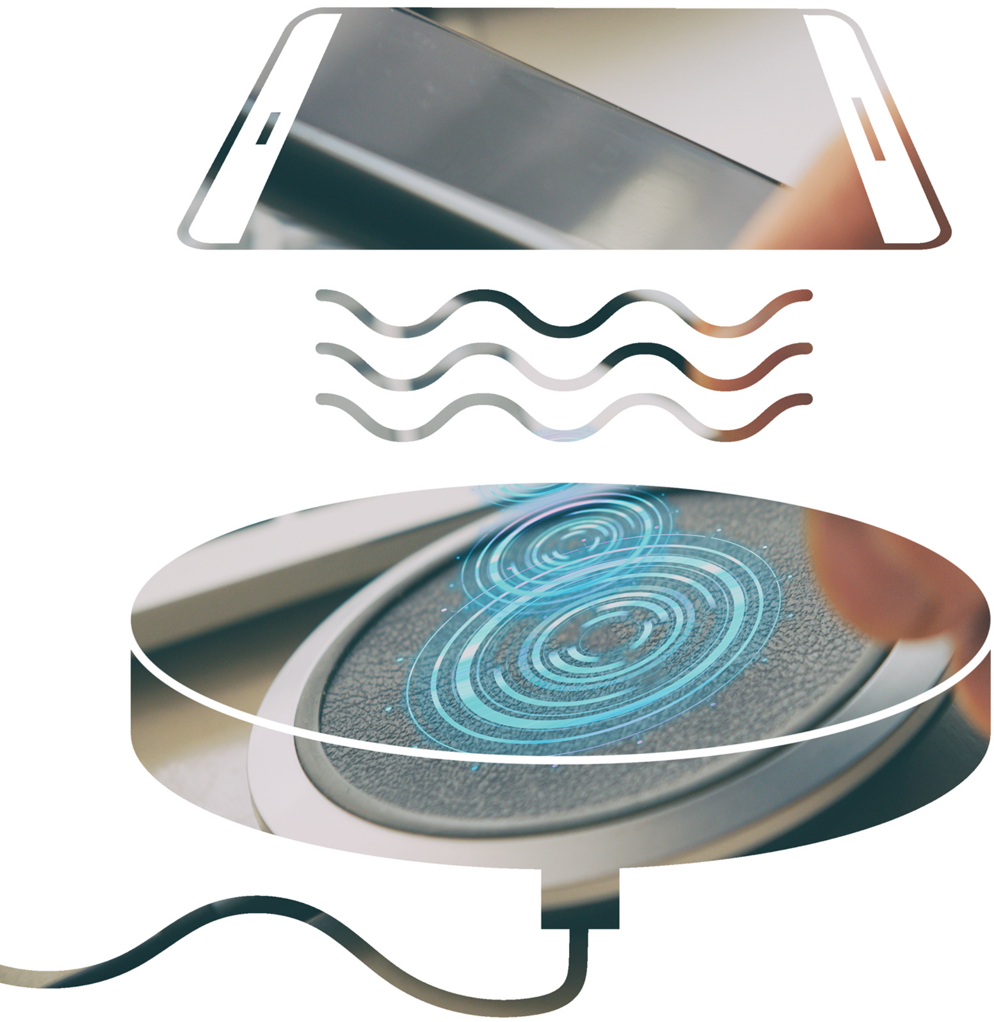
4E Electronic Devices & Networks Annex
EDNA



Global Forecast of Energy Use for Wireless Charging

JULY 2019

The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP), has been supporting governments to co-ordinate effective energy efficiency policies since 2008.

Fifteen countries have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds, which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions.

The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.

Current members of 4E TCP are: Australia, Austria, Canada, China, Denmark, the European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK and USA.

Further information on the 4E TCP is available from: **www.iea-4e.org**

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.

Further information on EDNA is available from: **www.edna.iea-4e.org**

This report was commissioned by the EDNA Annex of the 4E TCP. It was authored by Xergy Consulting and Energy Solutions. The views, conclusions and recommendations are solely those of the authors and do not state or reflect those of EDNA, the 4E TCP or its member countries.

GLOBAL FORECAST OF ENERGY USE FOR WIRELESS CHARGING

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1. INTRODUCTION

1.1 MARKET TRENDS

Wireless battery charging is becoming an increasingly prevalent feature of consumer electronics (such as smartphones, wireless earbuds, and wearables) and an increasingly popular service in public spaces around the world. In 2012, the Nokia 920 became the first smartphone with built-in Qi wireless charging capability—instead of using a wired battery charger, consumers could rest the smartphone on a wireless charging pad (Mearian 2018). By 2013, the companies Powermat and Powerkiss already had wireless chargers in over 1,500 locations in the United States (U.S.) and 1,000 locations in Europe, such as airports, hotels, restaurants, and cafes (Mearian 2013).

Wireless charging continues to gain popularity, principally because consumers value the increased convenience. In some cases, such as wearable fitness trackers (e.g., Fitbits) and action cameras (e.g., GoPros), wireless charging may also be desirable because it allows for hermetic sealing, and therefore watertight, form factors. Companies that currently offer wireless charging in smartphones (without an aftermarket product) include: Apple, Samsung, Sony, LG, Nokia, Huawei, Microsoft, Google, and Blackberry (MobileFun 2018b). Wireless charging is also making inroads in laptops, although adoption lags smartphones; the first wireless charging compatible laptop was Dell's Latitude 7285 (shown in Figure 1) which was introduced in the summer of 2017 (Luciano 2017). Additionally, there are currently 18 car brands that offer wireless charging in cars either as a standard option or an additional add-on (FoneSalesman 2018).

Figure 1: Examples of products that use wireless charging. Left: MobileFun 2018a. Right: Portnoy 2016.

1.2 WIRELESS CHARGING TECHNOLOGIES

Wireless charging can be accomplished through three different technologies: inductive, magnetic resonant, and radio frequency.

- **Inductive** charging uses magnetic coils to transfer energy between a transmitter and a receiver. An alternating magnetic field is created in one coil within the transmitter, which induces an alternating current in a second coil within the receiver. Since the energy transmitted through inductive charging is proportional to the square of the distance between the two coils, this technology is only effective at relatively short distances (less than 10 mm). For efficient energy transfer, the coils must also be properly aligned (Digi-key 2016; BFE 2017). The Swiss Federal Office Of Energy (BFE) investigated health effects from inductive chargers and found that the SAR (Specific Absorption Rate) from these products are below the allowable limits by a factor of 1,000 (BFE 2017).
- **Magnetic resonant** charging builds on the principles of inductive technology but allows for larger distances between transmitter and receiver. It is also not as dependent on proper coil alignment and allows for transfer from one transmitter to multiple receivers. The coil within the transmitter first creates an oscillating magnetic field at a specific frequency. Receiver coils are designed to resonate at this same frequency, ensuring power transfer even over distances of several inches. This allows magnetic resonant charging and power transfer to be integrated into furniture, such as tables and desktops (IDT 2018). BFE also investigated health effects from magnetic resonant chargers and found that the SAR (Specific Absorption Rate) from these products are below the allowable limits by a factor of 1,000 (BFE 2017).
- **Radio frequency (RF)** charging transmits power through electromagnetic waves rather than magnetic fields and can be used at even further distances than magnetic resonant (up to 15 feet). An electronic receiver converts the RF waves into a direct current voltage, similar to reception from an AM-FM radio (Humavox 2016). RF technology offers the most freedom with regard to size and shape and also allows for charging several devices with one transmitter. To date, there has not been any conclusive evidence that links RF exposure from wireless devices to any known health issues (FCC 2018). Nevertheless, several regulatory agencies around the world including the Federal Communications Commission (U.S.), Industry Canada, and the Council of the European Union have set Specific Absorption Rate limits on the allowable amount of energy that can be absorbed by humans when exposed to RF fields produced by wireless devices (GSMArena 2018).

1.3 STANDARDIZATION EFFORTS

The Qi specification, developed and supported by the Wireless Power Consortium (WPC), encompasses a combination of inductive charging and magnetic resonance technologies. Qi is currently the most widely adopted standard for wireless technology and is used in more than 2,700 products (WPC 2018). These include smartphones; chargers integrated into vehicles; and chargers available in public places like hotels, restaurants, and airports (WPC 2018).

AirFuel Alliance (founded as a result of merging between Alliance for Wireless Power and Power Matters Alliance) has created standards for magnetic resonant and RF technologies. The magnetic resonant technology is available in one laptop model to date (Dell Latitude 7285) and is more widely deployed in public infrastructure charging (i.e. airports, cafes, etc.). The RF portion of the standard is not yet commercially available (AirFuel 2018).

The last major player is Energous, which created the WattUp standard. WattUp recently received Federal Communications Commission certification but products are not yet commercially available (Jansen 2018). They plan to leverage the flexibility of the RF technology to eventually integrate wireless charging across all sectors and products including gaming controllers, smoke detectors, charging within vehicles, charging within offices, inventory scanners, security cameras, and medical devices (Energous 2018).

Wireless charging, regardless of the technology employed, is inherently less efficient than wired charging. Furthermore, current energy efficiency test procedures and policies do not address the vast majority of wireless battery chargers as there is no national standard that exists with a minimum energy efficiency requirement for wireless chargers (CLASP 2018, U.S. DOE 2016a).[1] Due to the rising popularity of wireless charging, its inherent inefficiencies compared to wired charging, and the lack of minimum efficiency standards for this technology, it is important to understand the possible and likely impact of wireless charging on global energy consumption as well as strategies for limiting increased energy consumption through more efficient designs.

1.4 REPORT OVERVIEW

In this report, we have built on the modeling methodology published in a recent white paper by Natural Resources Defense Council (NRDC) and Suzanne Foster Porter of Kannah Consulting, “Wireless Power for Residential Devices: What is the Energy Penalty of Cutting the Cord?” to a create a scenario-based 2030 forecast of the global energy impact of wireless charging relative to a wired baseline (Foster Porter and Delforge 2018). Foster Porter and Delforge (2018) provides a comprehensive treatment of today’s wireless charging market, wireless charging technologies, specific technology pathways for improved energy efficiency, test procedure development, as well as a U.S.-based model that contains a “low impact” and “high impact” scenario for wireless charging incremental energy consumption (Foster Porter and Delforge 2018). This report expands on that modeling by:

- Independently varying assumptions about wireless adoption (across low, medium, and high values), wireless transfer efficiency (low, medium, high), and the efficiency of other components of wireless battery charger systems (low, medium, high) to generate 27 scenarios for wireless charging energy consumption;
- Incorporating data on wireless charging efficiency from a recent study published by BFE to inform modeling inputs (BFE 2017);
- Defining scope and scaling energy use at the level of product categories and operational modes;
- Calculating country-specific estimates of wireless charging energy for every country;
- Estimating the total global impact of wireless charging under various scenarios, including under a most likely scenario; and

[1] The U.S. DOE only regulates the efficiency of small induction-based battery chargers that are specifically designed to operate in wet conditions (U.S. DOE 2016a). From a practical standpoint, that means electric toothbrushes are within the scope of the U.S. DOE standard.

Finally, we discuss the current status of efforts to develop wireless test procedures and the implications of our findings for test procedure development, complementary data collection and research, and policy initiatives to improve wireless charging efficiency.

2. MODELING ASSUMPTIONS AND METHODOLOGY

Development of our scenario-based model involved the following four steps:

- **Baseline and scope –** Defining the wired baseline and our scope of product categories to analyze;
- **Scenario descriptions and assumptions –** Deriving our low, medium, and high estimates for wireless adoption, wireless transfer efficiency, and the efficiency of the other components in wireless battery charger systems;
- **Calculating U.S. battery charger energy use by impact scenario –** Combining our adoption and efficiency assumptions to inflate the portion of in-scope battery charger energy that we forecast to be wireless (based on the relative efficiency of wired and wireless chargers); and
- **Global extrapolation –** Scaling results to be country-specific.

These phases are described in further detail below.

2.1 BASELINE AND SCOPE

The U.S. Department of Energy (DOE) Technical Support Document (TSD) and National Impact Analysis (NIA) for its 2018 energy conservation standards for battery chargers (U.S. DOE 2015, 2016b) served as the foundation of our model. The U.S. DOE's TSD and NIA are rich, well-structured data sources that allow us to create a granular model with dozens of product categories and then scale results to other countries.

We defined our baseline as a scenario in which all in-scope battery charging energy is wired.[2] To calculate the energy associated with all battery chargers in the U.S. in 2030, assuming they are all wired, we multiplied DOE's 2030 forecasts for the number of battery chargers in each product category (in the U.S.) by the per-unit annual energy consumption for each product category that would result from typical real-world usage patterns and U.S. DOE's minimum required efficiency levels (U.S. DOE 2015, 2016b).[3]

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[2] As previously discussed, some battery charging is already provided wirelessly. However, for simplicity and to isolate the energy impact of the wired-to-wireless conversion, our baseline is an entirely wired counterfactual.

[3] In doing so, we are implicitly using the U.S. 2018 battery charger standard as the global efficiency assumption for the wired baseline. This simplification, which was motivated by a lack of data to forecast wired battery charger efficiency by country, will tend to overestimate the 2030 energy consumption of wired charging in the

We only analyzed the energy impact of wireless adoption for a subset of the product categories regulated by the U.S. DOE battery charger standard representing 35% of our forecast of 2030 U.S. battery charging energy in the wired baseline. Figure 2 identifies the product categories that we defined as in- and out-of-scope and their relative energy consumption in the wired baseline scenario. We excluded the following products from our scope: electric toothbrushes (which already charge wirelessly), light transportation (such as golf carts and toy ride-on vehicles), and legacy products (such as answering machines, cordless phones, and DVD players).

Our analysis also does not include product categories that were not modeled in the U.S. DOE bottom-up analysis, either because they did not exist (or were nascent technologies) or because they were outside of the scope of the U.S. DOE small battery charger standard. Some of the most consequential product categories that are excluded for these reasons are:

- Wearables (such as smartwatches and fitness trackers);
- Electric vehicle chargers for full-sized vehicles;
- Chargers for industrial or military applications (such as manufacturing robotics or military drones), chargers for medical devices; and
- Kitchen appliances that are currently mains-connected but which may become battery-powered and wirelessly charged in the future (WPC 2017).

Due to these omissions from the scope of our analysis, it is important to note that for the remainder of this report when we refer to and present statistics for "battery charger energy use" we are referring only to the product categories within the scope of this analysis.

U.S. and underestimate it in countries that still have not achieved efficiency levels commensurate with the 2018 U.S. standard by 2030.

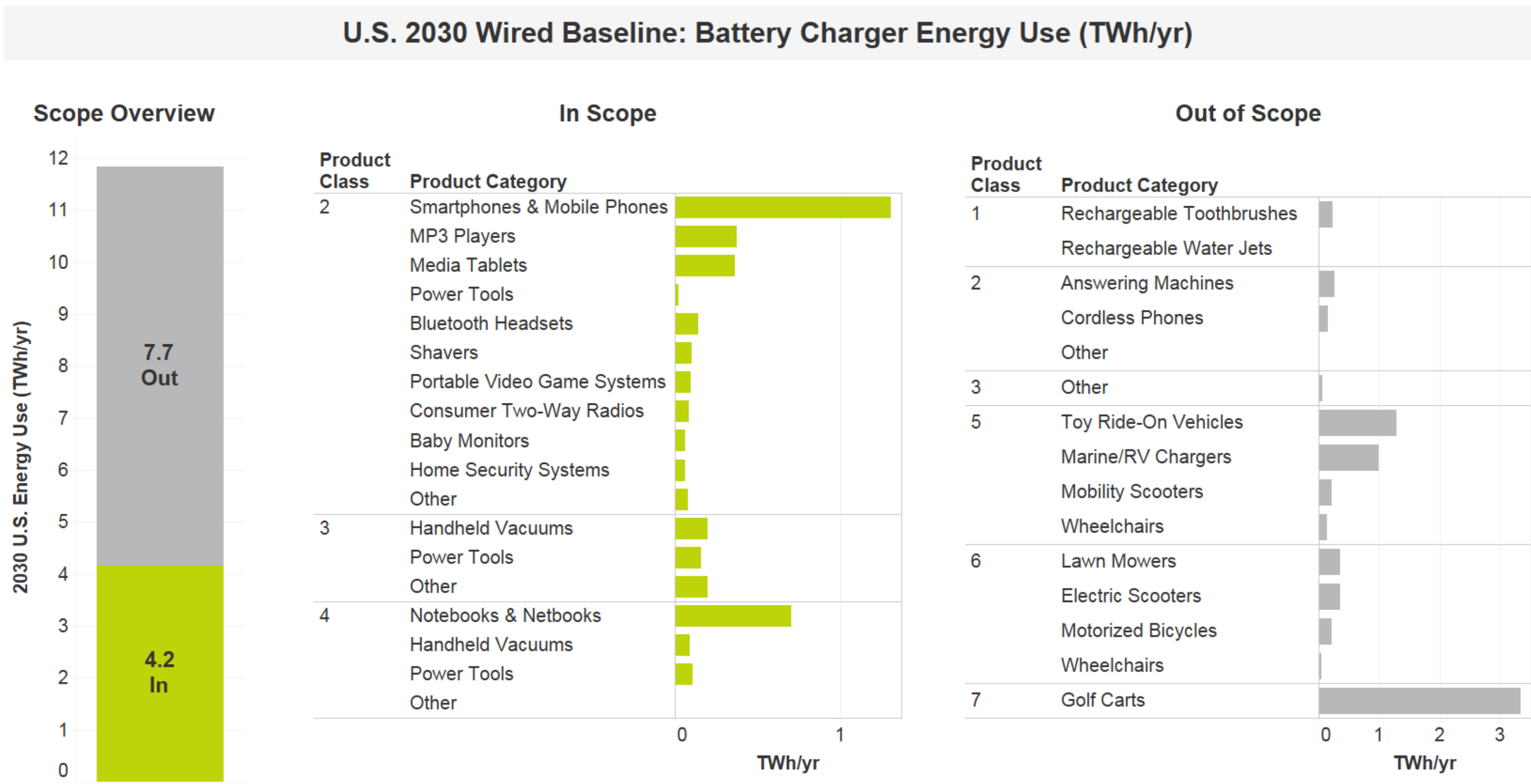

Figure 2: Estimated 2030 U.S. energy use in the wired baseline scenario. We only analyzed the energy impact of wireless adoption for the product categories classified as "in scope." Product categories are grouped by their U.S. DOE product class. The "other" category represents an aggregation of product categories with much smaller energy use that we present together for legibility.

2.2 SCENARIO DESCRIPTIONS AND ASSUMPTIONS

2.2.1 Wireless Adoption

Most of our methodology and assumptions for modeling wireless adoption scenarios are derived from Foster Porter and Delforge (2018). Across our three adoption scenarios, we assumed a range of 64 to 89 percent for the fraction of smartphones (and similar products) that will be wireless-compatible in 2030. For notebook computers (and similar products), we assumed a range of 40 to 90 percent. Like Foster Porter and Delforge (2018), we assumed that people will not always charge their wireless-compatible products wirelessly. We assumed a range of 80 to 90 percent for the fraction of the time that people will charge their wireless-compatible devices wirelessly.[4] For more detail on our wireless adoption assumptions and sources, see Appendix A: Adoption Assumptions.

2.2.2 Wireless Charging Efficiency Levels

We analyzed and independently varied two aspects of wireless battery charging energy efficiency:

- The "**transfer efficiency**," which quantifies the energy lost from in transferring energy from the transmitter to the receiver in in electronics associated with the transmitter and receiver; and
- The **efficiency of all other components**, such as the power supply, charge control circuitry, and the battery itself.

Our efficiency assumptions and underlying sources are summarized in Table 1. As indicated by the stars in Table 1, most of our efficiency assumptions align with those made by Foster Porter and Delforge (2018). One notable exception is that whereas Foster Porter and Delforge (2018) assumed 65 percent as the upper bound for transfer efficiency, our high-case transfer efficiency assumption is 80%, the upper bound of transfer efficiency from BFE (2017).[5]

[4] Technically, 80% to 90% represents the fraction of charging energy across all wireless-compatible devices that will be provided wirelessly.

[5] When the authors of BFE (2017) analyzed that the efficiency of wired and inductive battery chargers, they found that the inductive battery chargers were 67% to 80% as efficient as the wired chargers. The system boundary of their measurements was such that the difference in efficiency can be attributed to transfer efficiency, not the efficiency of other components (BFE 2017).

Table 1: Energy efficiency assumptions for the wired baseline and wireless scenarios

Efficiency Category	Wired	Wireless		
		Low	Mid	High
Transfer efficiency	100% (1)⋆	25% (2)⋆	53% (3)	80% (4)
Efficiency of other components	50% (5)⋆	30% (6)⋆	50% (5)⋆	70% (7)⋆

Sources:
1. Implicit assumption used by Foster Porter and Delforge (2018)
2. Lower bound of magnetic resonance transfer efficiency reported in Perzow 2016
3. Average of the low and high transfer efficiency assumptions
4. Upper bound of inductive transfer efficiency reported by BFE (2017)
5. Average 24-hour charge efficiency of wired cell phone battery chargers in the appliance database maintained by the California Energy Commission (CEC)
6. Lowest 24-hour charge efficiency of wired cell phone battery chargers in the CEC appliance database
7. Highest possible efficiency of wired battery charger systems reported in Geist et al (2006)

⋆ Indicates values that were derived and used by Foster Porter and Delforge (2018)

2.3 CALCULATING U.S. ENERGY USE BY IMPACT SCENARIO

We next calculated 2030 U.S. battery charger energy use for a variety of impact scenarios, each of which is defined by low, medium, or high assumptions for (1) wireless adoption, (2) transfer efficiency, and (3) the efficiency of other components.

In modeling wireless energy use, we had to consider that battery charger energy use is comprised of three different modes—charging, maintenance, and no-battery mode—and each mode might merit a different scaling factor for translating from the wired to wireless.[6] Unfortunately, due to limitations in the U.S. DOE battery charger test procedure, which involves a 24-hour charge cycle, we were not able to differentiate between charging and maintenance mode energy use. Furthermore, the available data did not justify scaling no-battery mode energy use (up or down).[7] The net result is that we used the efficiency assumptions in Table 1 to scale the combined energy from charging and maintenance modes, and we left the no-battery mode energy use unchanged in the wireless scenarios.

[6] *Charging* (or "active") mode occurs when the battery charger is connected to a power source and the charger is working to equalize the battery cells. *Maintenance* mode occurs when the battery charger is connected to a power source and the battery is fully charged. *No-battery* mode occurs when the battery charger is connected to a power source, but not connected or coupled with a battery-powered device.

[7] According to U.S. DOE's TSD and NIA, the maintenance mode power draw corresponding our wired baseline is 300 mW (0.3 W) for all the product categories in scope (U.S. DOE 2015, 2016b). BFE (2017) has a small sample of data on the no-battery mode power draw of inductive phone chargers, ranging from 70 mW to 450 mW. We felt this was insufficient data to justify scaling no-battery mode power from the wired baseline to wired scenarios.

Then, for each wireless impact scenario, for each product category, we adjusted the wired baseline energy use by following these steps:

- Calculate the portion of battery charging energy that will be wireless;
- Calculate the overall wireless battery charger system efficiency;
- Calculate a wired-to-wireless scaling factor based on relative efficiency; and
- Apply the wired-to-wireless scaling factor to the wireless portion of battery charging energy.

For more detail on how we inflated the energy use in the wired baseline to represent wireless scenarios, see Appendix B.

2.4 GLOBAL EXTRAPOLATION

Once we had calculated battery charging energy in each wireless scenario, scaling from our 2030 U.S. wired baseline, the final stage of our analysis was to scale U.S. estimates to every other country. We did so by estimating the number of smartphones in each country in 2023 and then using those 2023 smartphone estimates as a linear scaling factor. For more detail on how our methodology, data sources, and rationale, see Appendix C.

3. RESULTS

3.1 DRIVING FACTORS IN GLOBAL ENERGY INCREASES

We estimate that worldwide in 2030 the battery charger products in the scope of this analysis would consume 66 TWh/yr if they were all wired (i.e., in the wired baseline scenario). This is equivalent to 0.3 percent of global electricity consumption in 2017 (Enerdata 2018).

Figure 3 shows how much that energy would increase depending on adoption rates and the efficiency of wireless power transfer. The impact scenarios in Figure 3 assume the mid-case for the efficiency of other wireless charger components, meaning they assume that wireless chargers will be, on average, as efficient as wired chargers in their power supplies, charge control circuitry, and batteries. Each bar is labeled with its relative energy use compared to the baseline. For example, the mid-case efficiency and mid-case adoption scenario yields 1.4 times as much global battery charger energy use as in the wired baseline.

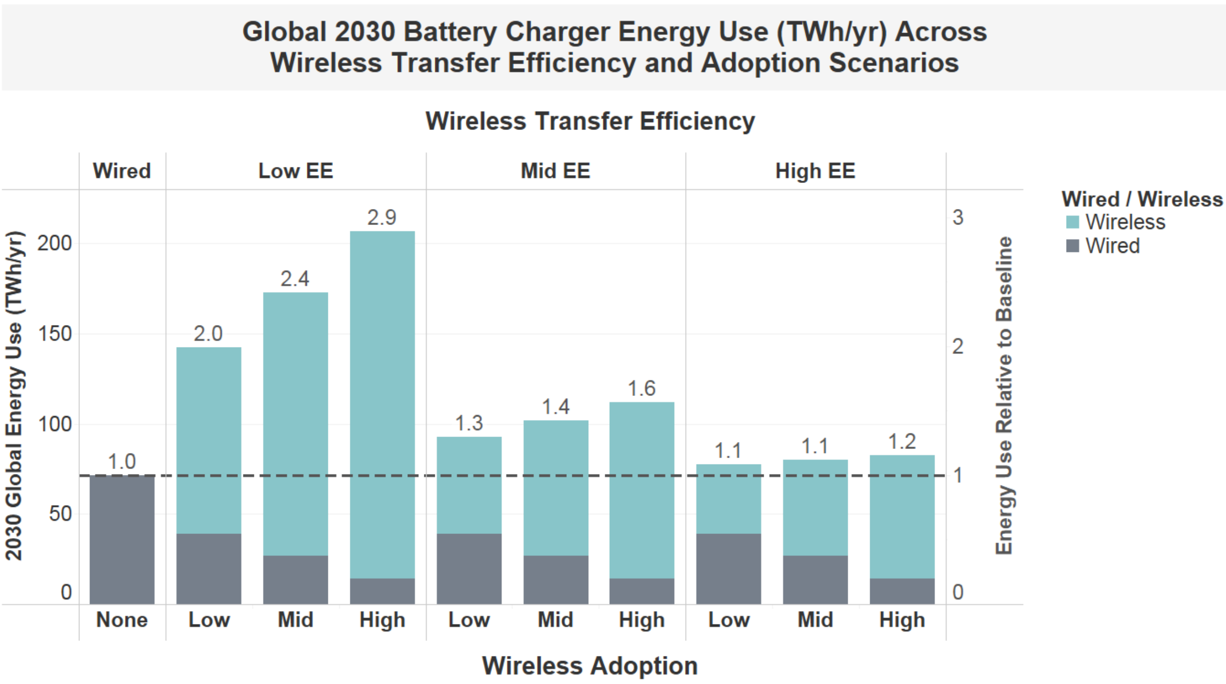

Figure 3: Global battery charger energy use across wireless transfer efficiency and adoption scenarios

Notably, in the highest impact scenario in Figure 3, in which global adoption is uniformly high and average transfer efficiency is low (commensurate with the worst performance of today's magnetic resonance chargers), battery charger energy is 2.9 times its baseline value. In this case, the increase in 2030 global electricity consumption is equivalent to 125 TWh/yr or 55 percent of Australia's 2017 electricity consumption (Enerdata 2018). In contrast, if average transfer efficiency is high (commensurate with today's high-performing inductive chargers), then even with high wireless adoption battery charger energy is only 1.2 times its baseline value, equivalent to 10 TWh/yr of additional load or 5 percent of Australia's 2017 electricity consumption.

Figure 4 shows a different combination of impact scenarios, this time holding wireless adoption constant (assuming mid-case adoption) and varying both transfer efficiency and the efficiency of other components.

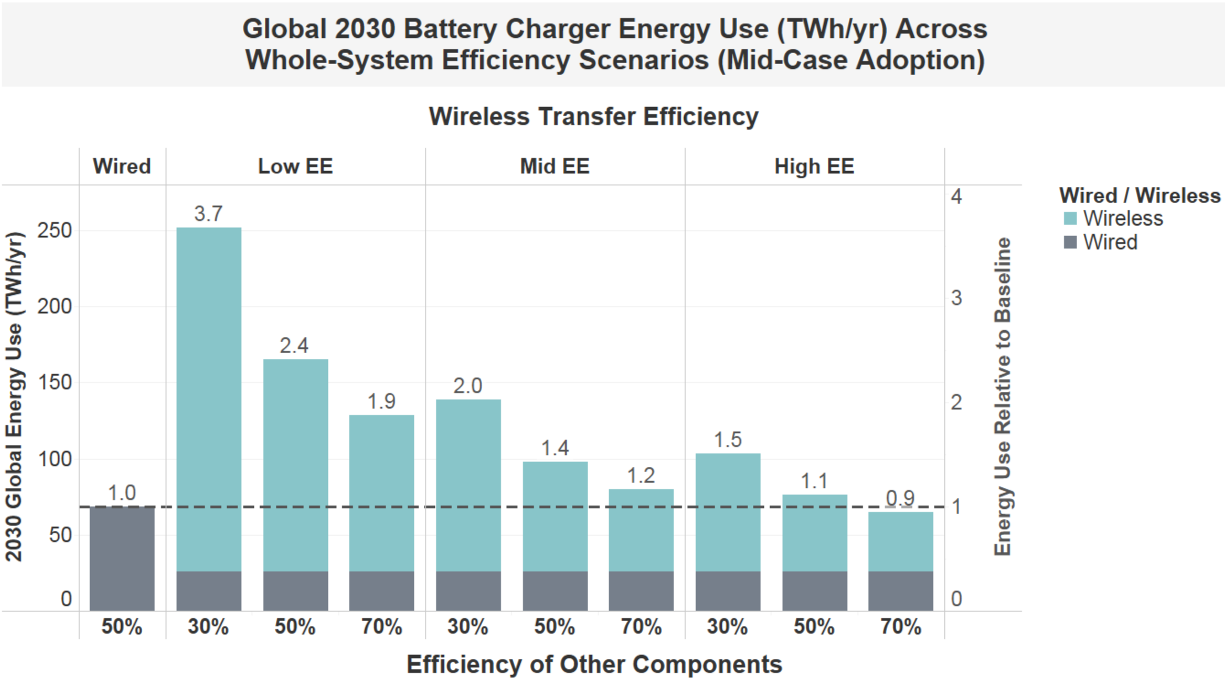

Figure 4: Global 2030 battery charger energy use across whole-system efficiency scenarios

From a policymaker's perspective, Figure 4 illustrates the importance of collecting data to better understand not just transfer efficiency, but also the efficiency of the rest of the system. For example, given mid-case transfer efficiency, the battery charger energy use can range from 1.2x baseline to 2.0x baseline, given the wide range of efficiency of other component that is seen in wired chargers (Foster Porter and Delforge 2018).

Unlike transfer efficiency, there are no strong theoretical reasons to assume that the power supply, charge control circuitry, and batteries used in wireless charging systems will be any better or worse than their wired counterparts.[8] However, if those other components in wireless charging systems are as inefficient as those in the least efficient wired systems, it would counteract the efficiency gained from improving wireless transfer efficiency from the mid-case to the high-case.

On the other hand, the lowest impact scenario in Figure 4 highlights the possibility that wireless battery charger systems could actually use less energy than today's wired chargers if the transfer

[8] Because of this, the mid-case efficiency assumption for transfer efficiency is the same as in the wired baseline.

efficiency is high and the efficiency of the rest of the battery charger system is optimized. This modeling outcome is corroborated by BFE (2017), which reports in its literature review system efficiency for "optimized" induction chargers than overlaps with the range of system efficiency provided for wired chargers. For an overview of technical pathways for improving wireless battery charger efficiency, including transfer efficiency and efficiency of the rest of the system, see Foster Porter and Delforge 2018.

3.2 REGIONAL ENERGY IMPACTS

Figure 5 shifts focus to the global distribution of forecasted battery charger energy for the product categories we analyzed.[9] Fifty-eight percent of the 2030 battery charger energy we forecast is within Asia. Thirty-seven percent is within China and India alone (which represent 21 and 15 percent of forecasted global battery charger energy use, respectively). Other regions and countries with notably large shares of global battery charger energy use include the EU (13 percent), U.S. (six percent), and Brazil, Indonesia, Russia, Japan, Turkey, Mexico, and Germany (all approximately two percent).

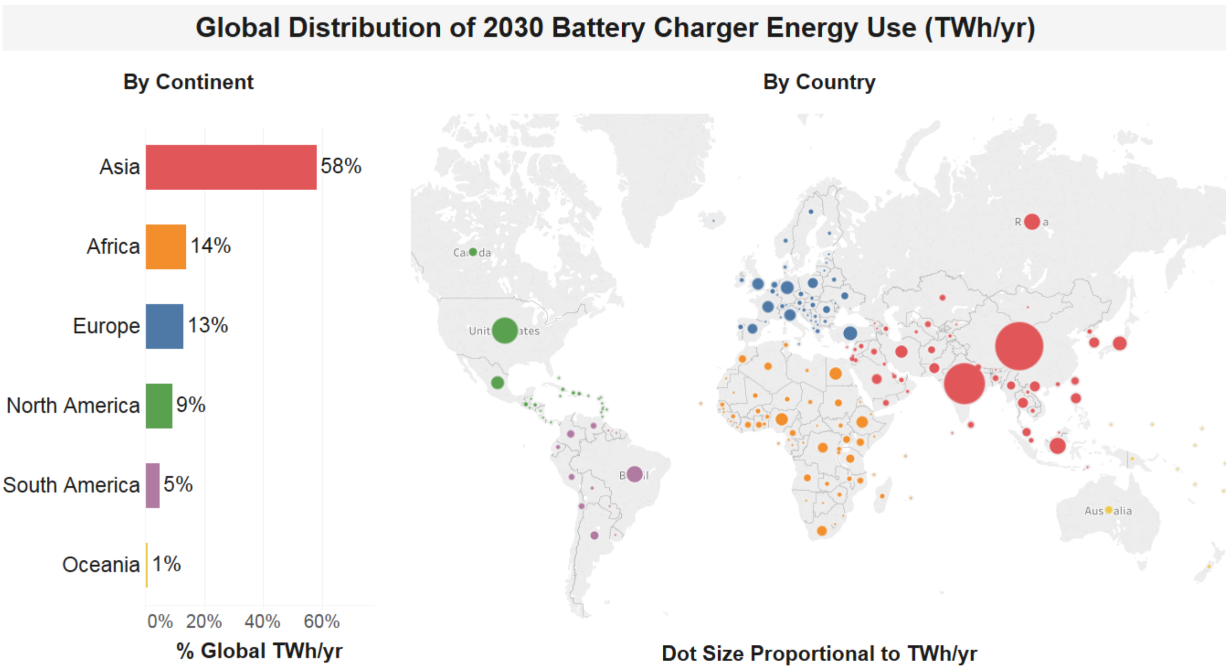

Figure 5: Fraction of global 2030 battery charger energy by continent; country-specific distribution

Figure 7 presents the full range of the 27 wireless impact scenarios we modeled, including the scenarios with the lowest and highest energy use as well as the scenario with all mid-case assumptions. These global scenario results are combined with the geographic distribution from

[9] Due to our modeling methodology, the distribution of all battery charger energy is proportional to the distribution of wireless energy, of additional energy due to wireless charging, and fundamentally to our country-specific forecast of smartphones in 2023.

Figure 6 to give readers an order-of-magnitude understanding of the possible range of energy impacts by continent.

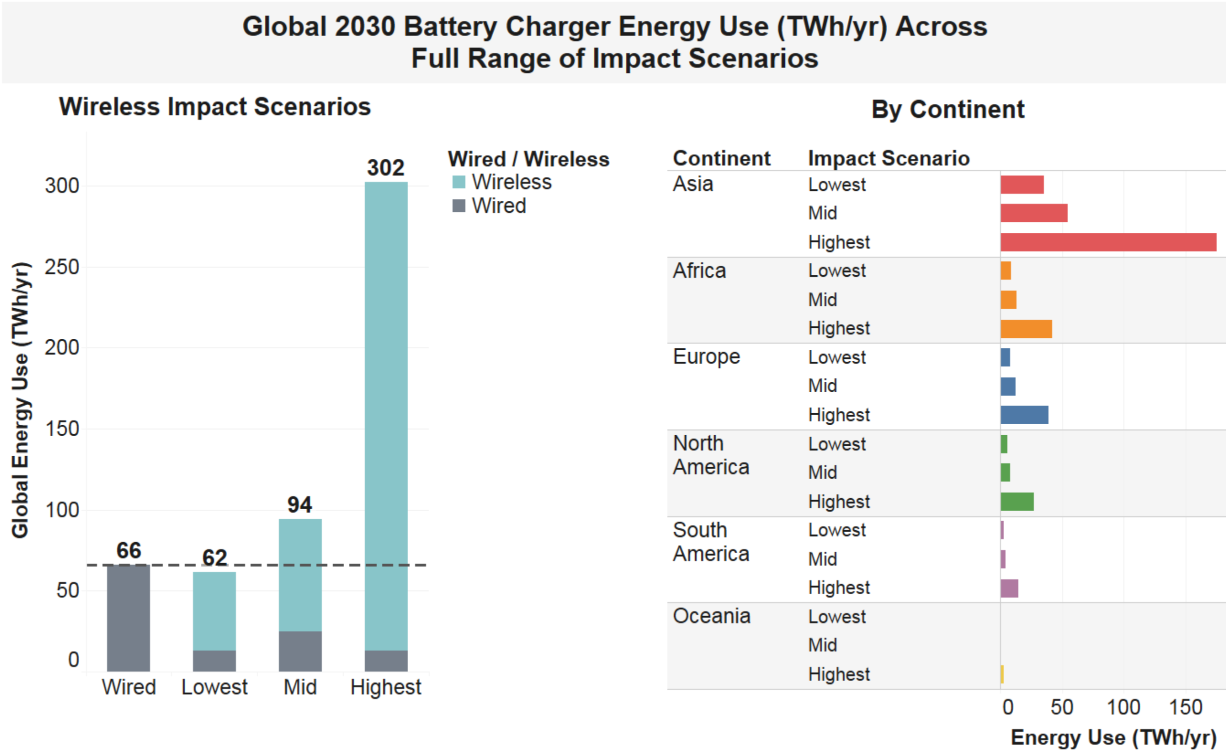

Figure 6: Global battery charger energy use, including geographic breakdown, across the full range of impact scenarios

The highest impact scenario in Figure 7 represents a dramatic increase in global energy use for battery charging, equivalent to 1.1 percent of the entire world's electricity consumption in 2017 or 103 percent of Australia's 2017 electricity consumption (Enerdata 2018). However, the highest impact scenario is truly a worst-case scenario, particularly because it assumes the efficiency of other components in wireless chargers is 67% lower, on average, than in wired chargers (i.e., 30 percent as compared to 50 percent efficiency), but also because it assumes 25 percent average transfer efficiency, which would suggest that wireless technologies with greater range become popular and are not optimized for efficiency.[10]

The impact scenario with all mid-case assumptions represents our best estimate of wireless charging energy use without policy intervention. In this scenario, the additional global electricity from wireless charging in 2030 is 31 TWh/yr, which is equal to 1% of Europe's 2017 electricity

[10] The efficiency of inductive charging is sensitive to displacement of the receiver relative to the transmitter, both horizontal and vertical; however, even a misaligned inductive charger would not have a transfer efficiency as low as 25 percent. When misalignment exceeds a certain threshold, inductive charging stops (BFE 2017). Based on data from BFE (2017), we can estimate what the real-world efficiency would be given our mid-case transfer efficiency scenario (53% efficiency) and the worst-case displacement would not cease charging—a vertical displacement of 2 mm. In this situation, the real-world efficiency of inductive charging would be 53% x 80% (the penalty for a 2 mm vertical displacement) = 42%, which is still higher than our low-case transfer efficiency assumption (25%).

consumption or 140% the electricity currently used to mine bitcoin worldwide (Enerdata 2018; The Economist explains 2018).

Finally, the lowest impact scenario reinforces that it is technically possible for wireless chargers to have greater whole-system efficiency than today's typical wired chargers. To achieve this, it would be necessary to have high transfer efficiency and optimize the efficiency of the rest of the battery charger system.

4. POLICY CONSIDERATIONS, RECOMMENDED NEXT STEPS

In this section, we discuss the current status of efforts to develop wireless test procedures and the implications of our findings for test procedure development, complementary data collection and research, and policy initiatives to improve wireless charging efficiency.

4.1 CURRENT WIRELESS TEST PROCEDURES

Developing agreed-upon test methods and efficiency metrics for quantifying the efficiency of wireless chargers is one of the most important next steps to improve the efficiency of wireless chargers.

There is currently no formal and internationally recognized test procedure for measuring the efficiency of wireless power transfer, but several efforts are currently underway, mostly focused on near-term inductive charging applications. In the U.S., the WPC has been working in collaboration with the U.S. Environmental Protection Agency (EPA) and the U.S. DOE on measurement methods for measuring the efficiency of wireless power transfer. A proposed method for measuring the relative efficiency of wireless power transmitters (comparing one transmitter against another) has been developed. The proposed test method is limited to magnetic induction-based wireless power transmitters designed to supply up to 100 W (essentially of the type used in Qi products). The proposed protocol is now underway to validate the test protocol and address concerns around repeatability of results, applicability to the diverse range of receivers that could be in products on the market. It is not clear whether this protocol will gain wide industry acceptance with industry members whose products are designed to other standards. The U.S. American National Standards Institute (ANSI) and Consumer Technology Association (CTA) have published a measurement standard, ANSI/CTA-2042.3. It outlines a procedure to measure transmitter standby power and power transfer efficiency (ANSI/CTA 2018). It is less detailed than the WPC protocol and the extent to which it has been used is unknown.

Independently, the International Electrotechnical Commission (IEC) is developing international standards in two separate wireless power transmission Technical Committees (TCs) because of the wide variation in the power demands of various devices and systems ranging from cars to smartphones. These standards are "IEC TC 100/Technical Area (TA) 15: Wireless power transfer of multimedia systems and equipment" and "IEC TC 69: Wireless charging of electric vehicles, including industrial trucks, buses, and scooters." WPC presented the status of their work to the TA 15 group. The TA 15 task group is interested in the work of WPC and is awaiting the final results. They would consider harmonizing with an ENERGY STAR test protocol, should one be developed.

Developing wireless charging test procedures will be challenging, even for the limited use case of inductive charging. Wireless charging systems are unique for two main reasons. First, there are a range of potential receiver-transmitter combinations, and interactions between the two are known to impact overall power transfer efficiency. This begs the question of how one can generally characterize the efficiency of a charging pad or other charging "base station" that could be used with dozens of different devices. Finally, device positioning can have a substantial impact on transfer efficiency. For example, orientation of an induction-charged product on a charge pad can significantly impact power transfer efficiency, and the effect is so pronounced that industry test procedures currently recommend taking multiple measurements with various random device placements to control for this effect. Device proximity, orientation, and even electromagnetic conditions could come into play as stakeholders attempt to extend test procedures to cover other wireless charging technologies, such as magnetic induction and RF.

4.2 RECOMMENDED NEXT STEPS

Based on our modeling research and results, we have the following recommendations for test procedure development, complementary data collection and research, and policy initiatives to improve wireless charging efficiency.

4.2.1 Consider Whole-System Efficiency Wherever Possible

As shown in Figure 4, transfer efficiency is not a reliable indicator of wireless charging system efficiency. Furthermore, the efficiency of the other components in a wireless battery charger system have a large effect on the whole-system efficiency.

Ideally, test procedures would capture whole-system efficiency wherever possible; however, because wireless chargers are often sold independent of the devices they charge, this can be difficult. In the long term, it is valuable to work towards holistic test procedures where appropriate. One of the chief benefits of whole-systems approaches is that they provide manufacturers with more flexibility in meeting any voluntary or mandatory efficiency targets: wireless chargers with lower transfer efficiency could compensate with efficiency improvements in other components. In the near term, it may be more practical to focus on test procedures with a narrower scope but complement the information derived from test procedures with laboratory testing.

4.2.2 Better Characterize Maintenance Mode Energy Use

Maintenance mode—the battery charger mode in which the battery is fully charged but still interfacing with the charger—could constitute a large portion of the energy impact of wireless charging. In BFE (2017), the authors found that the power draw of inductive chargers in maintenance mode were much higher than in no-battery mode. Moreover, they found that the maintenance mode energy use of a smartphone over the course of 24 hours could be greater than the energy required to provide a full charge. As wireless charging stations become prevalent in public places, the amount of time that devices spend fully charged on wireless charging pads may grow well beyond the usage assumptions upon which our model is built, thereby causing wireless energy consumption in each scenario to exceed our estimates.

In our modeling, we were unable to separate maintenance mode and charging mode energy, because the U.S. DOE test procedure involves a 24-hour charge cycle and does not report how long it takes the device to become fully charged. We recommend that any wireless test procedures based on a 24-hour charge cycle report the duration for a full charge as well as maintenance mode wattage. For a breakdown of modeled wireless energy use by product category and mode, see Appendix D: Wireless Energy by Product Category and Mode.

It would also be valuable to commission field studies to characterize the “duty cycle” of wireless battery chargers in public places—that is, how often they are in charging, maintenance, and no-battery mode. These duty cycle assumptions are just as consequential for modeling the impact of wireless charging as assumptions about power draw.

4.2.3 Estimate the Impact of End Uses Outside the Scope of this Report

Finally, it is important to recognize that this report only covers the product categories designated as “in scope” in Figure 2 and does not include wearables, kitchen appliances that are currently wired, or loads outside the residential and commercial sectors, such as full-sized vehicles, robotic for manufacturing, or military drones. An order of magnitude estimate of the potential wireless energy use associated with these end uses and some form of sensitivity analysis is needed to understand the implications of excluding them from this global impact analysis.

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APPENDICES

APPENDIX A: ADOPTION ASSUMPTIONS

Our adoption assumptions are summarized in Table 2. We retained the same low and high assumptions that Foster Porter and Delforge 2017 used for U.S. DOE product classes 2 and 4, which are based on the authors' synthesis of wireless charging market research and forecasts, as detailed in Foster Porter and Delforge 2018. We included some product categories from U.S. DOE product class 3 in our analysis (see Figure 1), whereas Foster Porter and Delforge 2018 focused only on product classes 2 and 4. We determined it was worth including product categories from product class 3 even though--due to a lack publicly available data--our adoption assumptions simply represent our estimate of a plausible range of adoption for the sake of sensitivity analysis.

Table 2: Low, medium, and high wireless adoption assumptions

U.S. DOE Product Class	Fraction of Devices that Will Be Wireless-Compatible			For Wireless-Compatible Devices, Fraction of Charging Energy that is Wireless		
	Low	Mid	High	Low	Mid	High
2 (e.g., smartphones)	64%	77%	89%	80%	85%	90%
3 (e.g., power tools, handheld vacuums)	25%	50%	75%			
4 (e.g., notebook computers)	40%	65%	90%			

APPENDIX B: SCALING ENERGY FROM WIRED TO WIRELESS

After separating the charging and maintenance mode energy for each product category, we adjusted it to reflect the given wireless impact scenario by following these steps:

- **Calculate the portion of battery charging energy that will be wireless:** This is the product of our two wireless adoption assumptions. For example, in the mid-case adoption scenario, we estimate that 77% of smartphones will be wireless compatible and that wireless-compatible phones will do 85% of their charging wirelessly. Therefore, 77% x 85% = 65% of smartphone battery charging energy will be wireless.
- **Calculate the overall wireless battery charger system efficiency:** This is the product of our two wireless efficiency assumptions, which we vary independently. For example, given mid-case transfer efficiency (53%) and high-case efficiency of other components (70%), the system efficiency of a wireless smartphone charger would be 53% x 70% = 37%.
- **Calculate a wired-to-wireless scaling factor based on relative efficiency:** This is simply 50%--the global assumption for wired system efficiency--divided by wireless system efficiency. For the sample efficiency assumptions above, the resulting ratio is 50% / 37% = 1.35, meaning that wireless battery charging consumes 1.35 times as much energy for charging and maintenance compared to wired charging.
- **Apply the wired-to-wireless scaling factor to the wireless portion of battery charging energy:** For example, given the adoption and efficiency assumptions above, we would multiply 65% of the wired baseline energy (for charging and maintenance modes) by a scaling factor 1.35 to estimate the equivalent wireless scenario energy.

APPENDIX C: GLOBAL EXTRAPOLATION

Table 3 summarizes the key inputs for our forecast of smartphones in each country in 2023, how we used each input, and the underlying data sources.

Table 3: Inputs and methodology for deriving country-specific energy scaling factors

Input	Function	Source
2018 smartphone penetration by country (for 50 countries)	Used to estimate smartphones in each country in 2018 (for 50 countries representing 91% of 2017 GDP)	1
2017 GDP per capita (all countries)	Used to as the predictor variable in a linear regression to statistically estimate 2018 smartphone penetration for the remaining countries.[11]	2
2017 population (all countries)	Multiplied by 2018 smartphone penetration—reported if possible, otherwise statistically estimated—to estimate smartphones in 2018.	3
2018-2023 forecast of smartphone subscriptions (by region)	Used to scale 2018 smartphone estimates for each country to 2023. We did not extrapolate the highly linear 2018-2023 trends to 2030 due to uncertainty about limits to growth of the underlying drivers of the smartphone subscription trend.	4
Sources: 1. Newzoo 2018. 2. CIA 2018a. 3. CIA 2018b. 4. Ericcson 2018.		

The resulting scaling factors are strongly driven by population but also reflect a forecast of the per-capita adoption of premium consumer electronics. As such, they are a simplified but reasonable proxy to scale our global analysis of wireless battery charging.

[11] Among the 50 countries for which public data on smartphone penetration was available, GDP per capita is well correlated with smartphone penetration (R^2 = 0.74), following a fairly linear relationship.

APPENDIX D: WIRELESS ENERGY BY PRODUCT CATEGORY AND MODE

Figure 7 presents our results with all mid-case assumptions, split into product categories and operational modes. Charging and maintenance mode dominate energy use across all product categories. No-battery mode makes up the largest share of smartphone and mobile phone energy use, which is the product category with the largest global energy consumption.

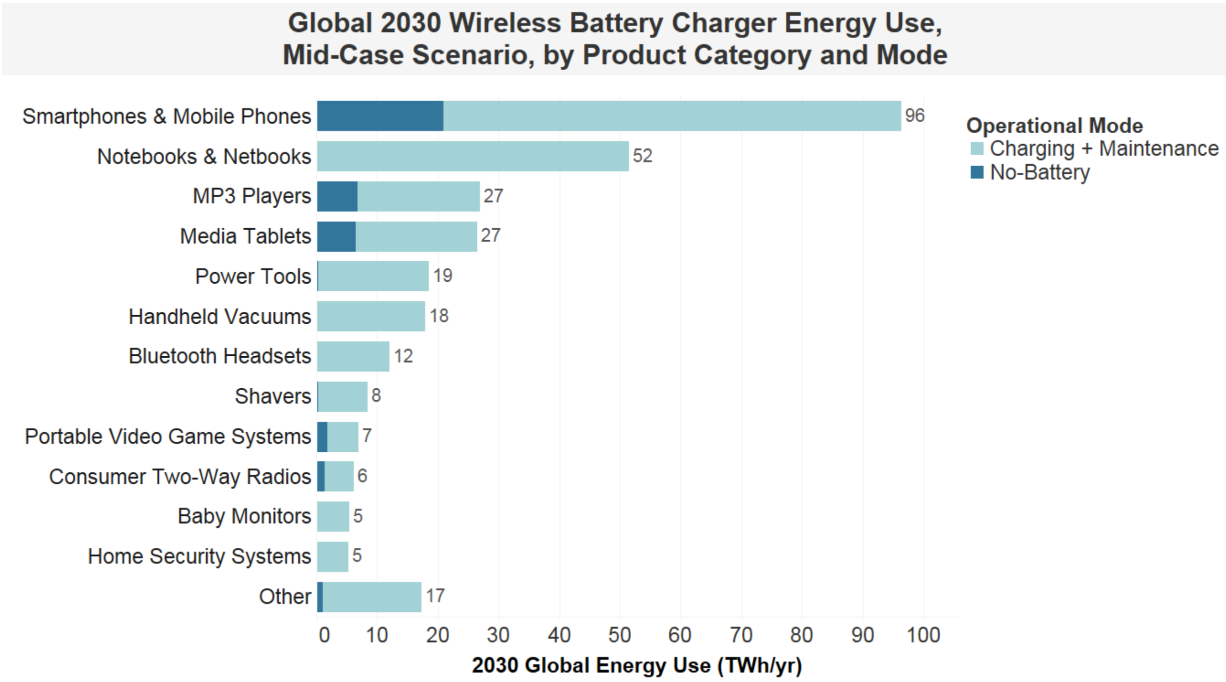

Figure 7: Mid-case scenario wireless energy use by product category and mode

We did not have sufficient data to justify scaling no-battery mode (up or down) from wired to wireless. Further data collection is needed to determine whether wireless phone chargers typically have higher no-battery mode power draw than wired phone chargers.

APPENDIX E: WIRELESS POWER FOR RESIDENTIAL DEVICES: WHAT IS THE ENERGY PENALTY OF CUTTING THE CORD?

Wireless Power for Residential Devices: What is the Energy Penalty of Cutting the Cord?

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ABSTRACT

Wireless chargers—devices that recharge batteries without a wired connection—are quickly becoming more common for consumer products such as cell phones and wearables (e.g., smart watches). They promise to enable waterproof electronics and increase charging convenience. Other corded kitchen appliances, such as blenders and slow-cookers, are also on industry's road map for wireless power. However, transferring energy without a direct electrical connection has an inherent efficiency penalty, and these newest wireless pad-style chargers and other types of wireless power transmitters are not covered by the U.S. DOE battery charger or external power supply standards. How much does "cutting the cord" increase energy use? Preliminary estimates in this paper reveal that a wireless charger may use 50% to 400% more energy to charge and maintain the battery than a wired charger. Furthermore, by 2022 wireless charging growth could offset the energy savings expected from the U.S. DOE battery charger standards. The paper concludes with recommended next research steps to further evaluate the energy efficiency of wirelessly powered devices.

Introduction

Powering products without cords is no longer a futuristic notion reserved only for science fiction. Wireless chargers for small battery-powered devices, such as cell phones, power tools and shavers are quickly becoming more commonplace. Wireless charging can enable hermetically sealed devices and eliminate the need to carry around small cell phone chargers. Wireless models of small countertop kitchen appliances—such as toasters, slow-cookers and bread makers—are under development by manufacturers with product releases expected within the next few years. Designers envision cord-free kitchen countertops with interoperable wireless under-counter power supplies.

This report focuses on current and industry-identified future residential wireless power products and begins to examine the possible national "energy penalty" (the incremental energy use) of switching from wired to wireless power for these products. Specifically, this includes residential wireless battery chargers and small countertop kitchen appliances.[1]

Over the course of five months in 2017, we reviewed readily available information on wireless power. We focused on determining whether "cutting the cord" is likely to significantly increase U.S. energy use and investigating possible test protocol approaches. To the extent possible, we updated this research in early 2018. Specifically, we:

1. reviewed the current and forecasted market data
2. identified current standards, technologies and efficiency measurements

[1] Resource constraints of the original study did not allow us to address wireless electric vehicle chargers and wireless medical chargers, but future research of these categories may be warranted.

3. crafted high-impact and low-impact energy scenarios for near-term and long-term projections
4. Considered test procedures needed to collect consistent, fair and reliable data
5. Developed next steps for further research.

Market Analysis and Product Reach

Our market analysis included products readily available today and anticipated shifts in consumer usage. The 2018 wireless power market is dominated by battery charging applications including professional-grade power tool chargers, tabletop cell phone chargers (Figure 1), chargers for wearables (such as smartwatches), cordless shaver chargers, and aftermarket products for many other small electronics (e.g., game controllers and wearable cameras). Samsung, Apple and Blackberry are among manufacturers that already incorporate mobile phone wireless charging compatibility from the factory. Wireless charging stations—primarily for mobile phones—have been installed on tabletops and in lounges by such influential companies as Starbucks, McDonald's and Marriott. A significant number of auto-makers, luxury and budget alike, are bringing wireless charging for mobile phones to their newest vehicle lineups. Planned end use wireless chargers not yet available from original equipment manufacturers (OEMs) include laptops, tablets and drones.

Figure 1. Examples of currently available consumer wireless chargers. Left: Proprietary Bosch wireless charging system for power tools. *Source:* Bosch 2017. Right: Example of large wireless charger in corporate meeting room. *Source:* Treffers 2013.

Consumer awareness and demand for wireless charging is also increasing. According to a 2017 industry survey, more than one-third of U.S. consumers have already used wireless chargers (Yussuff 2017). Another industry survey indicates that 70% of consumers want wireless charging with their next device: 50% of consumers would spend $20 more for wireless charging, and 12% would spend as much as $120 to utilize non-wired charging options (Berg Research 2017). Small electronics, especially cell phones and wearable electronics (e.g., smart watches), are the majority of current products, but the laptop market is expected to see growth over the next five years. An independent survey showed 75% of consumers would like to see wireless charging adopted in laptops (Yussuff 2017). Companies—many of them market heavyweights—have responded to increasing consumer demand with a variety of products, as shown in Table 1.

Table 1. Examples of products and companies involved in the wireless charger market

Wirelessly charged product examples (current and planned)	Sampling of brands, companies and communities installing wireless chargers for consumer use
Integrated by OEM: Cell (mobile) phones (e.g., Apple, Samsung, Blackberry); cordless power tools (e.g., Bosch); wearables (smart watches and fitness bands) (e.g., Motorola and Apple) *Aftermarket:* Cell phones—nearly all top smart phones; wearables, including smart watches, fitness bands, action cameras; game console controllers; toys (drones, remote controlled cars, etc.); office electronics (Bluetooth speakers, Bluetooth mouse); other small electronics (mp3 players, blue tooth headphones, handheld cameras, etc.); tablets *Planned:* Medical devices, drones, laptops, tablets, larger electronics	*Hospitality* (on tables and furniture): Marriott, Starbucks, and McDonald's *Auto* (in vehicles): Honda, Chevrolet, Cadillac, Toyota, BMW, Hyundai, Lexus, among others (Haj-Assaad 2016). *Corporate* (meeting rooms): Facebook, Google, Texas Instruments, and Verizon *Airports:* John F. Kennedy (New York); Newark Liberty (New Jersey); Miami (Florida); Los Angeles (California); Beijing Capital (China) *Cities* (airport, subway, restaurants, etc.): Shenzhen, China *In other devices for personal use*: iHome (alarm clocks)

In addition to wireless charging, industry has identified currently corded small kitchen appliances as the next opportunity for developing wireless power systems. One industry standard[2] is underway to enable interoperability of under-counter power transmitters and wirelessly powered appliances, including blenders, toasters, mixers, slow cookers, juicers, cooktop and other similar appliances. Concept products were on display at the 2018 Consumer Electronics Show (CES) in Las Vegas, Nevada (Treffers 2018). Together, expectations for growth are significant.

- Market analysts indicate that wireless power components and accessories sold with consumer electronics accounted for about 60% of the global revenue of the wireless power market in 2014, and they predict that consumer electronics will continue to dominate the wireless power market at least through 2022 (Grand View Research 2016).
- Forecasters expect the U.S. to play a significant role in this market that is expected to have a compound annual growth rate (CAGR) of 35% to 40% between 2016 and 2023 (Global Market Insights 2016).
- Although small electronics constitute much of the 2018 product, companies are developing wireless power for small (currently corded) kitchen appliances and portable appliances with larger batteries, including medical devices, drones, laptops and others.

[2] This kitchen appliance standard is under development by the Wireless Power Consortium (WPC). We discuss more information on industry standards in the subsequent section entitled Technology, Standards and Efficiency.

If this expected growth is realized, we estimate that approximately 50% of all small electronics, such as cell phones, and 50% of all laptops in use would be compatible with wireless charging in the U.S. by 2023.

Wireless Power and Current U.S. Appliance Energy Policy

Even though wireless charging has captured the interest of many consumers and market analysts expect rapid growth in wireless charging solutions, the current U.S. Department of Energy (DOE) test procedures and standards do not cover most current and future consumer products with wireless power consumer products.[3] Similarly, none of these products are addressed by the U.S. Environmental Protection Agency ENERGY STAR® Program. Furthermore, some of the technologies have an inherent efficiency penalty associated with the wireless charging format that may increase energy use by as much as 400% per charger when compared to conventional wired chargers. To better understand these implications on energy use, we analyzed the technologies and industry design standards, and then compiled the various ways efficiency could be impacted and/or improved. The next section discusses each aspect in detail.

Technology, Standards and Efficiency

Technology Approaches

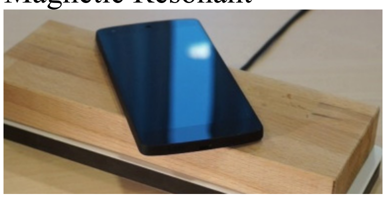
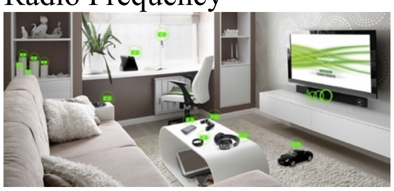
Wired appliances that plug into a wall outlet transfer electric energy via conduction through copper wire. Wireless appliances transfer energy across a gap without a conductive medium using a number of different technologies: electrodynamics, electrostatics, ultrasonic transduction, infrared radiation,[4] microwaves and lasers are among those developed or under development. Different technologies enable different distances between the receiver (in the device with the battery that is charged) and the transmitter (the charger that sends the charge signal). Three categories of range (displacement) are generally used:

- Far-field (the charger and the battery are meters apart)
- Mid-range (the charger and the battery are centimeters apart)
- Near-field (the charger and the battery are millimeters apart)

The three technologies that emerged as the most relevant in today's market are inductive, magnetic resonant and radio frequency (RF). Inductive and magnetic resonant have the greatest market adoption. Pre-sale of consumer RF product and charger systems became available this year (Energous 2018). A summary of the advantages, disadvantages and range of the three market-relevant technologies can be found in Table 2.

[3] Wireless chargers designed for wet or damp environments are included in the current U.S. DOE scope as class 1.
[4] An example of the infrared solution is Wi Charge. Accessed June 2017; www.wi-charge.com/technology/

Table 2. Summary of current market-relevant technologies

Technology	Range	Advantages	Disadvantages
Inductive[a] 	Near-field: no more than 5-mm gap	Improved power transfer efficiency compared to magnetic resonant	Performance (i.e., efficiency and charge rate) may be sensitive to placement location on the charge mat
Magnetic Resonant[a] 	Mid-range: mm to cm gap, both horizontal and vertical	Vertical displacement from charging surface possible (e.g., can be installed under table or counter); multi-device charging inherent	Lower power transfer efficiency and more heat produced than inductive, higher electromagnetic interference (particularly in single coil configurations)
Radio Frequency[b] 	Near-field, Mid-range, and Far-field: (up to 4.5-meter gap)	No specific location required; charging can happen anywhere in a room while device in use; 3 mm receivers easily embedded in devices	Consumer perceptions about health impacts of focused RF signals; product pre-sales only

[a] *Photo credit:* Wireless Power Consortium 2017a. [b] *Photo credit:* Energous 2017.

Industry Design Standards

Today's key industry design compatibility standards are Wireless Power Consortium's Qi (pronounced chi) open standard, AirFuel Alliance's Resonant open standard, and Engerous' WattUp proprietary standard. The AirFuel Alliance also hosts a RF working group. Other companies have additional proprietary wireless charging standards and associated products. A summary of these industry standards—including the enabling technologies, number of developed products and participating companies—is provided in Table 3.

Which standards will dominate over time is still uncertain, but currently the two main competing standards for small electronic products are Qi and Airfuel. Qi currently has more market momentum, as it has been adopted by automakers and doubled its number of members and products over a sixth month period from late 2017 early 2018. Yet, Energous' far-field wireless chargers provide more charge-location freedom that may be valued by consumers. Regardless, analysts predict that once original equipment manufacturers agree on a standard for wireless charging, barriers to market growth will diminish (Global Market Insights 2016).

Table 3. Summary of today's key wireless power industry design standards

Technology standard/ Ecosystem	Enabling technology and displacement	Developed products[5]	Number of participating companies[3]
Qi standard Open standard maintained by non-profit Wireless Power Consortium Started 2008	Inductive (near-field) Magnetic Resonant (mid-range) for battery chargers and currently corded kitchen appliances	First smart phones announced 2011 1,630 products certified, including both receivers and transmitters	569 companies: Apple, Sony, Philips, Bosch, LG, Verizon, Toshiba, Nokia, Samsung, Panasonic, among others
AirFuel Resonant standard *AirFuel RF Working Group* Open standards maintained by non-profit AirFuel Alliance Started 2012	Magnetic Resonant (mid-range) RF (far-field)	At least 60 products certified, including both receivers and transmitters	68 companies: LG, Dell, Energous, Duracell, HP, Bose, SHARP, Samsung, Sony, among others
WattUp standard Proprietary standard of for-profit publicly traded Engerous (WATT) Started 2013	Radio Frequency (near-field, mid-range, and far-field up to 4.5 meters)	First products in pre-sales phase	Not available; Participate in Air Fuel Alliance RF working group

Efficiency and Wireless Power

We expect the efficiency of wireless power systems to be lower than wired systems. Our research suggests there are ranges in the efficiency of wireless charging technological solutions and opportunities to optimize the wireless power transfer for efficiency. Given more information is on currently available products, this discussion focuses only on wireless battery chargers for small electronics, beginning with an overview of components in wired and wireless systems.

There are many components to any battery charging system, all of which can enhance or reduce battery charger system efficiency. For a wired charger, the basic components are ac-dc power conversion, charge control and the battery. Wireless chargers are more complex and have more components. Instead of using wire cable or pressure-based metal connectors to deliver charge to the battery, most wireless chargers use transmitters and receivers. Additional components required for inductive and magnetic resonant technologies[6] (the two most common wireless technologies in the market today) include:

- transmission electronics— to control the signal in the transmitter coils
- wire coils in transmitter (Figure 2)—to transmit the power to the receiver

[5] As of May 30, 2018.
[6] Alternatively, radio frequency technologies require a large centralized charger that transmits charge to multiple products at once and a small microchip receiver circuit inside the battery-charged product.

- wire coils in receiver—to receive the power from the transmitter
- rectification circuit in the receiver—to turn the power into a form that can be used by the charge control circuit to charge the battery

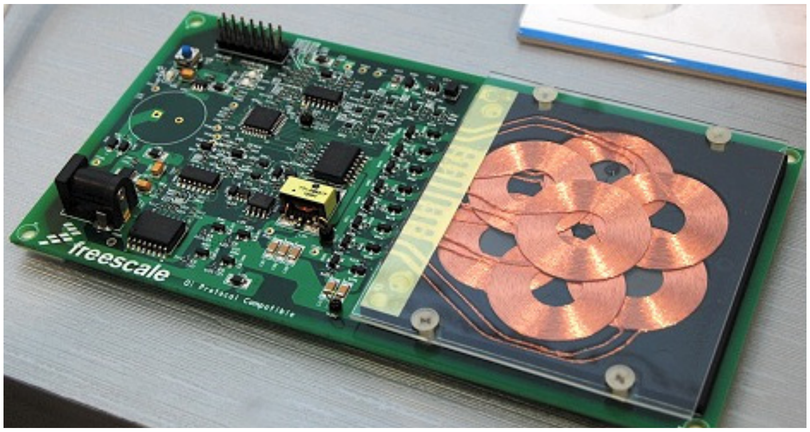


Figure 2: Example of multiple coil transmitter for inductive/magnetic resonant charger. *Source:* Accessed June 2017 https://www.wirelesspowerconsortium.com/technology/magnetic-resonance-and-magnetic-induction-making-the-right-choice-for-your-application.html

We estimate that wireless charging system efficiency as measured under the U.S. DOE battery charger system test procedure will be lower than direct wired chargers. Industry's own measurements of inductive and magnetic resonant transfer efficiency during charge range from 25% to 65% (Perzow 2015). These efficiency values exclude losses in the power supply, the charge control circuity, and the battery. If we assume losses in these additional components are similar to the average losses in current wired cell phone/smart phone/mobile phone chargers in the California Energy Commission (CEC) database,[7] then total system efficiency of wireless chargers on a 24-hour cycle may be 13% to 33%.[8] For comparison, the average 24-hour efficiency for cell phones in the CEC database is 50%.

Figure 3 provides an illustration of how wireless energy transfer affects efficiency and compares those efficiencies to an average wired cell phone charger that is similar to the CEC cell phone average (50% efficient over a 24-hour charge and maintenance cycle). The theoretical summary assumes average losses for other components, but if we consider the range of losses found in current wired cell phone chargers and the industry-reported range of wireless transfer efficiency, the range of 24-hour efficiency of wireless chargers may be even wider, from

[7] Review of CEC data base with 184 cell/mobile/smart phone chargers accessed June 16, 2017 from cacertappliances.energy.ca.gov/Pages/Search/AdvancedSearch.aspx. The 24-hour efficiency of 184 wired chargers for cell phones posted to CEC database in 2016 and 2017 have an average 24-hour efficiency of 50%. The range was from 30% to 60%. USB chargers with high efficiencies were eliminated as they do not include efficiency penalties of ac-dc power conversion.

[8] The 184 wired chargers for cell phones posted to CEC database in 2016 and 2017 have an average 24-hour efficiency of 50%. This calculation assumes that other systems in the battery charger, including the power supply, charge control, and battery, are otherwise similar to wired chargers. The efficiencies multiply, so to find the lower range, we take the product of 50% and 25%, we get 13% efficient on a 24-hour cycle (50%*25%=13%). To get the high range, we take the product 50% and 65%, we get 33% efficient on a 24-hour cycle (50%*65%=33%).

approximately 8%[9] to 45%.[10] These are estimates only, as no independent studies of typical wireless charging products have been conducted. More research is needed to further understand the energy penalty of wireless charging.

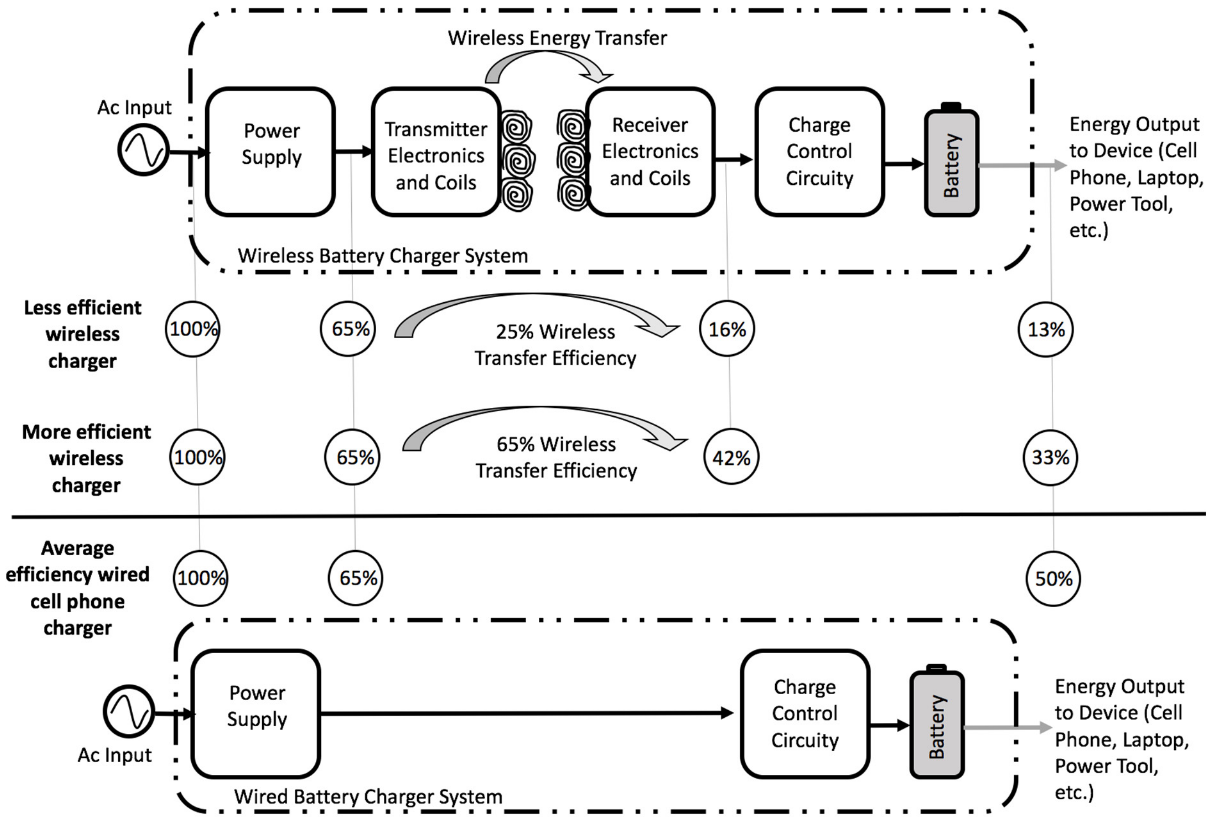


Figure 3. Summary of theoretical losses associated with wireless charging

Because battery charging includes a system of components, the efficiency of wireless chargers can be improved with approaches used with wired chargers. (Given wireless power systems for corded appliances would also be more complex with wireless power, the items marked with an "*" would also be applicable opportunities to optimize efficiency of currently wired small kitchen appliances.) Strategies might include:

- **Ac-dc power conversion improvement*:** Increases efficiency of power supply of the transmitter (charging pad) through resonant switching and synchronous rectification (Geist 2006).

[9] The least efficient cell/mobile/smart phone chargers (on a 24-hour cycle) of 184 in the CEC database was 30%. Accessed June 16, 2017 from cacertappliances.energy.ca.gov/Pages/Search/AdvancedSearch.aspx. The efficiencies multiply, so if we take the product of 30% and 25%, we get 8% efficient on a 24-hour cycle (30% (low)*25% (low)=8%).

[10] The highest efficiency possible for a wired mobile phone charger (70%) was outlined in EPRI's Battery Charger Technical Primer Report (Geist 2006). The efficiencies multiply, so if we take the product of 70% and 65%, we get 45% efficient on a 24-hour cycle (70% (high)*65% (high)=45%).

- **Higher internal system voltage:** Reduces resistive and conversion losses, and reduces system current (Geist 2006).
- **Battery sensing circuitry:** Drops no-battery mode power, can reduce unnecessary overcharge energy usage, reduces heat in the battery and can also lengthen battery life.
- **Reduced fixed energy consumption*:** Lowers standby power of control electronics in associated with the wireless power control and reduces standby losses associated with ac-dc power conversion.
- **"Right-sizing" transmitter for application*:** Using a wireless transmitter meant for wide range of devices to routinely transmit power to one type of device is likely to be less efficient than using a dedicated single device transmitter.

In addition, there are other ways of increasing efficiency of inductive and magnetic resonant transmitters and receivers used in battery chargers. Specifically, there are losses in the transmitter coil, losses in the receiver coil, and stray (leaked) energy (Wireless Power Consortium 2017b). Also, there are opportunities for component integration in the device that is being charged. (Again, items marked with an "*" would also be applicable for currently wired small kitchen appliances.) These strategies could include:

- **Increasing efficiency of wire coils used*:** Coil losses can be reduced by using thicker wires, though there will be weight and volume constraints on the receiver coil that may limit wire gauge. Transmission frequency can be optimized for efficiency (Ecova 2014a).
- **Minimizing stray energy*:** Displacement (both horizontal and vertical) can affect efficiency. Designers can minimize stray energy by providing guides (e.g., physical, magnetic, etc.) to limit the positions available for the receiver to rest relative to the transmitter. Resonant magnetic induction has a lower efficiency penalty associated with displacement when compared to inductive techniques.
- **Integrating charge control circuitry and the receiver:** Higher efficiency may be possible when the charge control and receiver are integrated instead of separate, yet separate charge circuity more easily enables both wired and wireless modes of charging today (Siddabattula 2017).

There are opportunities to investigate these technologies further with additional research. Next, we assess possible test procedure approaches for wireless-powered products and systems.

Test Procedures for Wireless Power

Although policymakers and industry are interested in understanding more about the efficiency of wireless power systems compared to wired and the variation in efficiency among wireless power systems, there is not yet an industry-accepted method for measuring efficiency of wireless power transmission.[11] Engineers in the industry have tried different approaches, but methods are not comparable to one another and may have a bias for certain technologies/standards (Lipsky 2015).

[11] The Wireless Power Consortium (WPC) that developed the Qi standards is, as of this publication, developing a test protocol to assess the efficiency of wireless transmitters. However, it is not clear whether this protocol will gain wide industry acceptance with industry members whose products are designed to other standards.

Options for test procedures include testing the transmitter and receivers as a system (as in the U.S. DOE battery charger system test procedure), or developing new test procedures that address the efficiency of transmitters and/or receivers as units separate from their product end use (similar to the approach of the U.S. DOE external power supply test procedure). Table 4 provides a summary of advantages and disadvantages of these possible approaches.

Table 4. Test procedure options for wireless power

Test procedure approach	Advantages	Disadvantages
Option 1: System Efficiency Test Modified U.S. DOE battery charger system test procedure to address wireless chargers	Captures efficiency of transmitter and receiver with most likely system. Takes advantage of existing technology-neutral test procedure that addresses a variety of chargers and has been subject to public scrutiny. Allows wired and wireless solutions to be compared to one another.	Does not fully address wireless power systems with interoperability. Research needed to address more complex technical test procedure issues (transmitter / receiver selection protocol, standard displacement values, RF shielding, etc.).
Option 2a: Test efficiency of transmitter only Use standardized receiver(s) to measure the efficiency of a transmitter (charging pad or other transmitter)	Simpler test procedure that focuses on the efficiency of the power supply portion that is always plugged in and "on"; WPC is in the process of developing and testing a transmitter test procedure	Does not evaluate the efficiency of the receiver or the efficiency of the receiver-transmitter system; Does not allowed wired and wireless products to be compared to one another
Option 2b: Test efficiency of transmitter and receiver with an efficiency metric for each separate unit	Addresses efficiency of each "side" of the wireless power transfer (receiver and transmitter)	May be difficult to separate the measurement of the efficiency of the receiver from the end use product; More effort required than other two options

Regardless of the approach taken, a number of technical issues require further exploration in the test procedure development process, including:

- **Varying the displacement between the receiver (battery charged device) and the transmitter (charger).** Wireless transfer efficiency is dependent on the horizontal and vertical displacement from the transmitter. The California Investor-Owned Utilities suggested capturing the range of efficiency by testing with the receiver at two locations: one at optimal placement, and one edge of the viable charging range (The California Investor-Owned Utilities 2014). WPC's test procedure for measuring transmitters uses an algorithm based on transmitter size to generate random test locations, and then averages those test points (John Perzow, personal communication, October 27, 2017).

- **Receiver design selection protocol.** More research is needed to ensure any receivers used in testing are representative of real-world use cases. Further research is also needed to understand the impact of the different receiver designs when used with the same charging base or pad.
- **Radiofrequency (RF) shield box.** Stray RF signals may affect wireless charger operation and reduce repeatability. For wireless small network equipment, the ENERGY STAR test procedure specifies the use of an RF shielded box (Ecova 2014b). Our conversations with the WPC indicate that this is unlikely to be needed for testing inductive and magnetic resonant technologies (John Perzow, personal communication, November 3, 2017).

Wireless Power Energy Penalty Today and Tomorrow

Due to these efficiency penalties described above, expected increases in market adoption, and the fact that U.S. DOE standards do not fully address wireless power, we suspect wireless charging of consumer devices will result in increased energy use and may be large enough to warrant attention from policymakers and researchers.

In order to understand the possible range of additional energy use associated with wireless power between 2017 and 2030, we built a model with high-impact and low-impact scenarios (Table 5). We considered wireless power market growth assumptions as a percentage of stock and sales outlined in the U.S. DOE SNOPR for battery charger products (U.S. DOE 2015). We also assumed the baseline efficiency values for wired chargers were equal to the final U.S. DOE-adopted standard levels that will take effect in 2018. The efficiency characteristics, duty cycle, and energy use of wired chargers for each U.S. DOE product class were used as a baseline; we then estimated additional energy use that will occur if these devices increasingly employ wireless charging.

Projected market growth and wireless transfer efficiency of small wireless kitchen appliances were not available and so this consumer product group was excluded from our quantitative energy estimates. However, we presume that the energy penalty associated with wireless small kitchen appliances is lower in the near term than that of wireless battery charger systems, primarily because we expect more market barriers to adoption of wireless kitchen appliances. For example, installation of wireless under-counter transmitters, possibly by an electrical contractor, is required.

We estimated that by the end of 2017, 9% (160 million) of the total stock of all battery-powered consumer devices in the U.S. are compatible with some type of wireless charging.[12] This is equivalent to approximately 5% of the stock of all smart phones and 90% of all wearable devices (e.g., smart watches). Because products are still in development, we assume no small kitchen appliances are wirelessly powered in 2017. In the High-impact Scenario, we chose reasonable research-based market and technical assumptions that maximized the energy penalty of wireless power. For the Low-impact Scenario assumptions, we chose values that minimized the energy penalty. Most likely, the energy penalty will be somewhere in between.

[12] This starting point was developed based on global shipments of receivers in 2014 (IHS Markit 2015), receivers in 2015 (Happich, J. 2016), and projections of receivers for 2017 (Markides 2017). Global shipments were converted to U.S. shipments using GDP (U.S. is approximately 25% of world GDP) and the percent of wireless revenue that is consumer electronics: 60% (Grand View Research 2016). Consumer battery charger stock is from U.S. DOE 2015.

Our modeling focused on calculating the "energy penalty," which we define as the incremental energy used as products switched from wired to wireless (i.e., the losses associated with wireless transmission of power). For the purposes of the model, we assumed that individual devices would drive energy use. The wireless power market is expected to be driven by mobile phones (U.S. DOE Product Class 2) and laptops (U.S. DOE Product Class 4). These two DOE classes together make up approximately 90% of all battery chargers in use in the U.S. Therefore, the predicted shift to wireless charging for these product types suggests a large number of future battery-charged devices will be compatible with wireless charging (note assumptions in Table 5). This model does not account for extra standby losses associated with multiple wireless chargers that may be installed in secondary locations (offices, coffee shops, restaurants, etc.).

Table 5. Assumptions used for High-impact and Low-impact energy model scenarios

Value	High-impact Scenario	Low-impact Scenario
Approximate CAGR of unit sales over 5-year period (2017 to 2022)	35%[13]	20%
Approximate CAGR of unit sales over 13-year period (2017 to 2030)	17%	13%
For battery chargers only: percent of total device charges per year (duty cycle) that are wireless	2022: 50% 2030: 90%	2022: 40% 2030: 80%
Percent of all battery charger products in use that are compatible with wireless charging (driven by cell phones and laptops)	2022: 50% 2030: 85%	2022: 28% 2030: 66%
Percent of mobile phones, smart phones, wearables and other similar electronics (DOE Product Class 2) in use (stock) that are that are compatible with wireless charging	2022: 56% 2030: 89%	2022: 33% 2030: 64%
Percent of laptops, tablets, and other devices (DOE Product Class 4) in use (stock) that are compatible with wireless charging	2022: 50% 2030: 90%	2022: 20% 2030: 40%
Wireless transfer efficiency (Perzow 2015)	25%	60%

The results of the High-impact Scenario modeling (Figure 4) suggest that by 2030, the energy penalty associated with all wireless chargers in use (nearly 10 TWh per year) may be more than five times the average annual savings expected from the current U.S. DOE battery charger standard (1.7 TWh per year). The energy penalty of wireless charging in 2030 is almost as large as U.S. DOE's estimate for annual energy use of wired consumer chargers,[14] approximately doubling the energy use of consumer battery chargers. Five years from now (2022), the energy penalty from wireless charging (High-impact Scenario) is lower (about 1.7 times the annual battery charger savings from the U.S. DOE standard, and 20% of U.S. DOE

[13] This is a growth rate in sales worldwide indicated by multiple market research firms. We assume sales of units is proportional to revenue (Grand View Research 2016 and Global Market Insights 2016).
[14] The "Average Annual Forecasted Wired Battery Charger Energy Use After DOE Standard" used as a comparison point in this discussion is the average annual use over the thirty-year period considered by U.S. DOE in its analysis. We divided the total energy savings from the battery charger U.S. DOE standard by 30 years to get this average.

estimates of total wired use), primarily because we expect fewer wirelessly charged devices in 2022, and more wired charging of those devices even though they are compatible with wireless charging.

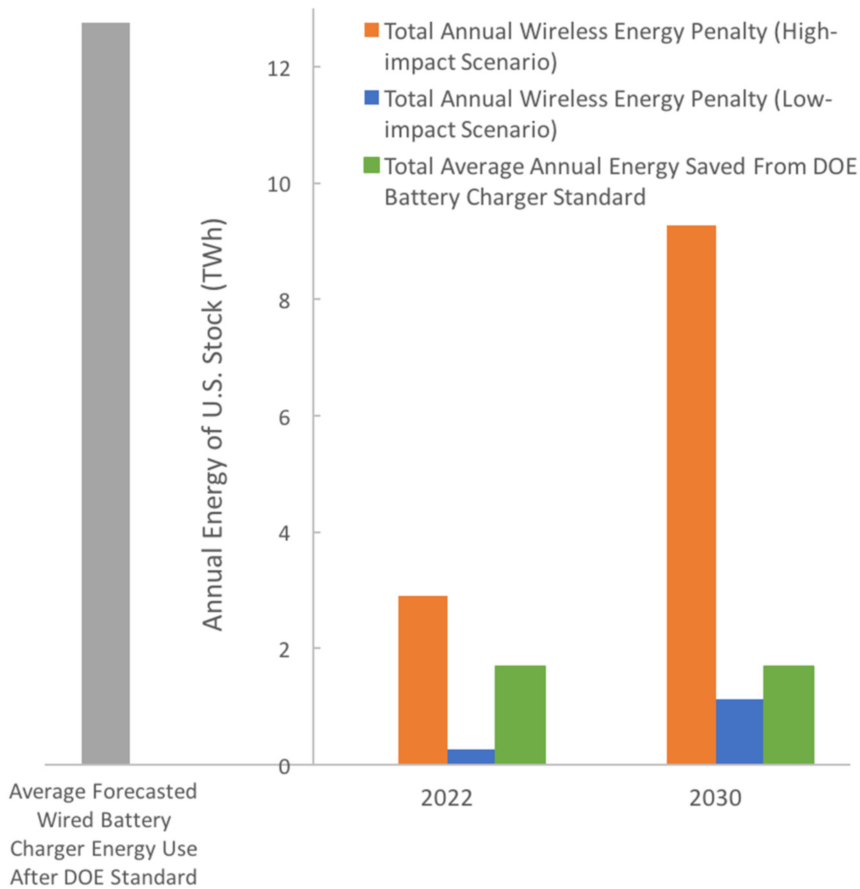


Figure 4. Wireless battery charger annual energy penalty compared to the average forecasted annual national energy use (over a 30-year period) and energy savings in U.S. DOE battery charger standards analysis

In the Low-impact Scenario, we assume wireless transmission efficiency is higher (60%), growth of the market slower, and lower consumer use of wireless chargers, thus estimates are an order of magnitude lower than the High-impact Scenario. In the Low-Impact Scenario, the annual energy penalty of wireless charging erodes 40% of expected U.S. annual savings from DOE battery charger standards in 2022 and more than 80% of expected U.S. annual savings in 2030. Here, the wireless charging energy penalty is approximately 10% of average annual U.S. DOE estimates of annual wired charger energy use.

In summary, the primary driver of the total size of the energy penalty is the efficiency of wireless energy transfer. Losses associated with wireless transfer can mean a wireless charger can use 50% to 400% more energy than a wired system to charge and maintain the battery. Further study required to build more refined estimates is outlined below.

Recommendations

Our research suggests additional study of wireless power transfer efficiency in consumer products is warranted. We recommend the following actions:

1. engage further with the wireless power industry to gather more detailed technology and market information
2. finalize a test procedure approach to measure the efficiency of today's wireless power products
3. select and test representative wireless products to vet the test protocol(s) and obtain wireless transfer efficiency data
4. refine energy use and savings potential estimates based on new market, technology and laboratory research, and
5. develop specific recommendations for U.S. DOE, ENERGY STAR, state policymakers, and electric and gas utilities to support the development of highly efficient consumer products in this market.

Test procedure development should first focus on the product category available today and within the next five years: wireless battery chargers. Wireless battery charger systems can be tested with a modified version of the U.S. DOE Test Procedure and compared directly to the wired product energy efficiencies posted to the U.S. DOE and CEC databases. The same products can also be evaluated with a WPC-proposed test procedure (currently in draft form) that evaluates the wireless transmitter efficiency. Testing a subset of products with these two different methods and comparing that back to the wired efficiency of the same products would enable greater insight into the most effective test procedure approach.

One possible outcome could be employing two test procedures for different parts of the wireless charging market. The U.S. DOE Test Procedure could be used for those wireless chargers designed as a proprietary system with limited device interoperability (Option 1, Table 4). A future version of the WPC-proposed test procedure could evaluate wireless transmitters designed to interoperable design standards such as Qi and AirFuel that are sold separately from battery-powered devices (Option 2a, Table 4).

Once details of the test procedure(s) are solidified, we suggest testing a variety of wireless battery chargers. The WPC is testing the efficiency of transmitters with their proposed protocol, and opportunities may exist to coordinate testing plans and share data with them and other members of industry. Lab results would better inform our energy model, allowing for refined energy estimates that can enable concrete recommendations to policymakers, giving them time to act before cutting cords causes a significant increase in consumer product energy use.

Conclusions

Research suggests that the energy penalty of moving from wired to wireless power in consumer products could be significant and additional study of wireless charging efficiency is warranted. Although less information is available about wireless kitchen appliances, we developed high and low impact scenarios of the energy penalty associated with wireless charging of small electronics, including laptops and cell phones. If the energy penalty is high, wireless power could erode U.S. savings from the current battery charger standard and increase energy use from battery charging over the next five years. If the penalty is lower, then only a fraction of the expected savings from the U.S. DOE mandatory standard for battery chargers would be effectively eliminated. We recommended next research steps needed to remove some of this uncertainty in the energy estimates. Once we have refined estimates, we can explore specific policies, market incentives and other stakeholder activities to mitigate possible increases in energy use.

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