Mass of 30 Year E-waste (kg)		Grid Resilient Network Standby Mass of 30 Year E-waste (kg)	
	Device Level	Building Level (full offset)	Device Level	Building Level (full offset)
Mini-split ACs and HPs	0.22 - 0.31 (100% offset)	0.22 - 0.28	1.91 - 2	1.06 - 1.12
Smart speakers	0.78 (9 to 88% offset)	0.005 - 0.006	1.4 - 2.57	0.9 - 0.9
Connected light bulbs	0.05 (100% offset)	0.006 - 0.006	0.22 - 0.24	0.1 - 0.1

The shorter lifespans of connected products compared to the expected lifespan of building-scale PV systems (estimated at 30 years), means that zero network standby solutions, if implemented at the device level, could result in increases in e-waste. For longer-lived products like HVAC equipment (our mini-split use case), the effect is less than a 1 percent increase in waste compared to the mass of the overall product; however, for relatively short-lived electronic products and lighting, device-level zero network standby solutions could increase e-waste by 20 percent or more, depending on the lifespan of the original product. When battery storage is incorporated at the device level, the impact is an order of magnitude higher, because in many products, these batteries would need to be replaced multiple times over the product's lifetime. These findings indicate the importance of evaluating and considering the broader life cycle impacts of zero network standby strategies as policymakers continue to debate this subject.

4.3. SUMMARY OF BUILDING-LEVEL FINDINGS

Our findings show that achieving net zero standby power offset and grid resilient standby power offset through building-level energy generation and storage technologies is generally preferable today from an economic standpoint. Device-level solutions also tend to produce greater amounts of e-waste, particularly when incorporating storage.

These findings are not entirely surprising. Outdoor solar radiation is a much greater source of energy than waste heat, artificial light, and other EHT mechanisms. Outdoor PV can produce much more energy at lower cost and with less material than indoor PV and thermoelectric devices, even when taking additional power conversion losses into account. The one use case that comes closest to having a strong economic advantage is the mini-split heat pump/AC unit, where we assume that energy is harvested using thin-film PV mounted on the HVAC system's outdoor unit.

For the grid resilient cases, battery storage could eventually convey some economic advantage, because the smaller capacity batteries used in consumer electronics come from a more mature market than building-level stationary storage (although energy storage technology used in buildings is rapidly maturing). This, coupled with the decreased need for exterior housing and weather proofing, makes device-level storage cheaper than stationary storage at the building level, from a strictly first cost perspective. Unfortunately, today's consumer device batteries must be replaced roughly every three years before their capacity significantly degrades, and this high rate of replacement erodes any first-cost economic advantages they may have. It also amplifies the amount of additional e-waste that might be generated from devices with internal energy storage.

5. OPPORTUNITIES TO ACHIEVE ZERO NET STANDBY ENERGY

5.1. THE GAP IN GETTING TO ZERO NETWORK STANDBY POWER

Generating and storing enough energy at the device level to support network standby functionality may be generally feasible with technologies we have today. However, achieving zero network standby in practice could still require years of research and development effort. Our analysis shows that outdoor use cases like mini-split HVAC systems could already harvest sufficient energy to meet their network standby energy needs. Products that reside entirely indoors may struggle to achieve zero network standby unless network standby power draw can be significantly reduced *and* users can ensure the appropriate environmental conditions (e.g. bright light) for energy generation. The smart speaker, for example, can only achieve net zero network standby if it is deeply power managed *and* located where there is ample ambient light. It is worth noting that only one of these factors, power management and energy-efficient design, is intrinsic to the product itself. The other, environmental conditions, is subject to the vagaries of consumer behavior.

One might assume that adding storage to EHT might help close the gap to zero network standby, but according to our estimates, it may not be feasible for EHT to harvest excess energy to store for later use while still powering the network standby function (at least not in an indoor environment).[7] In addition, batteries make it more difficult to offset network standby energy due to roundtrip efficiency losses, wasting some of the energy harvested.

5.2. TECHNOLOGICAL PATHS FORWARD

Today's EHT could supply enough energy for network standby functionality in many common, wirelessly connected products *providing that* network standby functionality can be aggressively power managed. The extent or depth of power optimization for network standby will hinge on several driving factors in the product's design, including tolerance for latency, the level of network standby functionality or "presence" that the device requires, among other factors (see EDNA's *Network Standby Power Basics* report for additional discussion of these factors). However, attempting to achieve net zero network standby through current network protocols without significant attention to power optimization will not be possible. In effect, we need to first close the gap between the capabilities of EHT and the power requirements of network standby functionality itself if we wish to achieve zero network standby.

Manufacturers will need to incorporate as much cost-effective efficiency and power optimization as possible into current networked products before attempting to offset the remaining energy draw with EHT and storage, adopting the mantra "reduce before you produce." This strategy works on several levels. First, driving down network standby power budgets may be necessary to make the network zero concept feasible within today's product form factors. Second, it will significantly reduce the size and expense of any EHT and storage that could eventually be added to the product. Consequently, it can help to reduce the e-waste impacts of EHT and storage as well.

Even with deep power management optimization, it may not be possible to close the current network zero gap for all products while working through existing high-bandwidth network protocols like legacy Wi-Fi. Proponents of zero network standby may, instead, need to set their sights on new use cases with somewhat more traditional (i.e. non-networked) secondary functionality. For example, researchers at Lawrence Berkeley National Laboratory (LBNL) have developed a method to wake a set-top box using infrared light energy harvested from a remote control signal (Gerber et al. 2018). A pulse of light from the remote control provides enough energy to wake the device's infrared sensor circuitry, which can then interpret the remote's signal for the set-top box to turn on. This use case can nearly eliminate standby power draw in these more traditional products without network connectivity, but the researchers do not yet provide a clear technological solution for products with network standby functionality.

[7] A PV-powered device that occasionally receives direct sunlight might be able to periodically produce excess energy, but so many location-specific considerations factor into such cases that we cannot assume they are generally true.

The international standards community is also looking to further address network standby power issues using low power Wake-Up Radio (WUR) technology. WURs are secondary radios that listen for a wake-up packet on the network and power up the main radio when the radio's "name" is called on the network. The IEEE 802.11 standards group is currently investigating WUR and developing associated protocols for the Wi-Fi standard. WURs will potentially draw on the order of one milliwatt (IEEE 2018), allowing Wi-Fi connected products to significantly reduce their network standby power to levels that indoor EHT can accommodate.

5.3. CONSIDERATIONS OF SCALE

The zero network standby concept applies the concept of zero net energy — first applied in high-performance buildings — at the scale of individual products. The goal of appliances that generate their own electricity is certainly laudable and can be applied in parallel with building-level distributed energy generation and storage projects. However, our preliminary results also illustrate that there may be significant economic and sustainability advantages from obtaining carbon-free energy at larger scales in the energy system. Appliance efficiency policymakers should consult with their peers in the building codes and standards realm to coordinate efforts and ensure that zero energy concepts are complementary, yield robust carbon reductions, and generally implemented with the lowest possible cost to society.

5.4. POLICY CONSIDERATIONS

Although zero network standby may not be economically feasible today for the use cases we investigated, we expect that power conversion efficiencies and costs will improve as technologies mature. Although the economics are currently challenging, zero network standby may someday be feasible for the right devices using emerging technologies described above.

Policymakers need to consider important non-energy issues, such as e-waste, that could impact the overall sustainability of zero network standby approaches. Our preliminary analysis suggests that network zero devices could significantly increase the amount of e-waste over a product's lifecycle, especially for small electronics with short product lifetimes. This issue should be studied further and more comprehensively as advocates consider device-level zero energy concepts in the future.

Even if zero *network standby* approaches may take years to realize, the broader *zero standby* concept may be achievable on shorter time scales by addressing products with more traditional standby functionality. Examples include lower power standby functions like waking a device with a remote (e.g., Gerber et al. 2018), or wearable products that might otherwise be charged via mains-connected battery chargers. Learnings and successes on these near-term feasible products can be transferred to networked products as power budgets improve and EHT matures.

Opportunity to offset network standby power may exist in low power, Internet-of-Things products that can tolerate low latency and use low power network protocols like Bluetooth LE, Zigbee, and Z Wave. Emerging technologies like low power WURs have the potential to expand the types of products that EHT can address.

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7. APPENDIX

Table 7: Device-Level Assumptions

		Network Standby Assumptions			Energy Harvesting Assumptions						
Product Use Cases	**Scenario**	**Power (W)**	**Duty Cycle (h/day)[2]**	**DC Energy (kWh) per Year**	**EHT**	**PV Capacity Factor[3]**	**Power Harvested per Module (mW)**	**Surface Available (cm^2)**	**EHT Duty Cycle (h/Day)**	**Total Power Harvested (mW)**	**Sources**
Mini-Split ACs and HPs	High insolation (>5.75 kWh/m^2/Day)	0.5	24	0.032 – 8.6	Outdoor PV	17.7%	n/a	5,000	n/a	n/a	1,4,5
	Low insolation (<4.00 kWh/m^2/Day)	0.5	24	0.032 – 8.6	Outdoor PV	12.7%	n/a	5,000	n/a	n/a	
Smart Speakers	Low Illuminance – 150 lux	0.9	24	0.033 – 9.2	Indoor PV	n/a	0.1	570	12	0.1	6, 7, 8, 9, 10
	High Illuminance – 1000 lux	0.9	24	0.033 – 9.2	Indoor PV	n/a	1	570	12	1	
Connected Light Bulbs	n/a	0.15	24	0.002 – 0.9	Thermoelectric	n/a	0.43	200	2	0.43	11, 12,13,14, 15,16

1. For the mini-split AC and HP network standby power, we use the connected allowance for room air conditioners in ENERGY STAR's program requirements for room air conditioners (ENERGY STAR 2018).
2. We assume that devices continually draw power for network standby functionality.
3. PV capacity factor is from PVWatts Calculator (NREL 2018).
4. Mini-split AC and HP surface available is assumed to be 0.5 m^2
5. Results generated using PVWatts Calculator (NREL 2018).
6. Network standby power estimate is based on best-in-class network standby power measurement from three measurements in a recent 4E EDNA report (EDNA 2017).
7. Power harvested per module is based on typical PV cell module identified in EDNA Task VI's Energy Harvesting IoT report (EDNA 2018b)
8. Surface available is calculated based on Amazon Echo.
9. We assume smart speakers and EHT have accessed to indoor light 12 hours per day.
10. Total power harvested is calculated by multiplying the number of potential modules by the power harvested per module.
11. Network standby power for light bulbs is the best-in-class power measurement from a recent report from SSL Annex (2016).
12. Power harvested per TEG module is based on a typical module (EDNA 2018b): EnOcean ECT310 Perpetuum.
13. We assume the temperature gradient across the TEGs is 30 K.

14. The energy harvested per module is based on the following TEG module: EnOcean ECT310 Perpetuum. Available at: https://www.sensorsmag.com/components/thermoelectric-energy-harvesting
15. The surface of the TEG module is based on EnOcean ECT310 Perpetuum, See: https://www.enocean.com/en/enocean_modules/ect-310-perpetuum/
16. The surface available is calculated based on typical dimensions for a general service lamp.

Table 8: Summary of Device and Building Level Technology Assumptions

Category	Device Level Technology	Building Level Technology
Solar PV	Cadmium telluride (CdTe) -- Mini-split ACAmorphous silicon (a-Si) -- Wireless speakers	Poly-crystalline silicon (poly-Si)
PV Cost	$0.77/W (€0.65/W)	$0.35/W (€0.30/W)
PV Capacity Factor	Arizona: 17.7% Minnesota: 12.7% (Only used in mini-split heat pump/AC case)	Arizona: 19.5% Minnesota: 15.2%
Battery Storage	Lithium cobalt oxide ($LiCoO_2$)	Lithium iron phosphate ($FeLiO_4P$)
Battery Storage Cost	$200/kWh (€170/kWh)	$400/kWh (€340/kWh)

1. PV cost for both thin film and crystalline modules is assumed to be $0.35/W (€0.30/W) (Fu et al. 2017). These prices reflect the post-gate factory price, as we assume the incremental labor and installation costs to be negligible, given the capacities.
2. Capacity factors for all outdoor PV technologies were generated using PVWatts (NREL 2018).
3. Device level battery cost is for module only. Building level stationary battery storage cost is assumed to include the battery module and housing (Lazard 2017).

Table 9: Key Assumptions in Non-energy Impacts Analysis

Use Case	Product Lifetime (years)	Product Mass Without EHT and Storage (kg)	EHT Technology	Mass of EHT	Units	Energy Storage Technolog y	Mass of Energy Storage (g/Wh)	Sources
Mini-split AC	20	57.2	Outdoor PV: CdTe	2.67	kg/m^2	$LiCoO_2$	5.71	1, 2, 3
Smart speakers	6	0.821	Indoor PV: a-Si	7.8	g/module	$LiCoO_2$	5.71	3, 4, 5
Connected light bulb	15	100	Thermoelectric	1	g/module	$LiCoO_2$	5.71	3, 6, 7
Building Level	PV System: 30 years	NA	Outdoor PV: poly-Si	4.4	kg/m^2	$FeLiO_4P$	9.52	8

1. For the mini-split AC, product lifetime was adapted from the 2016 US federal rulemaking for residential ACs and heat pumps (US DOE 2016).
2. All solar PV mass numbers are from the following 2011 Lawrence Berkeley National Lab Report: https://www.bnl.gov/pv/files/pdf/230_SolarEnergy_PV_LCA_2011.pdf
3. Mass for the two energy storage technologies is from: https://batteryuniversity.com/index.php/learn/article/types_of_lithium_ion
4. For smart speakers, the product lifetime is based on: https://www.cta.tech/News/Blog/Articles/2014/September/The-Life-Expectancy-of-Electronics.aspx
5. The smart speaker EHT mass is based on the module weight of the Panasonic AM1815 solar cell
6. Connected light bulb lifetime is based on an average of typical commercial and residential applications from: http://eta-publications.lbl.gov/sites/default/files/lbnl-1007090-rev2.pdf
7. Connected bulb EHT mass is based on the module weight of the ENOcean ECT310 thermoelectric energy harvesting device
8. Building level PV lifetime is assumed to be 30 years (Fu et al. 2017)