Redefining Smart: Evaluating Clean Energy Opportunities from Products with Grid Connected Functionalities

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ABSTRACT

Investing in smart grid technologies is promoted as a pathway towards greater energy efficiency and greenhouse gas emissions (GHGs) reductions. However, designing 'smartness' into products in order to connect to the smart grid is mainly framed from a demand response (DR) perspective, such as setting back thermostats in hot summer days or shifting clothes dryer cycles. This paper broadens the definition of 'smart' beyond DR, proposing a systematic framework for examining the landscape of potential energy savings and GHG reduction opportunities for products with grid connectivity and advanced communication and controls.

The landscape addresses a spectrum of opportunities — including peak load reduction, ancillary services, product fault detection and diagnostics, and reporting of product-level energy consumption — that can provide varying degrees of capacity and energy savings. On one end of this spectrum are demand response opportunities such as peak load reduction and load control for providing ancillary services, which reflect capacity resources, while fault detection and diagnostics offer energy savings. To illustrate, we map out opportunities for a select list of product types, including air conditioners, pool pumps, and refrigerators. We use this framework as a tool to estimate the GHG emissions reduction potential of opportunities along this spectrum.

We conclude with a policy relevant discussion. We illustrate the technical potential for GHG emissions reductions from providing ancillary services using connected products and contrast with the larger, untapped opportunities to achieve greater overall energy savings from grid-connected products. The landscape provides a useful framework to guide the evolution of policies and programs associated with 'smart' technologies.

Introduction

'Smart' or 'connected' products and the 'smart grid' are often promoted as a pathway towards energy efficiency and greenhouse gas emissions (GHGs) reductions. To date, the grid-connected product and smart grid discussions have been framed mainly from a demand response (DR) perspective (setting back thermostats during a few hot summer days) and more recently emphasize using grid-connected products to provide ancillary services (AS); both DR and AS provide capacity services. However, there is a spectrum of services that 'smartness' can provide, that range from capacity to energy benefits.

The basic components of a smart grid — sensors, communication networks, controls — may also be used to enhance energy efficiency and provide other services, such as permanent load shifting through optimal scheduling, fault detection and diagnostics, and controlling the output of devices. Consider as an example Advanced Metering Infrastructure (AMI), which is a central component in many smart grid deployments. While AMI can facilitate dynamic pricing, AMI also has the potential to enable a host of energy efficiency applications that are based on whole-building energy data or sub-metering.

Our objectives with this paper are two-fold. The first objective is to expand the definition and discussion on 'smart' connected products and smart grid to consider applications beyond capacity services that may bring value to the grid in the form of economic, reliability and environmental benefit. Towards this objective, we define the landscape of grid services that connected products can offer and describe the functions that would enable these services. The report focuses on the benefit from the services, not the technology; thus, we do not restrict ourselves to two-way communication to the utility or dynamic pricing structures.

The second objective of the paper is to place in perspective the GHG emissions reductions from the services grid-connected products have the potential to provide. We present a framework for evaluating the GHG emission reductions from the different grid services defined in the landscape and illustrate the framework with an example. We illustrate how the CO_2 reductions vary by time of day, and the amount of capacity and energy value.

Landscape of Opportunities

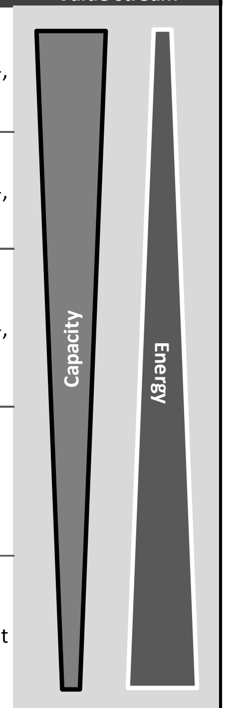
Grid-connected products vary by the type of grid services they provide. We discuss five broad categories of services that 'smart' appliances could provide including:

1. Emergency demand response
2. Economic demand response
3. Ancillary services (i.e., regulation, load following, spinning reserves)
4. Permanent load shifting
5. Energy efficiency

As illustrated in Figure 1, these grid services can be assessed by their environmental, economic and reliability impacts. The economic value of grid services (and any generation resource that provides these services) is composed of capacity and energy values.

To simplify traditional practices, as energy value increases, GHG emissions and the associated environmental benefit increases. As capacity value increases, the reliability benefit increases. All grid services have some capacity value and energy value, but in different proportions. The value streams of energy and capacity for the grid services generally follow the trend in Figure 1. For example, demand response functions predominately as a capacity resource, while reduced energy consumption is a relatively small portion of the total value provided. Conversely, energy efficiency applications have greater energy value than capacity value. Certain energy efficiency applications will have more capacity value depending on the load shape of the end use; air conditioning measures provide more capacity value than lighting measures, for example.

Category	Primary purpose	Timeframe	Communication required *	Value stream
Emergency demand response	Improve reliability	Seldom, during contingency	2-way (Available capacity status --> , Utility dispatch <--, return confirmation -->)	
Demand response	Reduce powerplant construction	<100 hours per year	2-way (Available capacity status --> , Utility dispatch <--, return confirmation -->)	
AS: regulation, load following, and spinning reserve	Compensate for minute-to-minute intra-hourly imbalances; provide backup generation	8760 hours per year	2-way (Available capacity status --> , Utility dispatch <--, return confirmation -->)	
Permanent load shifting	Improve load factor	Daily, all year, or by season	1-way (utility price <--) or 0-way (routine operations doesn't require communication)	
Energy efficiency	Reduce fuel consumption and emissions, avoid new powerplant construction	During device operation	1-way (utility price <--) or 0-way (routine operations don't require communication)	



* --> denotes signal from customer to utility; <-- denotes signal from utility to customer
Note communication and monitoring may be performed by an aggregator or utility

Figure 1. Landscape of benefits from different grid services.

The frequency at which the grid service benefit is procured is directly related to the relative values of capacity and energy benefit. At the far end of the spectrum, energy efficiency provides value at all times the energy efficient measure or process is operating. Demand response, on the other hand, is called a limited number of hours. Most demand response programs are called less than 100 hours per year, although some programs aim for more flexible, year round operation.

Contrasting the Old with the New

Demand response has been viewed as a valuable capacity resource for some time (FERC 2011)(Cappers, Goldman, and Kathan 2010). However, by adding communications and information functionality to products, greater energy benefits, also, can be realized by capacity resources. For example, advanced building (or device-level) Energy Management Control Systems (EMCSs) are being used to provide both verifiable capacity savings from demand response, as well as early diagnosis of problems in buildings that, if left undetected, would continue to waste energy. Traditional utility energy efficiency programs have relied on savings from lighting measures, however, this approach will be insufficient for future programs, especially in California, where energy efficiency is intended to be a serious tool for achieving GHG reductions. Rather, utility programs will need to address the largely untapped areas, such as behavioral energy efficiency, growing plug-loads, improved operations of products and HVAC systems, and deep energy retrofits. While past energy efficiency programs tended to adopt a "set it and forget it" approach, future programs will need to pay closer attention to persistence of savings that can only come from greater attention towards product and building operation. Enhanced product performance, geared towards energy efficiency, behavioral and operational energy savings, can help achieve the goal of persistent and deeper energy savings.

There are emerging opportunities to provide greater environmental benefits from capacity services than was the case with traditional grid resources, particularly with increasing levels of renewables. Cutter et al. (2012) describe that in the context of increasing renewables, demand side services that are flexible will become more important, yet the current pathways for load participation (primarily economic and emergency demand response, ancillary service markets) are inadequate for rendering DR to be similar to a combustion turbine. A recently conducted 50% Renewable Portfolio Standard (RPS) study for California indicates that flexible load, such as permanent load shifting (PLS), may be a useful strategy for integrating high penetration renewables by absorbing over-generation from solar energy (Energy and Environmental Economics 2014); similarly, PLS can absorb renewable energy produced at night, such as wind. PLS can be provided by individual products (e.g. moving the freezer defrost cycle or refrigerator precooling), central air conditioning systems (e.g., ice or stratified chilled water), by utilizing the thermal mass of the entire building (e.g. pre-cooling) and by process shifting (e.g., shifting motor processes). Sreedharan et al. (2012) review PLS case studies based on utility pilots.

With increasing renewables, grid operators may also rely on flexible load in the form of ancillary services. Regional integration studies have found that for every 100 MW of wind or solar generation installed, operating reserve requirements will increase roughly 5 MW in the western interconnection (GE Energy 2010) and, that as wind penetration increases from 20 to 30%, reserve requirements will grow by roughly one-third in the eastern interconnection (EnerNex Corporation 2011).

Example Opportunities

Mapping the Opportunities to the Landscape

For this paper, we consider products that fall into three broad categories:

1. Air conditioning and heating systems (e.g., central air conditioners room air conditioners)
2. Refrigeration systems, coolers (e.g., residential, refrigerators, vending machines)
3. Residential products (e.g., washing machines, clothes dryers, pool pumps)

We view whole home or building energy management systems or energy information systems as a separate product/service class that can manage energy consumption of the above products. We describe the mechanisms by which the air conditioning and heat pumps, and white goods categories provide the various services.

Table 1. Grid service mechanisms for air conditioning systems and heat pumps

Grid service	Mechanism
Emergency demand response	Use Programmable Communicating Thermostats (PCT) or Upgradeable Setback Thermostats (UST) to shut off the unit; continued use of legacy remote cut off switches.
Economic demand response	Use PCT or UST to modify the temperature setpoint according to retail price signal or other signal from the utility. The setpoint should be adjusted over the period of the event.
Regulation, spinning reserves and load following	Use PCTUST to modify the temperature setpoints and directly control the unit as required to deliver the AS. More complicated than providing DR due to differences in timing and duration.
Permanent load shifting	Precooling (or heating, if heat pump is in heating mode) the building (passive thermal storage); Thermostat schedules can be simple or programmed to be a function of price and/or forecasted weather.
Energy efficiency	Diagnostics on performance with alert to customer or service provider (e.g., overall kW/ton, problems with economizer, heat exchanger, refrigerant charge, etc.) e.g., 'engine light' ; diagnostics can be performed at the equipment level and at the whole building level to leverage both ‘top-down’ and ‘bottom-up’ diagnostics strategies.

Air conditioning systems and heat pumps with connectivity and smart features, along with the thermostats that control the scheduling of these devices, are well suited for offering demand response and certain types of ancillary services (spinning and non-spinning reserves). One advantage of connected features, as compared to traditional techniques (i.e., a radio signal that cycles off the compressor) is granular control; with a less aggressive setpoint, the air conditioner compressor can operate to maintain some level of thermal conditioning. A second advantage of the connected air conditioner is that the utility, aggregator, or ISO could receive real-time information that confirms a response. Air conditioners and heat pumps are well suited for PLS through precooling/heating. It is more challenging to provide ancillary services than demand response because of the nature of buildings and HVAC systems. An air conditioning unit may be called to use less or more energy, but because of thermal inertia, simply increasing or reducing the setpoint may not result in the desired response quickly enough. This problem can be potentially averted with aggregation. Advanced sensors and controls can be used to provide enhanced energy efficiency by monitoring energy consumption and detecting when the consumption is outside of ‘normal’ operation and diagnosing the problem (a process that is often referred to as ‘fault detection and diagnostics’). Diagnostics can also be used to fine-tune setpoints of air conditioners and heat pumps to occupant needs; this can either reduce or increase energy consumption. The strategies for delivering energy efficiency do not require two-way communication with the utility, as desired in DR, and can be conducted with the use of sensors, control strategies and data processing.

Table 2. Examples of grid service mechanisms for select residential products [1]

	Mechanism		
Grid service	**Pool pumps**	**Clothes washers, clothes dryers**	**Residential refrigerators**
Emergency demand response	Suspend or reduce (for multi or variable speed) pumping; continued use of legacy remote cut off switches	Defer the start of the cycle; possible temporary (e.g., 10-15 min.) suspension of operation if cycle is already in process	Avoid automatic icemaking, automatic defrost cycle; allow compartment temperature to float higher (within permissible safety limits)
	Automated frequency control (e.g., PNNL GridWise program[2])		
Economic demand response	Suspend or reduce pumping	Defer the start of cycle	Avoid automatic icemaking, automatic defrost cycle; allow temp. to float higher (within permissible safety limits) or precool to avoid compressor operation during high cost period
Regulation, spinning reserves and load following	Suspend, reduce pumping, or increase pumping for specified time period	Suspends operation (e.g., dryer shuts off heating element, ceases high-speed spin cycle) for specified time period (offers spinning reserves only[3])	Delays or advances automatic defrost, automatic icemaking or makes temperature adjustments for specified time period
Permanent load shifting	Timer based operation (shift to off-peak)		Scheduler automatically avoids running automatic defrost during on-peak periods
Energy efficiency	Add VSD to equipment to operate part-load, with timer based operation	Diagnostics on performance (e.g., 'engine light'); energy use feedback (e.g., communicating savings from choosing an 'eco' cycle)	Diagnostics on refrigeration components to identify faulty temperature sensors, compressor, defrost cycle

1. An override feature could provide customers with the ability to preserve appliance function when desired.
2. This refers to the GridWise pilot program in the Pacific Northwest in which a controller at the house monitored the grid frequency and in times of low frequency would temporarily curtail water heater load and the power to the heating element of the clothes dryer. A similar effect could be achieved through more traditional remote cut off switches.
3. Clothes washers and dryers are not well suited to offer regulation, spinning or load following services in markets that require the ability to both decrease or increase load.

The functions of home appliances are considerably different than the product categories, which are mainly thermal systems. However, the fundamental strategies for providing grid services are common and include modifications to schedules, controls output, and diagnostics. It is worth noting that the energy efficiency of new pool pumps is being addressed by the Title 20 energy standard in California which requires two-speed or variable speed pool pumps and through a new ENERGY STAR program for pool pumps launched in 2013.

Greenhouse Gas Emissions Reductions

Products with connected functionalities have the potential to avoid GHGs; the quantity of GHGs avoided differ by grid service and are estimated using different methods. For demand response, permanent load shifting, and energy efficiency, we estimate avoided GHGs based on the marginal generator and the quantity of load reduced or shifted. For ancillary services, we estimate avoided GHGs based on the efficiency, or heat rate, impact of the generator deviating from its optimal set point to provide ancillary services. Both of these methods are described in detail below.

GHG Reductions from Demand Response, Energy Efficiency and Permanent Load Shifting

The annual avoided GHGs are calculated based on a time-based CO_2 emissions factor and the 'load impact' of the service. We introduce the notion of the marginal generator, which is the generator that would be dispatched to meet a small increment of additional load, or conversely is the generator that is operated less if load is reduced by a small decrement. The marginal generator is time and location specific. Using the characteristics of the grid service and marginal generator, we estimate the annual avoided GHGs as follows:

- Estimate portion of load that can be shifted or reduced in each time period
- Identify the marginal generator displaced by the service in each time period
- For each time period, estimate the emissions avoided by the marginal generator using its heat rate and emissions factor.

$$\Delta CO_2 = \sum_{t=1}^{T} HR_t \times EF_t \times \Delta L_t \div 10^6$$

where,

- ΔCO_2 Annual change in CO_2 emissions (tonnes CO_2)
- t time period t
- T total number of time periods (e.g., if hourly, T = 8,760)
- HR_t Heat rate of the marginal generator in time period t (Btu/kWh)
- EF_t Emissions factor per unit of fuel input of marginal generator in period t (e.g., lb CO_2/MMBtu)
- ΔL_t Change in load in time period t (MWh)

A simple example illustrates the method described above. Assume that a refrigerator with grid connectivity is able to permanently shift load during peak hours by a total of 10%, and to improve energy efficiency over an efficient model that uses 380 kWh/yr by 5% (i.e., a 19 kWh/yr annual energy savings). We use generic summer and winter load shapes for a refrigerator/freezer.

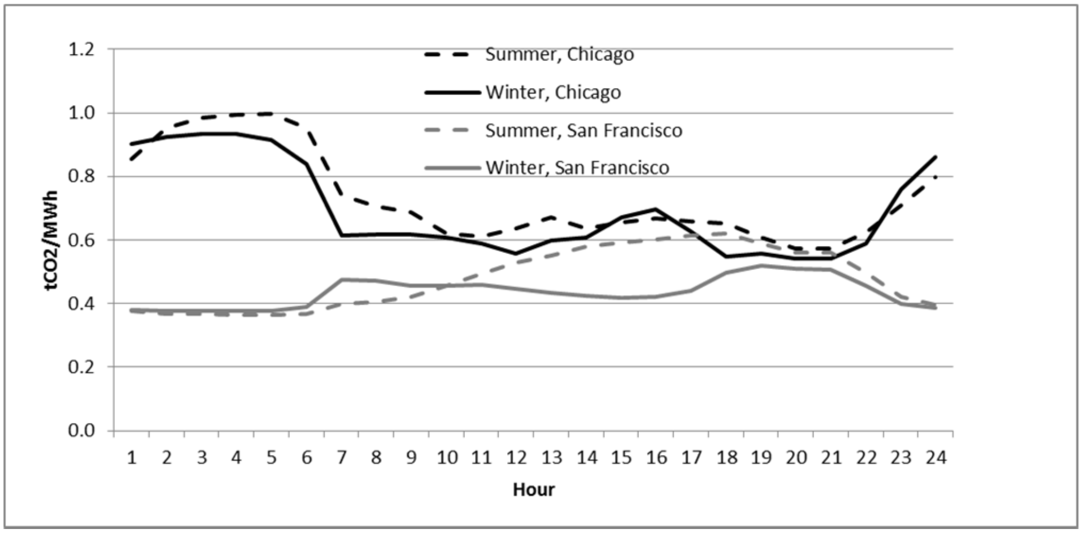


Figure 2. Average hourly summer and winter CO_2 emissions from the marginal generator in Chicago and San Francisco, respectively. *Source*: COMNET hourly data; developed by Energy and Environmental Economics for the Department of Energy.

Table 3. Annual CO_2 Emission Reductions from a Refrigerator with EE and PLS in Chicago and San Francisco ($kgCO_2$/yr)

Case	Chicago	San Francisco
Energy efficiency	13.3	8.8
Permanent load shifting	-1.3	1.1
Energy efficiency with Permanent load shifting	12.0	9.8

This example highlights two points. First, even with small EE improvements to a relatively efficient refrigerator, the CO_2 benefits of EE are significantly greater than the benefits of PLS, simply because EE is a load reduction in all hours. Second, load shifting can, in some cases, actually increase CO_2 emissions, as the negative number in in the table indicates. CO_2 emissions from load shifting in Chicago actually increase in this example from PLS because load is being shifted to a time of day where the emissions per kWh are higher because coal-fired power plants tend to be used as the marginal generator.

GHG Reductions from Ancillary Services

Generators providing regulation and spinning reserves operate at less than their optimal efficiency while waiting to be called, increasing their heat rates and CO_2 emissions. Providing regulation and spinning reserve from load curtailment, rather than generation, reduces CO_2 emissions by improving generator efficiency. We approximate avoided CO_2 emissions from ancillary service provision using the equation below.

$$\Delta CO_2 = \sum_{t=1}^{T} \Delta HR_t \times EF_t \times \frac{P}{1-P} \times MW_t^{AS} \div 10^6$$

where,

- ΔCO_2 Change in annual CO_2 emissions (tCO_2)
- t time period t
- T total number of time periods (e.g., if hourly, T = 8,760)
- ΔHR_t Change in heat rate from generator's optimal operating point to the AS standby point in time period t (Btu/kWh)
- EF Emissions factor per unit of fuel input for marginal generator in time period t (e.g., lb CO_2/MMBtu)
- P_t Percent of generator max capacity when standing by to provide AS in period t
- MW^{AS}_t MW of ancillary services bid/provided by operator in time period t

A generator providing ancillary services will typically also be providing energy. Therefore, we include only the incremental CO_2 emissions from the generator's ancillary service provision in CO_2 emission reductions from loads' provision of ancillary services. The results in this study assume P = 80%. Conceptually, imagine ten 100 MW generators running at 80% to provide 800 MW of energy and 200 MW of AS. If the AS were provided by load, eight 100 MW generators could run at 100% to provide the same 800 MW of energy. CO_2 savings result from the 800 MW of energy being provided at a higher efficiency. Estimates by E3 suggest no more than ~1% of total generation CO_2 emissions are from historical ancillary service requirements. Given the differences in load and generator types providing ancillary services across regions, E3 estimates greater emissions reduction potential in the Southeast and Midwest.

Policy and Program Implications

Examining the full landscape of the potential benefits of grid-connected products supports an integrated policy and program approach centered on providing value to both customers and their utility. Not all loads are suited for supplying each grid service, because the product must continue to meet its primary goal (e.g., cooling produce) with customer satisfaction while providing the grid service. Simultaneously, electricity grids are evolving to encourage greater load participation in capacity, ancillary services, and energy markets, which will continue to impact technological development in the products areas. Finding the balance between the needs of customers and utilities, across economic, reliability and environmental impacts, will require a mix of technological, market, and regulatory changes.

For example, technologies that utilize open communications standards are being explored to help foster greater opportunities for innovation and interoperability between different products, technologies, and services. Further, providing open access through release of APIs that cover at least some of the defined connected functionalities also supports innovation and expands consumer choice. Markets are also trending towards open standards whose connection resides in the cloud, as opposed to on the physical premises. Figure 3 illustrates how connected product features can be used to provide multiple services and benefits through the ENERGY STAR example.

Federal program example: ENERGY STAR Products with Connected Features
EPA's intent in offering connected criteria through the ENERGY STAR program is to help advance the market for products with intelligent features that can offer immediate energy or demand savings and convenience benefits for consumers and smart grid capabilities that will support a low-carbon, reliable, secure, and more affordable electrical grid over the long-term. As part of this ENERGY STAR is recognizing products with new 'connected' features that have the potential to:

- Offer consumers new functionality that can enable energy savings and convenience opportunities
- Ensure consumer control by ensuring users have the ability to override a DR request
- Encourage manufacturers to design products with DR capabilities that could support a more reliable, lower emission electric grid.

The generalizable criteria for all connected product features include:

- Interoperability with other devices and services in the home by requiring open standards and encouraging open access through release of APIs,
- remote control,
- energy use feedback,
- alerts (e.g., diagnostics) and status information
- default avoidance of operation during peak periods, and
- product-category specific demand response capabilities.

Figure 3. Federal program example: ENERGY STAR Connected Products with Connected Features.

Policies may also need to encourage aggregation since the amount of electricity used by individual products is too small for use on an individual basis to provide grid services, such demand response and ancillary services. Aggregation may need to be encouraged across multiple products and households, such as through a product/service provider; at the level of an individual building or plant, such as through an EMCS; and/or across multiple buildings and plants, such as through Curtailment Service Providers or utilities who aggregate demand response for regional electricity markets.

Market rules and program incentives currently do not render all products suitable across the spectrum of capacity and energy benefits. For example, market rules need to continue to evolve for loads to fully participate in ancillary services and demand response markets. How these loads will be aggregated and compensated will also impact how grid-connected products themselves will be designed. Programs should evaluate the cost-effectiveness of different strategies for providing the grid services along the landscape, taking into consideration the costs of the technology and connectivity, and the benefits to the grid and customers.

Conclusions

Connected products with new types of 'smartness" have the potential to provide value to the grid in the form of economic, reliability and environmental benefits. However, their value is not restricted to event-based demand response or ancillary services. Rather, the basic components that make a product 'smart,' such as sensors, automated control, scheduling, energy monitoring, can also help to make products and systems more energy efficient and to help avoid GHGs.

We develop a landscape of the potential benefits of 'smartness' that is rooted in a 'value' perspective. We consider the following services: energy efficiency, demand response, permanent load shifting, and ancillary services. Each of these services have different types of value; demand response and ancillary services, primarily, have capacity value, energy efficiency is primarily composed of energy value. While two-way communications systems and advanced metering may be ideal for demand response, they are not as 'essential' for energy efficiency or permanent load shifting. Ideally, programs' technology implementations will leverage a common technology infrastructure platform to offer multiple grid services, not just one.

We identify the types of strategies that can be used to provide the grid service based on product categories, such as refrigeration systems, air conditioning systems, and white goods. Not all loads are suited for supplying each grid service, because the product must continue to meet its primary goal (e.g., a refrigerator needs to cool and safely preserve perishable food) while providing the grid service. Simultaneously, markets are evolving to encourage load participation in ancillary services markets, which will continue to impact technological development in the product areas. Overall, when leveraging a large number of small products to provide a service such as ancillary services or demand response, aggregation may be needed. Aggregation will not render all products suitable for each grid service, however, and market rules for load participation in ancillary services and demand response markets, and products, are likely to continue to evolve. Programs should evaluate the cost-effectiveness of different strategies for providing the grid services along the landscape, taking into consideration the costs of the technology and connection, and the benefits to the grid and customers.

We also present a framework to estimate the GHG emissions reductions from each grid service. The GHG emissions reduction potential is strongly correlated with the energy value of the service. Therefore, energy efficiency tends to have the most impact on GHG emissions reductions. However, it is worth noting that the other grid services help to bring more flexibility to how the grid is operated, which is likely to be important as the U.S. moves towards integrating more intermittent renewable energy into the grid, which has not been quantified here. Future work could also be done to explore the effect of grid-connected products on improving the efficiency of the electricity grid itself, reducing the amount of electricity generated, which is lost along power lines.

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