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A Conceptual Framework to Describe Energy Efficiency and Demand Response Interactions

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Prepared for the
Building Technologies Office
U.S. Department of Energy

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Acronyms and Abbreviations

AC	air conditioning
BTO	Building Technologies Office
CAISO	California Independent System Operator
DER	distributed energy resource
DF	demand flexibility
DG	distributed generation
DOE	U.S. Department of Energy
DR	demand response
EE	energy efficiency
EIA	U.S. Energy Information Administration
EPRI	Electric Power Research Institute
ERWH	electric resistance water heater
GEB	grid-interactive efficient buildings
HPWH	heat pump water heater
HVAC	heating, ventilation, and air conditioning
iDSM	Integrated demand side management
ISO-NE	Independent System Operator New England
LED	light emitting diode
NLC	networked lighting controls
PCT	programmable communicating thermostat
VRE	variable renewable energy

Abstract

Energy efficiency (EE) and demand response (DR) resources provide important utility system and ratepayer benefits. At the same time, the rapid change in the amount and type of variable renewable energy, like solar and wind, is reshaping the role and economic value of EE and DR, and will likely affect time-dependent valuation of EE and DR measures. Utilities are increasingly interested in integrating EE and DR measures and technologies (as well as other distributed energy resources) as a strategic approach to improve their collective cost-effectiveness and performance. However, the specific EE and DR features that may be best integrated, the interplay between changing EE and DR resource potential, and the resulting utility system impacts, are not well understood.

We develop a framework to identify the EE and DR attributes, system conditions, and technological factors that are likely to drive interactions between EE and DR. We apply the framework to example measures with different technology specifics (e.g., presence of controls, building type, and targeted end use) in the context of different system conditions (e.g., peak demand, load-building periods during high renewable generation output). Ultimately, the framework defines EE and DR interactions not only by the change in discretionary load (i.e., DR potential) but also by the change in likelihood of participation in EE and DR programs—as well as the change in system need for, and the overall availability of, EE and DR resources. The framework is intended to improve the integration of EE and DR in utility operational and planning activities.

Executive Summary

Energy efficiency (EE) and demand response (DR) resources provide important utility system and ratepayer benefits. At the same time, the rapid change in the amount and type of variable renewable energy, like solar and wind, is reshaping the role and economic value of EE and DR and will likely impact time-dependent valuation of EE and DR measures. Utilities are increasingly interested in integrating EE and DR measures and technologies (as well as other distributed energy resources) as a strategic approach to improve their collective cost-effectiveness and performance. However, the specific EE and DR performance characteristics that may be best integrated, the interplay between changing EE and DR resource potential, and the resulting utility system impacts, are not well understood.

We developed a conceptual framework to identify the EE and DR attributes, technological factors, and system conditions that are likely to drive interactions between EE and DR.[1] The framework is intended to address the following question: *From the grid operator perspective, how do EE and DR compete with or complement each other with regard to system operations and economics?*

EE and DR differ from each other in ways that are important for understanding how EE and DR interact and are applied in the conceptual framework. We define EE as a *persistent* and *maintained* reduction in energy consumption required to provide a fixed level of service.[2] By contrast, we define DR as an *active* modification in energy demand or consumption on a limited-time basis, in response to an incentive or command signal, which may result in a reduced level of service. The framework incorporates another concept, demand flexibility (DF), which we define as the *capability* associated with a building to modify energy consumption in response to utility grid needs.[3] Like DR, DF is characterized by active load management on timescales consistent with utility system and grid needs. Unlike EE and DR, DF is not a resource in the traditional sense, but a potential that the utility or system operator can utilize to provide reliable electricity service. From the system operator's perspective, EE and DR are what you have in your portfolio and DF is what you can do with the resources you have.

EE and DR interactions may occur in four ways. First, EE and DR interactions may occur when a change in one resource increases (complements) or decreases (competes with) the size of the available resource. Second, EE resources might encourage more (complementary) or less (competing) participation as a DR resource. Third, changing the amount of either EE or DR may alter the utility system need for the other resource where an increase in EE may either decrease (complement) or increase (compete with) the need for DR resources to balance real-time utility grid supply and demand. Fourth, utility system operators use dispatchable resources to meet grid needs that reflect near real-time conditions. EE and DR interact in terms of resource

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[1] This framework is the first component of a broader research effort to assess the load impacts and economic relationships of EE and DR at the utility system level by developing an integrated valuation methodology based on EE and DR measure savings shapes and regional electricity features.

[2] This is consistent with other definitions of EE in the literature (e.g., York and Kushler, 2005; Goldman et al., 2010).

[3] See recent literature on grid-interactive efficient buildings (GEB) (Eckman et al., 2019; Neukomm et al., 2019).

availability when an EE measure results in an increase (complement) or decrease (competition with) the availability of dispatchable DR resources.

The framework describes the interactive effects of a “change,” which is defined by the point at which an EE or DR investment is made by a residential customer, commercial customer, or aggregator operating across multiple buildings. The framework is comprised of two levels, each of which is subdivided further into two sublevels exploring one of the interactions identified in the previous paragraph. The first level assesses changes that occur at the building. The second level aggregates buildings to represent utility-scale changes. For each sublevel, we identify the defining analytical question and metric by which the interaction between EE and DR is measured. We assess interactions across three different types of demand flexibility (DF) and DR: (1) peak shed (i.e., reduction in load at peak demand periods or during system emergencies), (2) load shifting from one time period to another (e.g., from peak to off-peak), and (3) modulation (e.g., frequency reserves).

Table ES-1 describes the conceptual framework, including the perspective, change metric, and definition of competition, complement, and neutral EE and DR interactions for each level and sublevel.

Table ES-1. Conceptual framework levels, change metrics, and definitions

Level	Perspective	Change Metric	Competition	Complement	Neutral
1a	Building	Demand flexibility (DF)	Less load able to shed, shift, or modulate	More load able to shed, shift, or modulate	No change in load able to shed, shift, or modulate
1b	Building	DF participation fraction	Lower fraction of DF participating as a demand response resource	Higher fraction of DF participating as a demand response resource	No change in the fraction of DF participating as a demand response resource
2a	Utility system	Demand response (DR) need	Increased likelihood of needing DR resources to meet utility system conditions	Decreased likelihood of needing DR resources to meet utility system conditions	No change in the likelihood of needing DR resources to meet utility system conditions
2b	Utility system	DR availability	Reduced availability of DR resources to meet specific system need or condition	Increased availability of DR resources to meet specific system need or condition	No change in the availability of DR resources to the system operator

To qualitatively demonstrate the framework's application, we assessed six EE measures among different customer end uses (e.g., commercial lighting, residential HVAC) with a variety of different control or communication technologies (e.g., networked lighting controls, utility direct load control switch) and identified three key attributes driving EE and DR interactions. To be sure, there are many EE measures beyond those explored in this report with passive load shapes post-EE that may pose interactions with DR. We focused on a handful of commonly installed measures with existing technology and attributes likely to drive interactive effects (e.g., seasonality, customer class profile, magnitude of energy savings, timing of energy savings, presence of customer controls, and utility dispatch capability). Specifically, among our EE measure examples, we found the following:

1. The change in the passive load shape[4] is an important determinant of whether EE and DR compete with or complement each other. Some of our example measures have post-EE measure load shapes that are lower in all hours of the day, while there are other examples with post-EE demand that is sometimes lower and sometimes higher. Any reduction in the post-EE measure load shape would reduce the total level of load, which would seemingly reduce the amount of DF, all else being equal.

2. The addition of controls or operational strategies to shift load may increase the DR capabilities of EE measures. Despite reductions in the post-EE measure load shape, EE measures with increased capabilities enable access to previously untapped DF. Ultimately, whether or not EE and DR complement each other with additional capability depends on the net effect of several changes: the extent of the change in passive load shape (which reduces the overall DR resource) compared with the offsetting increase in DF, the fraction of DF participating as a DR resource, and reliability of the DR.

3. We found that the coincidence of changes in load and system peak or load-building conditions matters. It is important, therefore, to consider the temporal alignment of EE and DR impacts with grid needs, as it defines much of their value to the utility system. This is especially significant for grid systems with a high amount of variable renewable energy generation that can dramatically and unpredictably alter hourly marginal costs within a short time span.

Importantly, we found no universal relationship between EE and DR in our qualitative analysis. Instead we found that EE and DR interactions depend on measure and technology specifics (including building type and targeted end use), as well as utility system conditions. We also found that EE and DR interactions are defined by more than just the change in discretionary load (i.e., DR potential); they also are defined by the change in likelihood of participation in DR programs, as well as the change in system need for, and the overall availability of, DR resources.

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[4] "Passive load shape" refers to an end-use load profile that is not controlled or modified over time.

Despite the broad representation of EE measures used to apply the framework, all measures exhibited implications for DR and DF. This suggests that EE and DR interactions exist for measures and programs that are not explicitly delivered as an integrated demand side management (iDSM) measure. Indeed, virtually any change in the electricity end use characteristics of a building (including end use fuel switching) would be expected to have some effect on both total usage and timing of that usage, and therefore pose interactions that could be expressed through this framework.

This framework applies to the electric industry in several ways. First, regulators and utilities are seeking to improve the integration of EE and DR in utility operational and planning activities (at the bulk power and distribution system levels). Applying the framework in these cases might entail representing EE impacts on an hourly basis and using operational and planning models to endogenously select DR resources (after accounting for EE load impacts) subject to cost and reliability constraints. Second, the framework can inform the design of EE and DR programs that incorporate complementarity to bring down enablement and incentive costs. Adding capabilities to enable or automate DR strategies generally drive complementarity between EE and DR. For example, some DR controls technologies may be jointly installed with an EE measure (e.g., commercial lighting controls) to allow increased DR program participation.

Finally, this conceptual framework lays the foundation for future research to better quantify and analyze EE and DR interactions of specific end uses under realistic grid scenarios. Topics and questions for future research include defining and evaluating key metrics, quantifying load trade-offs, and quantifying changes in system economics.

1 Introduction

Energy efficiency (EE) and demand response (DR) resources provide important utility system and ratepayer benefits. The benefits include reducing and/or shifting load to increase system capacity factors or to facilitate economic or security-constrained dispatch of generation resources (Alstone et al., 2017; Joung and Kim, 2013; Safdarian et al., 2016; Wang et al., 2017); deferral of generation, transmission, and distribution system investments (Baatz, 2015); and reductions in fuel and purchased power costs for utilities and end users of electricity (Lazar and Colburn, 2013). In addition, EE programs typically cost less per kilowatt-hour than average retail electricity rates (Arimura et al., 2012; Hoffman et al., 2018; Molina, 2014).

At the same time, the rapid change in the amount and type of variable renewable energy (VRE), like solar and wind, is reshaping the role and economic value of EE and DR. The proliferation of distributed generation (DG) has reduced utility retail sales and changed the timing of net peak demand. Additionally, the diurnal patterns and volatility of wholesale prices are changing due, in part, to large increases in utility scale renewable generation resources with zero marginal costs (Seel et al., 2018). These changes will likely affect time-dependent valuation of EE and DR measures (Boomhower and Davis, 2020). In some cases, EE and DR resources by themselves may no longer be cost-effective on the basis of cost avoidance alone as marginal energy costs decline (Agan and Jones, 2017). Utilities are increasingly interested in integrating EE and DR measures and technologies (as well as other distributed energy resources) as a strategic approach to improve their collective cost-effectiveness (Potter et al., 2018; York et al., 2019).

Integrating EE and DR is an emerging research area with limited implementation experience (Potter et al., 2018; York et al., 2019). Prior studies on EE and DR interactions and integration have focused primarily on institutional and market barriers (Goldman et al., 2010), driving customer acceptance and participation (Starr et al., 2014; Webb et al., 2016), implementing behavior-based programs targeting EE and DR goals (Cook et al., 2016), and optimizing EE and DR resource benefits (Alstone et al., 2017; Jewell, 2014; Jewell, 2016). There are literature gaps regarding which specific EE and DR features may be best suited for integration, the interplay between changing EE and DR resource potential, and resulting utility system impacts.

In this report, we develop a conceptual framework to identify the EE and DR attributes, system conditions, and technological factors that are likely to drive interactions between EE and DR.[5] We intend for the framework to support decision-makers and utilities considering changes to EE and DR program design to maximize EE and DR benefits and cost-effectiveness (e.g., adding DR capabilities to traditional EE measures to enhance the overall system value). The framework

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[5] This framework is the first component of a broader research effort to assess the load impacts and economic relationships of EE and DR at the utility system level by developing an integrated valuation methodology based on EE and DR measure savings shapes and regional electricity features.

focuses primarily on system impacts from the perspective of the utility or system operator.[6] We consider the customer perspective, to a lesser extent, as part of assessing the change in load that is available to provide demand flexibility (DF).[7] The framework and report do not explore changes in customer economics (e.g., bill savings), customer perceptions of or attitudes towards EE or DR (e.g., through increased awareness of energy consumption patterns), broader policy issues of utility financial impacts (e.g., changes in utility collected revenues, achieved earnings, and achieved return-on-equity), or the alignment (or lack thereof) between program design and retail and wholesale market opportunities. Though we acknowledge these are important factors for utilities and decision-makers to consider.

We follow typical practice to define EE and DR as separate resources in this report. Regulators have historically authorized separate ratepayer funding streams for EE and DR programs. Partially as a result, utilities and program administrators design, plan, and enroll participants for EE and DR programs separately (Goldman et al., 2010; Potter et al., 2018). Understanding the distinct characteristics of EE and DR resources (e.g., temporal savings, flexibility) can inform the interactive role of EE and DR combined to optimize DF in future electricity systems with greater adoption of VRE and distributed energy resources (DERs), including DG, storage, and electric vehicles.

We apply the framework to a set of example residential and commercial EE measures and technologies to qualitatively assess its comprehensiveness and provide a high-level directional assessment of the interactive effects of EE and DR. We identify which measures and/or grid conditions more clearly result in particular EE and DR interactive effects, as well as cases where the results are more conditional and uncertain, to identify key measure attributes and system conditions that are highly influential. We rely on hourly electricity system data from the U.S. Energy Information Administration (EIA) and end-use load shape data from the Electric Power Research Institute (EPRI) to describe coincidence of EE impacts and utility grid system conditions (see Appendix A for detailed EE measure descriptions).

More broadly, our approach illustrates situations where a qualitative application of the framework could be deemed sufficient for regulators, policymakers, utilities, and/or stakeholders looking to gain a general sense of the interactive effects and what that may mean for broad changes in programmatic activities, planning efforts, and/or operational situations. Alternatively, when the qualitative application of the framework produces more conditional and uncertain results, more quantitative and nuanced analysis is required to identify the conditions that drive the interactive effects in one direction or another, as well as to derive more precise estimates of the magnitude of those interactive effects. In these

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[6] Throughout the report, we use the terms “utility” and “system” to refer to the bulk power system inclusive of generating resources and high-voltage transmission, as well as to total customer load. Certainly, EE and DR interactions may also occur on the utility distribution system. However, EE and DR impacts on the utility distribution system are highly location-specific, have temporal scales which differ from the bulk power system, and are not explored in depth in this study. For more discussion of EE and DR distribution impacts, see, e.g., EPRI, 2014; Eckman et al., 2019.

[7] DF is discussed in Section 2.1 and is defined here as the technical capability, associated with a building, to actively lower, increase, shift, or modulate energy usage, compared to a baseline scenario reflecting the passive state of operation, and in response to utility grid needs.

circumstances, the framework can be applied as a means to guide quantitative analysis, to more comprehensively and precisely determine the interactive effects of EE and DR at both the building and system levels.

The report is organized as follows: Section 2 defines the key analysis question and terminology used in the framework. Section 3 describes and applies the framework using prototypical residential and commercial EE measures and technologies. Section 4 summarizes key attributes driving EE and DR interactions. Section 5 concludes with implications for decision-makers, utilities, and other industry stakeholders, as well as suggested future research.

2 Framing Question and Definitions

In this section, we pose the key question motivating the framework and define essential terminology, with the primary intent to bound the scope of the framework and contextualize the conclusions. Secondarily, the report terminology and definitions may be useful for broader discussions about technical and economic assessments of EE and DR beyond our narrower focus on the interaction between EE and DR.

The key question motivating our framework is as follows:

From the grid operator perspective, how do EE and DR compete with or complement each other with regard to system operations and economics?

The question can be subdivided into two components with contrasting concepts, specifically: (1) "EE and DR" and (2) "compete with or complement." In the following sections we elaborate on these concepts to more fully frame the question.

2.1 Defining energy efficiency, demand response, and demand flexibility

In this report and our framework, we define EE and DR as follows:

> ***Energy efficiency*** *is the persistent and maintained reduction in energy and/or demand, as compared to baseline consumption, to provide the same or an improved level of service.*[8]
>
> ***Demand response*** *is the active reduction, increase, shift, or modulation of energy and/or demand on a limited time basis, as compared to baseline consumption, in response to a price/incentive payment or command signal, which may result in a lower level of service.*

EE and DR differ from each other in two conceptual ways that are important for understanding how EE and DR interact:

First, we define EE activities as "persistent and maintained" because customers install more efficient devices or building improvements that use less electricity. This is consistent with other definitions of EE, including York and Kushler (2005) describing "long-lasting" savings and Goldman et al. (2010), which refers to "permanent changes" under similar device operation. We define DR by activities in response to program design elements (e.g., price or utility command signals) meant to elicit a change in electricity consumption during a specific time

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[8] We note that this definition does not necessarily align with the strict, physics-based concept of EE, which implies an increase in energy service per unit energy consumption but not necessarily an overall reduction in consumption.

period or periods.[9] From the utility perspective, DR is used for economic (e.g., high wholesale electricity prices) or reliability (e.g., high load or capacity shortage) events and the frequency and duration of DR events can vary greatly from one year to another (Faruqui et al., 2007). In many cases, DR programs limit the number of hours that customers can be called to provide DR resources (Goldman et al., 2010). Therefore, in practice, DR is a more circumscribed resource whose use is contingent on actual system needs that transpire in real time.

Second, EE presumes no loss in customer comfort and, in fact, may improve service levels. In contrast, DR may result in decreased energy service during DR event periods because DR activities typically disrupt baseline (or "normal") electricity consumption (e.g., turning off lights or appliances, changing building temperatures).[10] To be sure, certain DR controls, strategies (e.g., pre-cooling), and automated technologies may minimize the magnitude of the disruption to customers, but cannot necessarily eliminate it.

The framework incorporates another concept, demand flexibility (DF), which is consistent with recent literature on grid-interactive efficient buildings (GEB) (Eckman et al., 2019; Neukomm et al., 2019). Like DR, DF is characterized by active load management on timescales consistent with utility system and grid needs. Unlike EE and DR, however, DF is not a resource in the traditional sense (e.g., eligible to be bid into wholesale markets), but a potential that the utility or system operator can utilize to provide reliable electricity service. Another way to distinguish EE and DR from DF is that, from the system operator's perspective, EE and DR are what you have in your portfolio and DF is what you can do with the resources you have (see Figure 1). Notwithstanding this distinction between EE, DR, and DF, all three may provide value to the system and should be compensated accordingly. In this report and framework, the definition of demand flexibility is as follows:

> ***Demand flexibility*** *is the technical capability, associated with a building, to actively lower, increase, shift, or modulate energy usage, compared to a baseline scenario reflecting the passive state*[11] *of operation, and in response to utility grid needs.*

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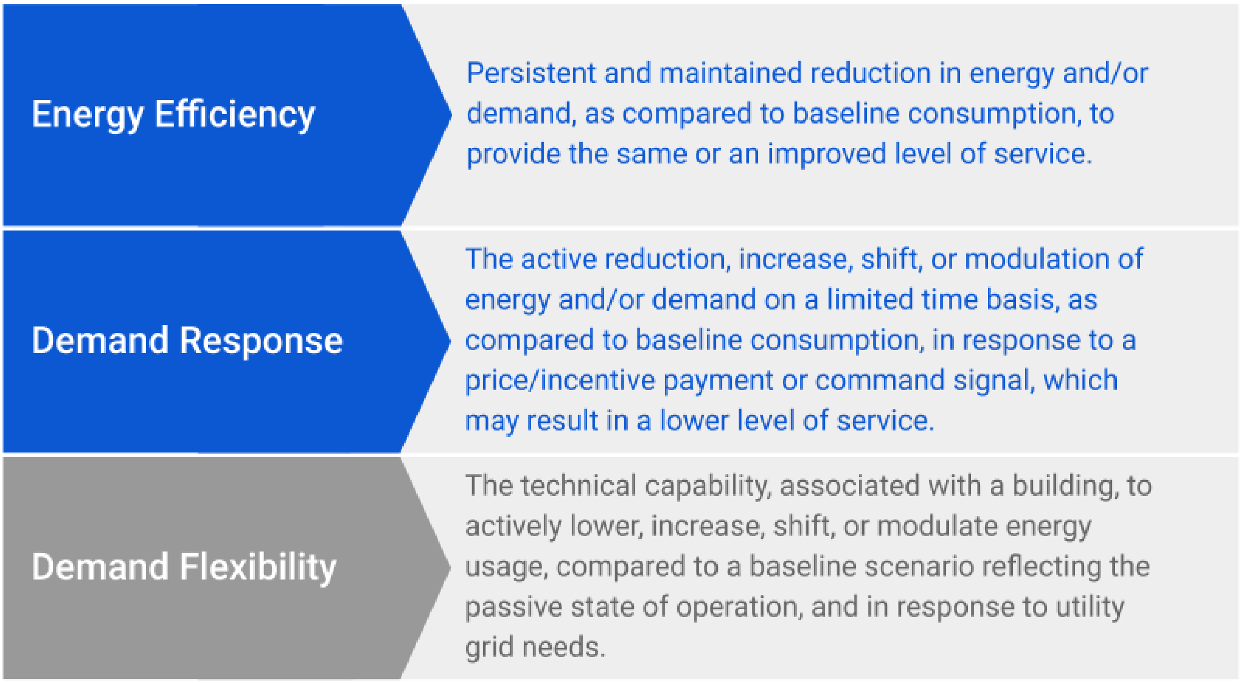
[9] The definition of DR used in this report is limited to load-based DR and is inclusive of load management. We do not consider the interaction between EE and behind-the-meter storage, which may be used as a DR resource, due to the many factors driving storage system operation (e.g., customer consumption, retail rate design, financial incentives).

[10] There may be instances where DR *increases* customer service levels (e.g., temperature increase in an over-conditioned office in the summer). Customer comfort factors into DR strategies and, therefore, into the report framework; however, we do not use customer comfort metrics when applying example measures to the framework in this report.

[11] "Passive state" refers to operation that is not controlled or modified over time.



Energy Efficiency	Persistent and maintained reduction in energy and/or demand, as compared to baseline consumption, to provide the same or an improved level of service.
Demand Response	The active reduction, increase, shift, or modulation of energy and/or demand on a limited time basis, as compared to baseline consumption, in response to a price/incentive payment or command signal, which may result in a lower level of service.
Demand Flexibility	The technical capability, associated with a building, to actively lower, increase, shift, or modulate energy usage, compared to a baseline scenario reflecting the passive state of operation, and in response to utility grid needs.

Figure 1. EE, DR, and DF definitions used in the framework

2.2 Defining competition and complementarity

EE and DR interactions may occur if changes in one resource (either EE or DR) affects the size, grid need, or availability of the other resource.[12]

Size of resource. EE and DR interaction may occur when a change in one resource increases (i.e., complements) or decreases (i.e., competes with) the size of the other resource. As an example of competition, an EE measure (like a heat pump water heater) might reduce the total amount of load available for load shedding or shifting. Likewise, modifying the timing of energy consumption through DR resources that shift load from peak to off-peak periods (i.e., *more* DR) might increase total energy consumption in aggregate or encourage the adoption of inefficient technologies to create more load flexibility (i.e., *less* EE). Complementarity between EE and DR may occur, for example, when EE measures may increase the fraction of load that is accessible via DF (e.g., building envelope improvements that enhance the effectiveness of pre-cooling strategies, allowing deeper HVAC load shedding during DR events).

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[12] We note that there are other important concerns and barriers driving EE and DR competition or complementarity. For example, Goldman et al. (2010) describes several types of institutional (i.e., market and regulatory), utility, and customer barriers, including: separate program administration and funding streams, customer perceptions, lack of alignment between retail rate design and program objectives, and insufficient utility and contractor expertise. Also, while we describe each dimension of competition and complementarity in isolation below, we acknowledge EE and DR resource value may change in interrelated ways. For example, in cases where EE reduces peak load, energy and capacity prices might be lower, which would, in turn, reduce payments to DR resources.

Grid need for resource. Changing the amount of either EE or DR may alter the utility system need for the other resource. For example, in the complementary case, an EE measure may reduce the need for DR by lowering overall system loads, lowering the probability of system conditions (economic or reliability) triggering a DR event.[13] There are instances, however, when increased load may be beneficial (e.g., during periods of renewable energy curtailment). If EE reduces load in those hours, then the system need for DR to shift load into the same periods has increased, consequently putting EE and DR in competition from the system operator's perspective (i.e., more EE increases the need for DR). Figure 2 shows the cumulative DR capacity developed under different EE scenarios in the Northwest Power and Conservation Council's 7th Plan, in which different EE resource cost assumptions alter the addition and timing of DR resources (Northwest Power and Conservation Council, 2016). The Northwest Power and Conservation Council found that assuming low cost EE resources (defined as EE measures with costs less than or equal to the short-run market price; red line in Figure 2) resulted in more DR development than assuming higher cost EE resources (defined as EE measures with costs less than or equal to the long run avoided cost; purple line in Figure 2).

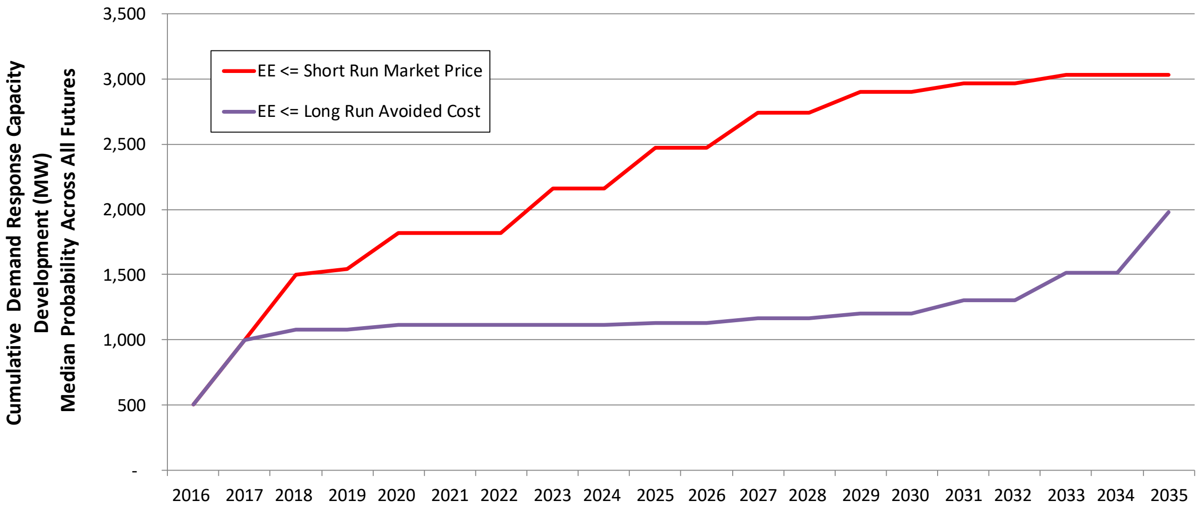

Figure 2. Cumulative DR resource capacity under EE resource cost scenarios[14]

Availability of resource. Utility system operators use dispatchable resources to meet system grid needs that reflect near real-time conditions. EE and DR interact in terms of resource availability when an EE measure results in the increased or decreased availability of dispatchable DR resources. In such cases, the presence of competing or complementary relationships depends on the particular system need. For example, a more efficient end use

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[13] This is more likely the case in the short-run with a fixed set of generating resources than in the long-run, as the generation portfolio changes and loss-of-load probabilities change as generating units retire.

[14] This figure was developed from a public dataset (available at: https://www.nwcouncil.org/sites/default/files/rpmfinalscenarioresults_data_032816-final.xlsx) as a result of testing alternative development strategies across 800 different futures created using randomly selected combinations of natural gas prices, carbon prices, load growth rates, and wholesale market prices.

(e.g., air conditioner) may reduce the load that can be dispatched and utilized by the utility system operator during a specific system event (e.g., summer peak). In contrast, the addition of programmable and communicating technologies as part of an EE investment (e.g., networked lighting controls) may increase the amount of flexible load that can be dispatched and utilized during DR events.

3 Framework

In this section, we define our framework for describing EE and DR interactive effects. The framework is comprised of two distinct levels addressing EE and DR interaction at the building[15] and utility system levels, respectively. We also define several concepts that help bound the scope. Finally, we apply the framework using six example measures and technologies.

EE and DR have varying temporal impacts by season, day, and more granular timescales. The timing and magnitude of EE and DR load impacts is dependent on many factors, including specific measure or end-use characteristics (e.g., hourly load shapes); the presence or absence of control technologies; building types and vintages; and underlying customer or building consumption patterns that are influenced by occupancy, weather, and season. The interactive effects of EE and DR measures are also driven by differences among regional electricity systems, especially as systems evolve to incorporate more VRE and DG. This is particularly the case for DR, which can be an event-based resource used to reduce or shift electricity demand during periods of high utility load or prices. Historically, DR has been planned and used as a resource mostly to reduce annual peak load through load shedding (FERC, 2011). The impacts of VRE, energy storage technologies, and transportation electrification, however, suggest DR may be valuable more frequently at shorter time frames for additional services such as load shifting and ancillary services (Alstone et al., 2017). Importantly, some of this value may be captured through overall *increases* in electricity consumption to absorb periods of excess VRE or DG (Satchwell et al., 2019; Vrettos et al., 2018) or to maximize value in the case of pre-conditioning for load shifting and/or modulation (Beil et al., 2015 Hammerstrom et al., 2007; Keskar et al., 2019).

The framework describes the interactive effects of a "change," which is defined by the point at which an EE or DR investment is made by a residential customer, commercial building owner, or aggregator operating across multiple buildings. EE and DR investments will change the end-use consumption on a temporal basis in different ways. When updating an end use with a more efficient technology, the load shape following the EE investment may represent an overall percent reduction, maintaining a similar shape. For example, commercial lighting EE measures tend to have hourly impacts proportional to the underlying lighting end-use hourly shape (see Figure 3, left panel). In other cases, the load shape may look quite different on an hourly or sub-hourly basis when an EE or DR investment includes controls technology, thermal improvements, or different operational strategies. For example, commercial lighting occupancy sensors may produce hourly impacts asynchronous to the underlying lighting end-use hourly shape as the sensors function based on human presence in specific locations and not the pre-existing lighting schedule (see Figure 3, right panel) (Baroiant et al., 2019).

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[15] We define "building" throughout this report to include residential single- and multi-family homes and commercial buildings.

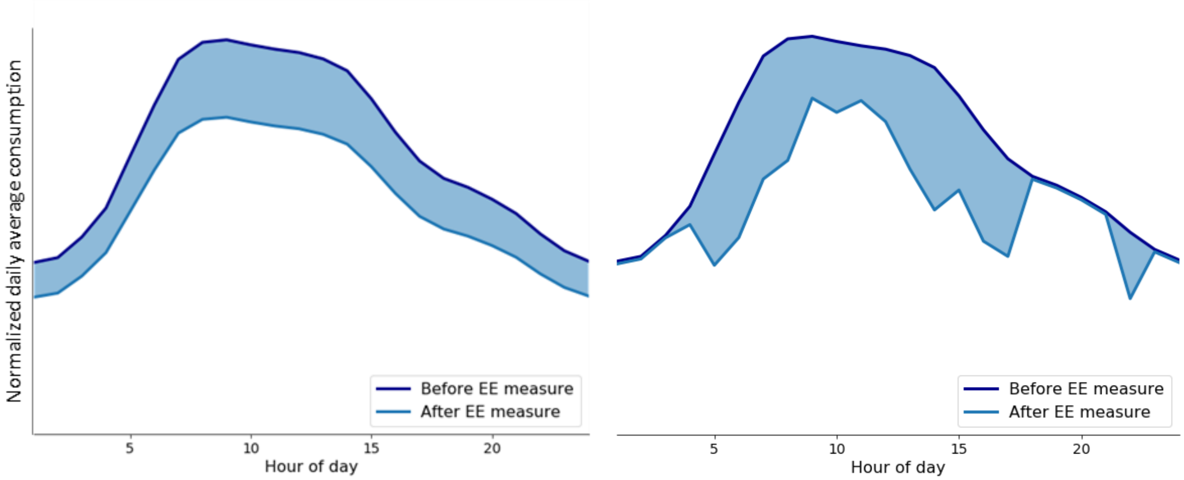

Figure 3. Illustration of normalized load shape pre- and post-investment with similar shape based on commercial efficient lighting example (left panel) and normalized load pre- and post-investment with different shape based on commercial lighting occupancy sensors example (right panel) from data accompanying Baroiant et al., 2019.

The framework is comprised of two levels, each of which is subdivided further into two sublevels. The first level assesses changes that occur at the building. The second level aggregates buildings[16] to represent utility-scale changes.[17] For each level, we identify the defining analytical question and metric by which interaction between EE and DR is measured.

We assess interactions across three different types of DF and DR: (1) peak shed (i.e., reduction in load at peak demand periods or during system emergencies), (2) load shifting from one time period to another (e.g., from peak to off-peak), and (3) modulation.[18] There are other grid services and requirements where DR and DF may provide value (e.g., emergency load transfer, forecast errors). However, most DR program designs lack sufficient temporal or geographic detail to meet system operational requirements for many of these grid services (Cappers et al., 2011; Cappers et al., 2016).

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[16] Changes in end-use load shapes can be aggregated with other loads (not affected by EE or DR) to represent the change in total building consumption following adoption of an EE or DR measure. Furthermore, building loads can be combined to represent the building contribution to total utility system load. The framework presumes aggregate building-level impacts at sufficient scale to result in measurable utility system-level impacts.

[17] Importantly, the second level of the framework is at the utility system level, where the presence and magnitude of aggregate EE and DR interactions is subject to the specific system conditions. When we apply the framework to different example changes, we will specify several prototype utility system conditions to demonstrate some of the ways in which system conditions may drive interactive effects. These prototypes do not, however, cover all the permutations of possible system conditions and are meant to instead reflect a subset of common system conditions. In particular, regional electricity systems differ in terms of supply mix, energy and demand requirements, and market products for which EE and DR may be eligible resources.

[18] See Neukomm et al. (2019) for characteristics and examples of load shed, shift, and modulate.

3.1 The EE and DR interactive framework

The framework levels and sublevels are each defined by a particular change metric and by the change direction that constitutes a competitive, complementary, or neutral interaction between EE and DR (see Table 1). Level 1 describes EE and DR interactions at the building level, and Level 2 describes EE and DR interactions at the utility system level.

Each sublevel has a different change metric, some of which are more straightforward to measure than others. For example, the change in building DF at Level 1a can be expressed as a change in kilowatts and/or kilowatt-hours. Likewise, the Level 1b change in DF participation fraction can be expressed as a percent of the building DF that is participating as a DR resource. However, expressing the change in utility system need for DR at Level 2a and change in DR availability at Level 2b can be challenging, as there are multiple dimensions, including timescale and location. Furthermore, changes at Levels 2a and 2b are dependent on the particular system conditions and DR services required by the system operator (e.g., load shedding at peak to meet system resource adequacy need versus load shifting during short duration morning ramps to meet system energy adequacy). We discuss metrics as a future research area in Section 5.

Table 1. Framework levels, change metrics, and definitions of competition, complement, and neutral interactions between EE and DR

Level	Perspective	Change Metric	Competition	Complement	Neutral
1a	Building	Demand flexibility (DF)	Less load able to shed, shift, or modulate	More load able to shed, shift, or modulate	No change in load able to shed, shift, or modulate
1b	Building	DF participation fraction	Lower fraction of DF participating as a demand response resource	Higher fraction of DF participating as a demand response resource	No change in the fraction of DF participating as a demand response resource
2a	Utility system	Demand response (DR)[19] need	Increased likelihood of needing DR resources to meet utility system conditions	Decreased likelihood of needing DR resources to meet utility system conditions	No change in the likelihood of needing DR resources to meet utility system conditions
2b	Utility system	DR availability	Reduced availability of DR resources to meet specific system need or condition	Increased availability of DR resources to meet specific system need or condition	No change in the availability of DR resources to the system operator

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[19] The focus on DR resources in Levels 2a and 2b is consistent with the characterization of DR as a dispatchable resource (as compared to EE) by utility system operators. The impacts and resultant value of EE at the utility system in levels 2a and 2b is captured by the size and timing of its reductions in utility system load.

3.1.1 Level 1a: Change in building demand flexibility

This first sublevel of the framework is focused on the change in the building-level DF due to an EE or DR investment. Specifically, this sublevel asks, *in the presence of a more efficient measure, what is the change in technical potential and capability to shed, shift, or modulate the affected load?* EE and DR are in competition at this level if there is less load able to shed, shift, or modulate; they are complementary if there is more load able to shed, shift, or modulate; and they have a neutral interaction if there is no change in the load able to shed, shift, or modulate (see Table 1).[20]

Whether EE and DR compete with or complement each other at Level 1a is a function of two distinct changes to DF: (1) the change in technical potential, as defined by the change in passive load shape, reflects whether and how the underlying load shape changes following an EE or DR investment (e.g., if the load is lower in all hours, there is less load technically available to participate in demand response); and (2) the change in capability reflects whether and how the building is more or less able to reliably[21] provide a responsive or flexible load when needed by the utility.

The concepts of changing technical potential and capability are individually subject to many assumptions and interrelated factors. For example, the technical potential of an end use to provide DF depends on several factors, including the physical and technological limits of the equipment, safe operating standards, and variations in baseline consumption among different types of customers and buildings. To illustrate the application of the framework at Level 1a, we represent the change in technical potential by the post-measure passive load shape and the change in capability by the presence of controls technology or of other measure characteristics that increase the load flexibility. Figure 4 illustrates a reduction in the passive load shape that reduces load across many hours (top row) and an increase in capability to shed load in later hours of the day (bottom row).

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[20] We apply each sublevel of the framework to examples measures in Section 3.2 and qualitatively describe how EE and DR competition and complementarity may differ by grid need (e.g., system peak demand reduction, renewable energy curtailment) and DR product type (e.g., shed, shift, modulate).

[21] The concept of reliability is represented here by automation or remote controllability that increases DF without changing anything about how much load can be controlled.

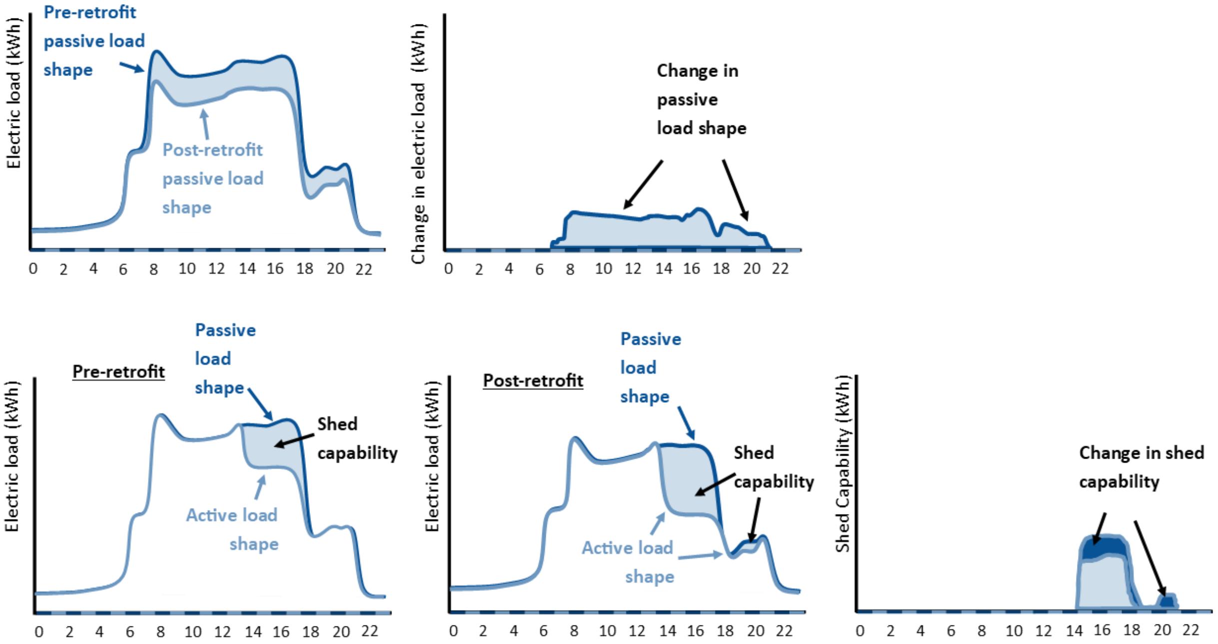

Figure 4. Illustration of change in passive load shape (top panels) and change in capability (bottom panels)

3.1.2 Level 1b: Change in the fraction of building demand flexibility participating as a demand response resource

The second sublevel of the framework is focused on the change in the fraction of the building's DF (computed relative to the total DF following any changes at Level 1a) that participates as a DR resource. Specifically, this sublevel asks, *is the fraction of a customer's/building's DF that is participating as a DR resource higher or lower?* EE and DR are in competition at this level if the change results in a lower fraction of building DF participating as a DR resource; they are complementary if the change results in a higher fraction of building DF participating as a DR resource; and they have a neutral interaction if there is no change in the fraction of building DF participating as a DR resource (see Table 1).

Changes at Level 1b are considered from the perspective of the participating customer. They do not encompass changes in technical potential and capability, which are addressed at Level 1a, but rather they encompass changes that may occur in participation drivers, like changes in customer comfort and financial incentives. In other words, Level 1a is about the change in technical potential and capability, and Level 1b is about how much of the technical potential and capability is participating and being utilized. Therefore, to fully assess whether EE and DR compete with or complement each other with respect to the fraction of DF that is participating, Level 1b must take into account participant preferences, behavior, and programmatic factors (e.g., customer baseline methodologies, retail rate design, financial incentive payments, and/or customer override capabilities).

3.1.3 Level 2a: Change in <u>need for demand response</u> in the utility system

The third sublevel of the framework is focused on the change in need for DR resources in the utility system. Specifically, this sublevel asks, *what is the change in likelihood that the system needs incremental demand response resources?* EE and DR are in competition at this level if the EE change increases the likelihood of needing DR resources to meet utility system needs; they are complementary if the EE change decreases the likelihood of needing DR resources at the system level; and their interactions are neutral if there is no change in the likelihood of needing DR (see Table 1).

Unlike Levels 1a (change in building DF) and 1b (change in building DF participation fraction), which take the building perspective, Levels 2a and 2b of the framework take the utility system perspective. Levels 2a and 2b also differ from Levels 1a and 1b by considering DR instead of DF. As discussed in Section 2.1, the framework distinguishes DR as the system resource and DF as the potential or opportunity. Levels 2a and 2b are, therefore, concerned with change in system resources. Levels 2a and 2b first account for the impacts of EE on utility system loads and resources and then consider the change in the utility system need for and availability of DR.[22]

Level 2a specifically considers whether the EE investments made by many customers or building owners have, in aggregate, increased or decreased the likelihood of needing DR resources to address utility system conditions. At this level of the framework, an increase in system need reflects competition, and a decrease in system need reflects complementarity between EE and DR. Interactions between EE and DR at Level 2a are almost entirely driven by the coincidence of the energy/demand savings at the building level and the net load driving system conditions.[23] The presence of controls capabilities is also an important driver, as they may increase or decrease the coincidence of energy/demand savings with system load. This depends on the specifics of how building controls are implemented.

3.1.4 Level 2b: Change in the <u>availability of demand response</u> in the utility system

The fourth sublevel of the framework is focused on the change in the availability of DR in the utility system.[24] Specifically, this sublevel asks, *what is the change in the quantity of DR that is available to meet specific system needs?* EE and DR are in competition if the change reduces the availability of DR to meet specific system needs or conditions (i.e., the DR is not there when the system operator needs it); they are complementary if the change increases the availability of DR when needed; and they have a neutral interaction if there is no change in the amount and timing of DR available to the system operator (see Table 1).

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[22] There are some instances when either the end use does not typically operate at the time of the system condition (e.g., the AC does not operate during the winter season) or the end use, particularly absent controls, is unable to respond at necessary timescales to meet the system condition (e.g., sub-hourly load response for frequency reserves). EE and DR have a neutral interaction at Levels 2a and 2b in these instances, as there is no change.

[23] The need for DR may also be driven by system conditions other than net load (e.g., generator unit outage). However, the probability of occurrence for system conditions that are *not* driven by net load would not change with a change in EE or DR resources.

[24] To be sure, the actual utilization of DR by the system operator (i.e., the dispatch decision) depends on many other interrelated factors (e.g., system frequency, generator status, transmission constraints).

Dispatchable resources, like DR, are used by utility system operators to meet system conditions and needs to maintain electricity reliability and service levels. EE may interact with DR by increasing or decreasing the amount of DR that is available to utility system operators. Whether EE and DR compete with or complement each other at Level 2b of our framework depends largely on the net effect of Levels 1a (change in building DF) and 1b (change in building DF participation fraction). Specifically, this depends on the interplay between the change in passive load shape, addition of capabilities (e.g., via controls or operational strategies), and change in participation.[25]

3.2 Applying the framework

To demonstrate the framework's application, we qualitatively use it to consider six EE measures with a variety of different control or communication technologies. There are many EE measures (e.g., the Scout model contains over 150 measures [Langevin et al., 2019]). Nearly all could include DR-interactive effects by, at a minimum, modifying the baseline customer load. We focus on a handful of commonly installed measures with existing technology and attributes that we hypothesize have a broad representation of factors likely to drive interactive effects (e.g., seasonality, customer class profile, magnitude of energy savings, timing of energy savings, presence of customer controls, and utility dispatch capability).

Tables 2 and 3 define the example residential and commercial measures in terms of the targeted end use, baseline load shape and operation, level of electricity demand post-measure, and control technology. Appendix A presents more detailed descriptions of the example measures. All examples assume a fairly inefficient technology and operation baseline (e.g., single-stage compressors, fluorescent lighting, manual control). The savings shape of each example measure is driven by the difference between the more efficient technology and this inefficient baseline. To derive directional EE and DR interactions in the framework (i.e., complement versus compete), we first characterize the load shape ("post EE load shape") as being in one of two possible states: (1) "generally lower" (i.e., lower energy consumption in most/all hours of the year; as depicted in Figure 2); or (2) "sometimes lower and sometimes higher" (i.e., lower energy consumption in some hours of the year and potentially higher energy consumption in other hours of the year).

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[25] The quantity assessed at this sublevel could be considered similar to the market potential in DR potential studies that measure the technical capabilities of end uses to provide DR and the propensity of customers to participate in DR programs.

Table 2. Example residential measure definitions

End Use[26]	Pre-EE Technology and Operation	Technology/ Device	Post-EE Hourly Load Shape	Control and Dispatch[27]	Measure Name
HVAC	Single-stage compressor with non-programmable thermostat	Single-stage compressor with programmable communicating thermostat (PCT)	Sometimes lower and sometimes higher	Programmable (with utility dispatch)	Res. PCT
Hot water	Electric resistance (ER) with manual on/off control	Insulating wrap	Generally lower	Manual control	Res. electric resistance water heater (ERWH) wrap
				Utility dispatch	Res. ERWH wrap + grid connection
		Heat pump	Generally lower[28]	Manual control	Res. heat pump water heater (HPWH)
				Utility dispatch	Res. grid connected HPWH

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[26] A category of equipment or service that consumes energy (e.g., lighting, refrigeration, heating, process heat) (NAPEE, 2006).

[27] Manual control indicates operation by customer with or without the use of a technology or device. Utility dispatch indicates operation by the utility, load serving entity, or aggregator via a technology or device.

[28] The load shape post-EE may be sometimes higher at sub-hourly timescales.

Table 3. Example commercial measure definitions

End Use[29]	Pre-EE Technology and Operation	Technology/ Device	Post-EE Hourly Load Shape	Control and Dispatch[30]	Measure Name
AC	Single-stage compressor with non-programmable thermostat	Variable speed compressor	Generally lower[31]	Manual control	Com. variable speed AC
		Variable speed compressor with programmable communicating thermostat	Sometimes lower and sometimes higher[32]	Programmable (with utility dispatch)	Com. variable speed AC + PCT
Heating and Cooling	Low efficiency building envelope and EMS	Mix of more efficient building envelope measures and EMS	Sometimes lower and sometimes higher	Programmable (without utility dispatch)	Com. building envelope upgrade
Lighting	Fluorescent lighting with manual on/off control (no dimming)	Light emitting diode (LED) lighting with dimming capability	Generally lower	Manual control	Com. LED lighting
	LED technology with manual on/off control	Networked (connected) lighting controls	Sometimes lower and sometimes the same	Programmable (with utility dispatch)	Com. networked lighting controls
Refrigeration	Low efficiency compressor with manual on/off control	High-efficiency compressor	Generally lower	Manual control	Com. Refrigeration upgrade
				Programmable (with utility dispatch)	Com. Refrigeration upgrade + controls

The second level of our framework can only be defined in relation to specific system conditions that can change at intervals ranging from seconds to hours based on several factors (e.g., load, generating resource, voltage, frequency, and transmission congestion). As such, we develop a limited number of utility system prototypes intended to generalize the system conditions that we consider the most significant for EE and DR interactions.[33] These system prototypes are then considered when applying Levels 2a and 2b of the framework. The system prototypes are defined as follows:

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[29] A category of equipment or service that consumes energy (e.g., lighting, refrigeration, heating, process heat) (NAPEE, 2006).

[30] Manual control indicates operation by customer with or without the use of a technology or device. Utility dispatch indicates operation by the utility, load serving entity, or aggregator via a technology or device.

[31] Experimental tests of a variable speed AC against a single-stage unit found efficiency savings averaging 31 percent, which varied by region due to climate and other factors. This result was consistent with literature on both experimental and simulated tests. Thus, over broader timespans such as hourly, we assume that the post-EE load shape will be generally lower (see Wang et al., 2019). Energy consumption may be higher on sub-hourly timescales when the single-stage compressor would be cycled off but the variable speed compressor would be operating at a low level.

[32] Some research on commercial A/C has shown an increase in electricity consumption over the efficient baseline when pre-cooling or expanding the deadband around a temperature setpoint. Hourly load may increase when recovering from setbacks to the desired temperature in the occupancy period, as opposed to operation at a constant setpoint (Cole et al., 2014).

[33] The four system prototypes described and used as examples in this report are not intended to be representative of all possible grid conditions. A vastly different scenario of loads and resources than what is represented by these four examples could produce different EE and DR interactions.

1. *Summer peak shed:* system need to reduce summer peak demand (i.e., shed) driven by high temperatures and AC load
2. *Winter peak shed:* system need to reduce winter peak demand (i.e., shed) driven by low temperatures and heating load
3. *Solar shift:* system need to shift load from high to low photovoltaic production periods to avoid renewable energy curtailment driven by high solar generation
4. *Frequency reserves:* system need to provide frequency reserves (i.e., modulate)

Figure 5 shows four example system load shapes that could correspond to each of these system needs.

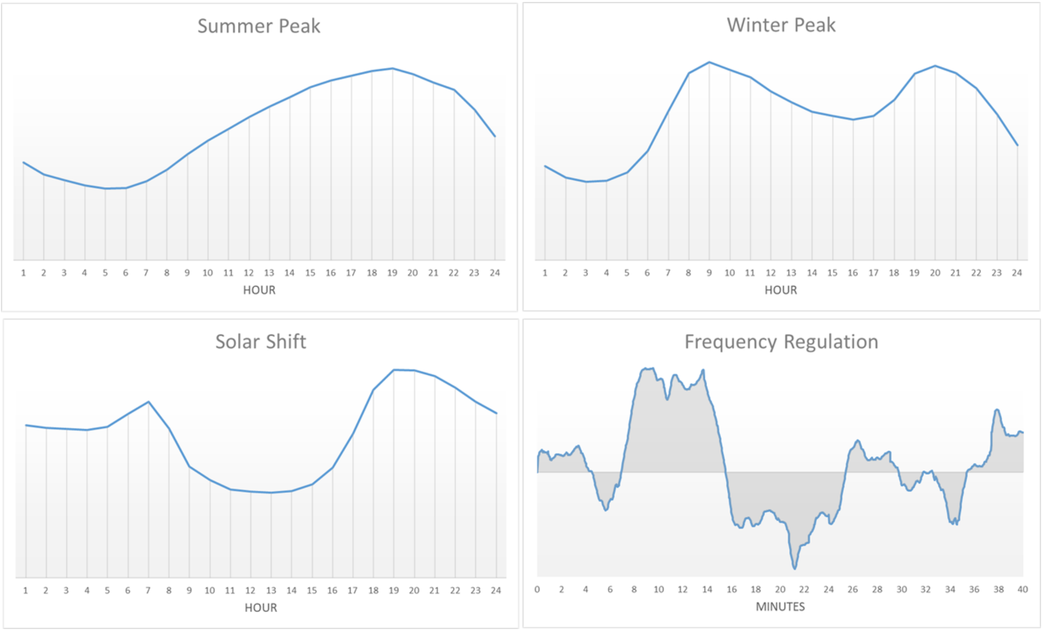

Figure 5. Illustrative system prototypes representing Summer peak shed (ISO-NE weekday average load in August, 2018), Winter peak shed (Northwest weekday average load in February, 2018), Solar shift (CAISO net load on March 5, 2018), and Frequency regulation (PJM RegD normalized signal). The Summer and Winter Peak prototypes illustrate the normalized hourly demand curve of the system; the Solar Shift system prototypes illustrate normalized hourly net load on the system; and the Frequency Regulation illustrates normalized fast frequency response needed both in the positive and negative direction over a period of 40 minutes (EIA n.d., CAISO n.d., PJM, 2014).

In the following sections, we qualitatively assess each level of our framework in detail, using these specific EE measures and system prototypes, to highlight important issues that can arise in applying the framework in specific contexts.

3.2.1 Level 1a: Change in building demand flexibility

Table 4 shows the grouping of our example measures by the change in passive load shape and the change in capability to provide demand flexibility, which are the two components of Level 1a. As described below, the interaction of EE and DR at Level 1a depends critically on the specific combinations of change in passive load shape and change in capability.

Table 4. Examples of change in passive load shape and change in capability for a building to provide demand flexibility (Level 1a)

			Change in Passive Load Shape	
			Generally lower	**Sometimes lower/sometimes higher**
Change in capability	**Unchanged**	**Without controls**	• Res. ERWH wrap • Res. HPWH • Com. LED lighting • Com. refrigeration upgrade • Com. variable speed AC	No examples considered
	Higher	**Without controls**	No examples considered	• Com. building envelope upgrade
		With controls	• Res. ERWH wrap + grid connection • Com. refrigeration upgrade + controls	• Res. PCT • Res. grid connected HPWH • Com. networked lighting controls • Com. variable speed AC + PCT

The examples in the top row (i.e., Res. ERWH wrap, Res. HPWH, Com. LED lighting, Com. refrigeration upgrade, and Com. variable speed AC) have lower demand in all hours of operation (driving a change in technical potential) and do not include control technologies (resulting in no change in capability), as compared to the baseline load profile and capabilities prior to the EE or DR investment. Essentially, among these examples there is less load to provide as a flexible resource and no increased ability to reduce the load, shift it into different time periods, or respond at sub-hourly timescales for modulation. Therefore at Level 1a for these examples, EE and DR compete with each other for load shed, shift, and modulation.[34] The second row contains only one example—Com. building envelope upgrade—with a passive state demand that is sometimes lower and sometimes higher. If HVAC operations are unchanged, demand is generally lower during peak daytime cooling hours, due to reduced

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[34] In instances where a load was not modulating prior to the EE or DR investment, there is no change (i.e., neutral EE and DR interaction) to load modulation among these examples.

thermal losses through the building shell, but may be increased (though still small relative to peak loads) during the overnight hours, since passive cooling is less effective and more mechanical cooling is required. The change in the passive load shape, therefore, either increases or decreases technical potential depending on the specific hour under consideration. In addition, the building may now also be able to more effectively employ pre-heating or pre-cooling strategies that shift the timing of the consumption in response to time-varying electricity rates (utilizing the existing thermostat or other HVAC controls).[35] While not a result of new controls technologies associated with the measure, the enhanced effectiveness of pre-heating or pre-cooling increases the DF capability specifically for load shifting. Similarly, the improved thermal stability of the building may allow cooling loads to be shed for a longer duration without unacceptably degrading occupant comfort. Thus, for this example, EE and DR may either compete with or complement each other at Level 1a, depending on the particular timing of the system need and on whether the increased DF from improved thermal stability outweighs the reduction in the total available load during peak hours.

The final row of examples in Table 4 adds controls to the change in passive state demand. Res. ERWH wrap + grid connection and Com refrigeration upgrade + controls have lower load in all hours after the EE investment and, in our examples, include the addition of programmable controls. Similarly, the remaining examples (i.e., Res. PCT, Res. grid connected HPWH, Com. variable speed AC, and Com. networked lighting controls) combine the addition of controls with a post-measure load shape that is sometimes lower and sometimes higher. Whether EE and DR compete with or complement each other in these cases depends on whether the reduced technical potential has a greater or smaller impact than the additional capability to control loads. Prior studies suggest the addition of capability via controls may overcome the reduced technical potential, thus driving complementary interactions between EE and DR (e.g., Ghatikar et al., 2014; Herter et al., 2009).

3.2.2 Level 1b: Change in demand flexibility participation fraction

The example measures point to three key factors driving EE and DR interactions at Level 1b: (1) customer participation prior to measure installation; (2) change in customer baseline and resultant impacts on participation financial incentives; and (3) additional controls or new capabilities to alter the timing of consumption.

First, it matters whether the customer is able to participate in DR prior to the measure. For example, consider a residential electric resistance water heater. Without utility dispatch (e.g., a utility direct load control switch) or customer programmable controls (e.g., a programmable thermostat), the water heater is difficult to turn off manually, thereby precluding event response. Simply improving the efficiency of this end use, whether through improved tank insulation or replacement with a HPWH, would not be expected to change the fraction of the

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[35] More specifically, efficient commercial building envelopes would likely increase the building's ability to maintain indoor temperatures without increasing demand during the peak period but not necessarily increase the ability to increase demand during the pre-cooling or pre-heating hours, which would also be limited by service level thresholds (e.g., over-cooling occupants in the middle of a summer day).

DF participating as a DR resource. Similarly, commercial refrigeration cannot easily be manually controlled to provide a DR resource. Commercial refrigeration may also need to meet local, state, or federal guidelines or regulations for food safety, thereby prohibiting participation.

Second, measures that result in a new, lower customer baseline would reduce DR participation payments and erode financial incentives to participate. In the Com. building envelope upgrade example, we assume the building's capability to shed or shift load has increased since its thermal retention properties have improved, enabling greater reduction in space conditioning without disrupting building services. However, the building's passive load shape is also lower during peak hours, and the customer may be less willing to participate if the DR financial incentive is reduced because the building has a smaller baseline load. It is also worth noting that competition between EE and DR may occur in situations where the EE investment precludes the customer from participating as a DR resource, as is the case for some residential water heater DR programs that do not include HPWH as an eligible end use (e.g., Hawaii Electric Company EnergyScout™ for Water Heaters program[36]).

Third, measures that increase DF capability, either via operational strategies or controls, are likely to increase the fraction of DF participating as a DR resource. For example, smart thermostat control capability (represented in the Res. PCT example) allows load reductions to be achieved regardless of occupancy (i.e., the thermostat can be adjusted automatically or remotely) and with less concern that the result will be unacceptable to the occupants, increasing the fraction of DF participation in individual DR events. Commercial lighting controls capability (represented in the Com. networked lighting controls example) allows load reductions to be achieved with a more uniform lighting density (in comparison to switching off banks of luminaires, for example) and with less concern that the result will be unacceptable to the occupants.[37] Because lighting levels can be controlled in ways that have minimal or no disruption to operation, the fraction of DF participating in DR is likely greater than that of the pre-measure state.

3.2.3 Level 2a: Change in utility system need for DR

At this level, it is necessary to assess EE and DR interactions in the context of our defined system prototype conditions. For summer and winter peak system conditions, most or all EE measures have a complementary interaction between EE and DR. This is because the reduced load from the EE or DR investment coincides (to some degree) with the utility summer or winter peak. Because the demand savings reduce the summer and winter peaks, there is a reduced need for DR resources (i.e., lower likelihood of reliability or economic system conditions necessitating DR). The degree of complementarity varies depending on the specific example being considered, where end uses that tend to drive system peaks have much greater complementarity (e.g., AC driving summer peaks, residential ERWH driving winter morning and

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[36] See Hawaiian Electric. Demand Response. Residential Solutions. https://www.hawaiianelectric.com/products-and-services/demand-response/residential-solutions

[37] This is based on the assumption that the baseline (i.e., pre-EE measure installation) uses manual (on/off) switching with the ability to control individual banks of luminaires independently. The example measure is advanced networked lighting controls that can dim individual luminaires in a more fine-tuned way.

evening peaks) than end uses that are less coincident with system peaks (e.g., commercial refrigeration that operates over many hours of the day).

Among the example measures, EE and DR more often compete with each other at Level 2a in solar shift and frequency reserve system conditions. The solar shift system condition is characterized by a need to *build load* during periods when solar generation is greatest and load is relatively low (typically in the early afternoon periods and during spring season). Therefore, demand savings in the load building periods (e.g., through more efficient commercial air conditioning) will only exacerbate the potential for renewable energy curtailment and declining net loads. The frequency reserve system condition is, in our example, characterized by the need to quickly increase or decrease generation over short timescales to meet steeply increasing or decreasing generation due to high solar generation penetrations. As generating resources must quickly respond to meet changing load, the timing of some demand savings may increase the steepness of the ramp periods and contribute to additional need for frequency regulation resources. Of course, these conclusions depend critically on the alignment between demand savings and solar production profiles (e.g., the greater the alignment, the greater the increase in need for DR), and the degree of competition may vary throughout the year.

3.2.4 Level 2b: Change in the availability of DR

The primary driver of the interaction between EE and DR at Level 2b is the amount of demand flexibility available during times of system need. Electricity consumption in commercial buildings have load shapes (post-EE) that closely match solar generation production curves, and EE measures likely have their greatest impact when load is high. Therefore, while a building could "take" by pre-cooling in hours of high solar production during the day, there is limited ability to shed during evening and nighttime hours due to the operation hours of commercial buildings. As such, there is a smaller load to displace or "shift" from the evening ramp and nighttime hours. Certain operational or technical characteristics of some end uses limit their availability as a DR resource. For example, commercial lighting cannot be stored or readily rescheduled and thus is not a load that can be shifted on demand. Similarly, heating or cooling loads do not typically occur outside their respective seasons (i.e., heating demand occurs in colder seasons and cooling demand occurs in warmer seasons).

EE and DR complementarity at Level 2b is most likely to occur with the addition of controls and operational strategies that increase both the resource capabilities (Level 1a change in building DF for an individual building) and participation (Level 1b change in building DF participation fraction). For example, smart thermostats (and other control technologies) enable a more flexible and reliable DR resource, providing the system operator more DR to dispatch when needed. Also, an improved commercial building envelope can maintain comfort with reduced cooling for longer periods and can pre-cool more effectively, increasing the ability for DR resources to reduce consumption or to shift from peak to off-peak periods.

4 Key Attributes of EE and DR Interactions and Framework Application

Among our example measures, we identify three key attributes qualitatively driving EE and DR interactions. First, the change in the passive load shape is an important determinant of whether EE and DR compete with or complement each other. Some of our example measures have post-EE measure load shapes that are lower in all hours of the day, while there are other examples with post-EE demand that is sometimes lower and sometimes higher. Any reduction in the post-EE measure load shape would reduce the total level of load, which would seemingly reduce the amount of DF, all else being equal. In such cases, EE and DR compete with each other at Level 1a (change in building DF) because there is less load available to participate in DR (as in the Res. ERWH wrap example). Furthermore, EE and DR complement each other at Level 2a (change in utility system need for DR) for load shedding system events because system peak loads are reduced. In contrast, if the post-EE load shape is higher in some hours, this would seemingly increase the amount of DF in those hours, all else being equal. In such cases, EE and DR complement each other at Level 1a (at least in some hours) because there is more load available to participate in DR. However, if these hours correspond to the system peak, EE and DR compete with each other at Level 2a for load shedding system events because system peak loads are now higher.

Second, some EE measures increase the DR capabilities of the affected load, via either the addition of controls or operational strategies to shift load. Despite reductions in the post-EE measure load shape, affected loads with increased capabilities to modify load enable access to previously untapped DF. Increased capability may occur via the addition of controls technologies that allow for pre-programmed DR strategies with varying degrees of human-intervention (Piette et al., 2006) or via the implementation of operational strategies that change the timing of electricity consumption to improve end-use efficiency and DR performance (e.g., Scott et al., 2015). If the increase in capabilities exceeds the concurrent decrease in the load shape, then this tends to suggest more complementarity between EE and DR, particularly at Levels 1a (change in building DF) and 2b (change in DR availability) of the framework. With the incremental addition of controls and utility communication/dispatch, several measures could provide modulation (driving complementarity at Level 2b). Controls and utility communication/dispatch also likely increase the fraction of DF participating in shed and shift events (driving complementarity at Level 1b, the change in building DF participation fraction). Ultimately, whether or not EE and DR complement each other with additional capability from a load-impacts standpoint depends on the extent of the change in passive load shape (which reduces the overall DR resource) compared with the offsetting increase in load flexibility, fraction of DF participating, and reliability of the DF.

Third, we found that the timing of savings and whether they are coincident with peak or load-building periods mattered at Level 2a (and Level 2b when also taking Level 1b change in building DF participation fraction into account). Importantly, we find few examples among our commercial measures that reduce the system need for load shifting in the “solar shift” system condition due to the fact that savings tend to occur in the times when the system needs to increase load. It is important, therefore, to consider the temporal dimension of EE and DR relative to the system shape as this defines much of their value to the utility system. This is especially significant for grid systems with a high amount of VRE generation that can dramatically and unpredictably alter hourly marginal costs within a short time span. Utilities should, therefore, employ strategies to maximize the overall reduction in energy consumption from EE measures, while avoiding competitive effects between EE and DR arising from the timing of load reductions.

Drawing from the key attributes identified above, analysis quantifying EE and DR resource potential may benefit from grouping measures into portfolios with different likely implications for EE and DR interactions. We offer three example portfolios of EE measures with different impacts on the building DF and grid need for DR:

1. *Equipment upgrades* involve installation of more efficient appliances, equipment, electronics, or lighting products. These will tend to reduce the amount of flexible load at the building level, but they may also reduce the grid need for DR.
2. *Controls measures* involve the installation of control technologies (e.g., programmable thermostats or occupancy sensors) that can reduce overall energy consumption. These will tend to increase DF at the building level, but, depending on the control strategies used, they may either increase or decrease the need for DR at the utility system levels.
3. *Envelope improvements* involve improvements to building insulation, reflectivity, solar heating gain, and the like. Because they increase thermal inertia, these measures will tend to increase DF at the building level, and they may also reduce the need for DR at the system level by decreasing peak loads.

Our qualitative application of the framework to a subset of EE and DR measures also suggests increasing complexity in evaluating EE and DR interactions when moving from standalone equipment to integrated systems. The EE and DR capabilities of standalone equipment are generally easy to evaluate at a component level with minimal interaction with the rest of the building. Examples of standalone equipment that has minimal influence[38] on the rest of the building include ERWH, HPWH, appliances, plug loads and miscellaneous equipment loads, elevators, and pool pumps. Building integrated systems such as HVAC and lighting systems, by contrast, are integrated with the building structure. HVAC loads are related to the building façade, windows, walls, and building mass. Lighting needs are also related to windows, and passive daylight may be available in many building configurations. While integrated systems may have more difficult-to-quantify EE and DR interactions, they may also be the most significant in terms of accessing DF through the addition of DR capabilities (e.g., EE retrofits that influence the façade will influence the need for DR and the DR capabilities of HVAC and lighting systems). In addition, many integrated systems that can drive increased DF participation in DR

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[38] Standalone equipment EE measures will have feedback on the building's heating and cooling loads, but these are typically small impacts.

programs will also enhance customer comfort (e.g., HVAC and lighting provide visual and thermal comfort and air quality).

5 Conclusions and Future Research

In this report, we develop and describe a conceptual framework that characterizes the ways in which EE and DR compete with and complement each other. We use example measures to qualitatively show the application of the framework and highlight key drivers of complementarity and competition.

Importantly, we find no universal relationship between EE and DR. Instead we find that EE and DR interactions depend on measure and technology specifics (including building type and targeted end use), as well as utility system conditions. We also find that EE and DR interactions are defined by more than just the change in discretionary load (i.e., DR potential) but also the change in likelihood of participation in DR programs, as well as the change in system need for, and the overall availability of, DR resources.

We use a diverse set of example measures when applying the framework that differ by targeted end use, temporal profiles, and customer class. Despite this broad representation of EE measures, they all exhibit important implications for DR and DF. This suggests that EE and DR interactions exist for measures and programs that are not explicitly delivered in an iDSM context. Indeed, virtually any change in the electricity end-use characteristics of a building would be expected to have some effect on both total usage and timing of that usage. While we do not consider end-use fuel switching and other technology and market trends that may impact underlying load shapes and grid demand (e.g., electric vehicle adoption) in this report, any resulting interactions could still be expressed through this framework.

The flexibility of this framework allows it to work under various scenarios and be applied to the electric industry in several ways. First, regulators and utilities are seeking to improve the integration of EE and DR in utility operational and planning activities (at the bulk power and distribution system levels). Applying the framework in these cases might entail representing EE impacts on an hourly basis (or a sub-hourly basis in the case of load modulation) and using operational and planning models to endogenously select DR resources (after accounting for EE load impacts) subject to cost and reliability constraints. This would capture the Level 2a (change in need for DR) and 2b (change in availability of DR) interactions.

Second, the framework can inform the design of EE and DR programs that incorporate complementarity to bring down enablement and incentive costs. Adding capabilities to enable or automate DR strategies drives complementarity between EE and DR at Levels 1a (change in building DF) and 1b (change in DF participation fraction). For example, some DR controls technologies may be jointly installed with an EE measure (e.g., commercial lighting controls) to allow increased DR program participation.[39] Retro-commissioning programs that include tuning up and programing DR controls at the same time as installation of EE measures may also provide a source of EE and DR complementarity. For example, some buildings may be over-

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[39] This source of complementarity is already recognized in some policies, such as California Title 24 building codes that require DR enablement in certain commercial lighting controls.

conditioned (especially over-cooled in the summer) and resetting the temperature during retro-commissioning may improve comfort and enable new DF capabilities for load shifting.

Finally, this framework lays the foundation for future research to better quantify and analyze specific end uses and EE and DR interactions under realistic grid scenarios. Topics and questions for future research include the following:

Metrics. Determining whether EE and DR compete with or complement each other, especially at Levels 1a (change in building DF) and 1b (change in DF participation fraction) of the framework, is determined largely by the interplay between capabilities and performance. Developing metrics to describe building DF capabilities and performance is a first step to better identifying and quantifying EE and DR interactions. We note this research is ongoing in complementary U.S. Department of Energy (DOE)-sponsored GEB projects.[40]

Quantifying load trade-offs. As is evident in the qualitative application of the framework to the example measures, EE and DR measures interact in numerous ways that can either enhance or erode their respective impacts on customer consumption and utility loads. This requires developing credible time-dependent characterizations of EE and DR load impacts, as well as calculating their joint impact on aggregate loads at the utility system level. Insights from such research can be used for deploying EE and DR jointly in a manner aligned with grid needs and with an understanding of the characteristics (e.g., load shifting, load shedding) that must be considered when designing joint EE and DR programs. This research topic will be the focus of the next phase of our broader effort to describe and quantify EE and DR interactions.

Change in economic costs and benefits. Historically, EE and DR cost-effectiveness has relied on avoided capacity and energy values calculated as an average and applied to all hours of the year. The precise value of utility system resources changes every hour of every day and critically depends on system conditions reflecting the intersection of supply and demand. To assess EE and DR's system cost impacts, economic trade-offs, and emissions impacts, they need to be considered within the context of bulk power system resources (e.g., utility-scale generating facilities) and loads. This will require improving the representation of EE and DR within utility resource planning tools (e.g., dispatch models), as existing approaches largely model EE and DR only as decrements to loads and not on the supply side as dispatchable resources. Also, future research should consider potential economies of scale or other reductions in incremental EE or DR enablement/capital costs when resources are implemented together. Research quantifying the system costs and benefits will be the focus of the last phase of our broader effort to describe and quantify EE and DR interactions.

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[40] "Framework and Metrics to Characterize Building Technologies that Can Provide Grid Services" and "Framework and Method to Define Flexible Loads in Buildings"

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APPENDIX A. Measure Descriptions

In 2018, the commercial sector consumed more than 36 percent of all electricity delivered nationwide.[41] While there are a variety of commercial building types, the average load shape across buildings closely follows that of solar production, beginning in the early morning, peaking in the early afternoon, and dropping to lower levels in the evening until the next morning (see Figure A-1). Four of the six example measures represent commercial end uses in cooling, refrigeration, lighting, and building envelope.

Commercial cooling. Commercial air conditioning (AC) is primarily used during the summertime and ranges widely throughout the course of the day, with the highest load around 3 pm and the near-zero load during the nighttime. Switching from a baseline single-speed compressor AC unit to a multi-speed compressor unit allows the appliance to operate at various speeds, as opposed to a binary on/off. Operating at a lower speed still improves humidity, which allows for improved comfort while using less electricity, which can increase efficiency and likelihood of DR participation. Multi-speed compressors run longer without switching fully off, making the unit more likely on a sub-hourly basis to be using more instantaneous load than if it would if it were fully off, and less than if the unit were fully on; however, overall electricity use decreases roughly 30 percent (Wang et al., 2019). The incremental addition of controls enables extended modulation and contingency services, DF, and more consistent participation and overall DR response (Hammerstrom et al., 2007). While efficiency should improve, if participating in utility services more frequently or for longer durations, there may be an overall increase in electricity use due to round-trip losses during pre-conditioning events (e.g., Cole et al. [2014] found a ratio of input energy to output energy of 0.61) or frequency regulation events (Keskar et al. [2019] found a wide range of round trip efficiencies between 0.34 and 0.81, and Beil et al., [2015] experiments yielded a similar average of 0.46).

Commercial refrigeration. Commercial refrigeration load remains fairly consistent over the course of the year, as well as throughout each day, with electricity load largely driven by ambient temperatures. As a result, the demand is coincident with almost all hours of any day. Even so, refrigeration is often used to preserve food and must comply with health and safety regulations, which may decrease its flexibility compared to other end uses. Commercial refrigeration applications cover walk-in coolers and freezers, refrigerated cases, and others with a variety of efficiency opportunities including, but not limited to, interior lighting, defrost cycles, and anti-sweat heater controls.

Commercial lighting. Commercial lighting has a diurnal pattern similar to, but more extreme than, cooling due to the on/off controls and the inability to store lighting. Its end use load shape remains fairly similar between seasons, and remains coincident with summer peaks. The technology is undergoing a transition from the traditionally common fluorescent technologies to light-emitting diode (LED) technologies. One key difference between the technologies,

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[41] U.S. Energy Information Administration. Electric Power Monthly. Table 5.1. Sales of Electricity to Ultimate Customers. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_01

besides LED’s superior efficiency, is that LED lighting systems are commonly able to be continuously dimmed, allowing LED light output to be more precisely tuned to the real-time need for lighting service, whereas this functionality is more difficult to implement in fluorescent lighting systems and therefore less common (Garbesi et al., 2015). The second major transition involves the growing adoption of networked lighting control systems (NLCs), which allow automated control of lighting in a building that is also very fine-grained (often to the level of controlling individual luminaires). Automated lighting controls have long been an important class of EE measures with significant savings potential (Williams et al. 2012); the addition of networked communications can yield very large energy savings, on the order of 50 percent (Kisch et al., 2017), while also opening an attractive pathway for accessing the lighting end use for DR. A recent study for the California Energy Commission (Schwartz et al., 2019) found a high degree of synergy available between the EE and DR benefits of NLCs, with the cost savings from EE alone often being sufficient to justify adoption of such controls, which would also unlock a DR resource that is still substantial, despite the reductions in overall lighting load.

<u>Commercial building envelope.</u> Improvements to the building envelope are a common strategy to reduce heating, ventilation, and air conditioning system (HVAC) load and include measures like air sealing, insulation (in walls and roofs), and dynamic windows (Wang et al., 2011). HVAC represents a large load that often drives wintertime heating demand and summertime cooling demand. Some of the measures, like dynamic windows and shading, are controllable (Lee et al., 2017). In addition to providing energy savings, these measures can also improve occupancy comfort by better regulating the interior environment’s temperature, lighting, and air flow (e.g., Jakob, 2006; Jewell, 2014).

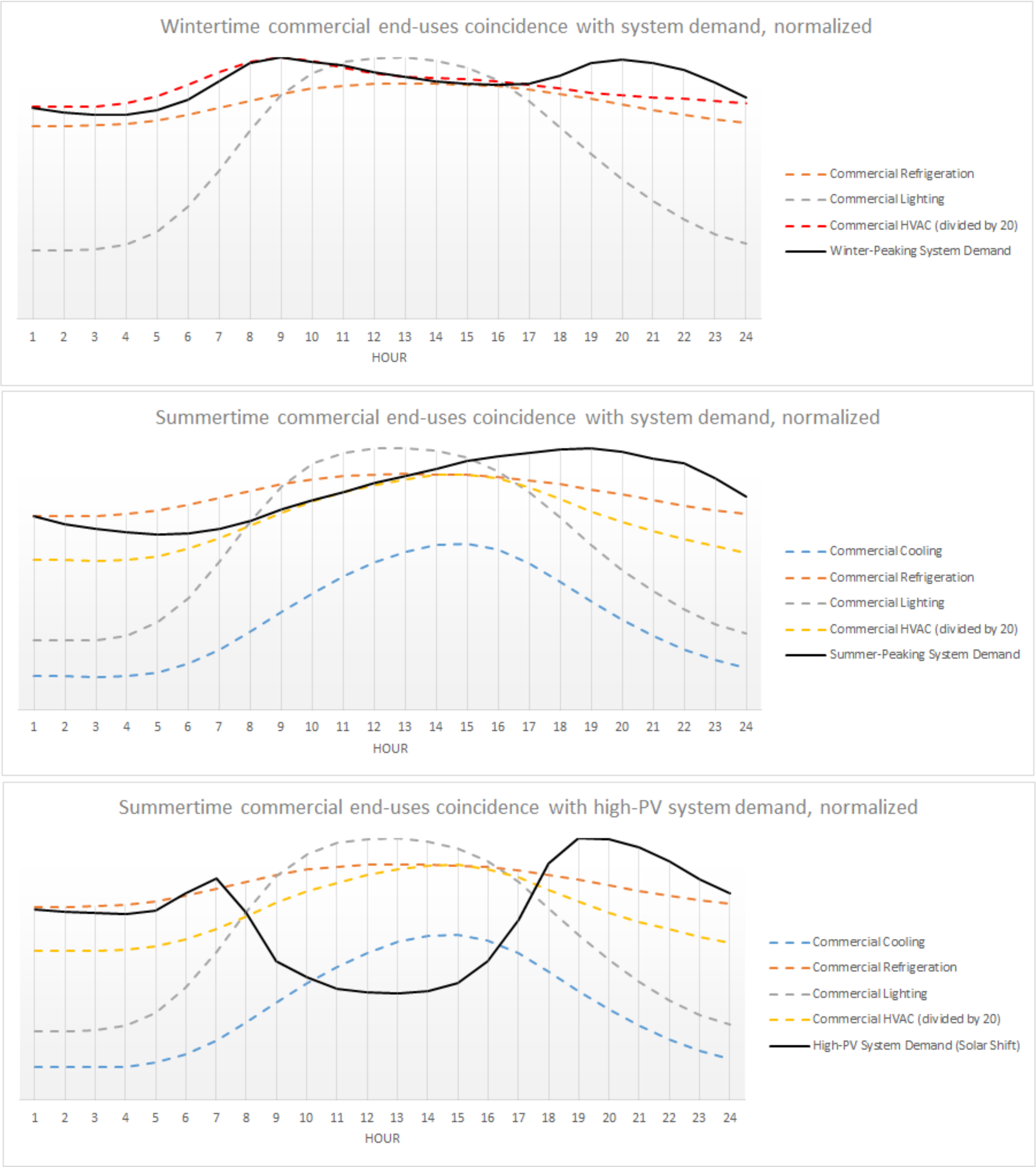

Figure A-1. Normalized commercial end-uses' coincidence with system prototypes (average weekday end use load shapes from EPRI, n.d.)

Hours of higher residential load diverge from that of commercial end uses, with increased morning and evening usage, often coincident with that of solar shift and winter peak system conditions (see Figure A-2). The two remaining example measures represent residential electric water heaters and thermostats.

Residential water heaters. Used throughout the year, electric water heater load peaks in the morning hours with a smaller evening peak. Over 45 percent of U.S. households use electric water heaters (EIA, 2017), most of which are electric resistance. Electric resistance heating elements offer very little opportunity for increased efficiency; however, the efficiency of electric water heating systems can be improved somewhat through better insulation of the tank. A more efficient option is a heat pump water heater (HPWH), which pulls heat from ambient air to heat water. Heat pump water heaters generally use less than half the electricity of electric resistance water heaters. Electric water heater loads can be shifted, curtailed, or turned on in several ways (Hledik, Chang, & Lueken, 2016). These include peak shaving (reducing peak demand), thermal storage (heating water at times of low demand or oversupply of generation and then curtailing heating during times of high system demand),[42] fast response (allowing real-time response to supply fluctuations, potentially alleviating the need for fast-ramping generation), and a controlled heat pump water heater strategy (in which the efficiency of a heat pump water heater is combined with heating curtailment to cut system peak demand). The efficiency of HPWHs may work against them in a DR context if it limits the amount of load that such programs can shift in order to deliver grid services and support variable output electricity generation sources. Additionally, HPWHs may not be able to respond as quickly as ERWHs to some demand response requests (Shapiro and Puttagunta, 2016), and cycling them too often may damage the units and require early replacement.

Residential smart thermostat. A building's HVAC is a significant electrical load in many residential structures across the country and acts as a substantial driver of bulk-power system coincident peaks in the summer and winter months. Smart thermostats not only reduce electricity consumption during normal operation, which can result in customer bill savings, they facilitate greater utility access to potential participants in DR programs. For example, Nest Labs claims its smart thermostats can provide energy savings of 10 to 12 percent for heating usage and about 15 percent for cooling usage.

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[42] Storage capability for 50-gallon tanks can allow curtailment of heating for up to four hours while still providing acceptable provision of hot water, whereas 80-gallon tanks can allow 16 hours of curtailment (Hledik, Chang and Lueken, 2016).

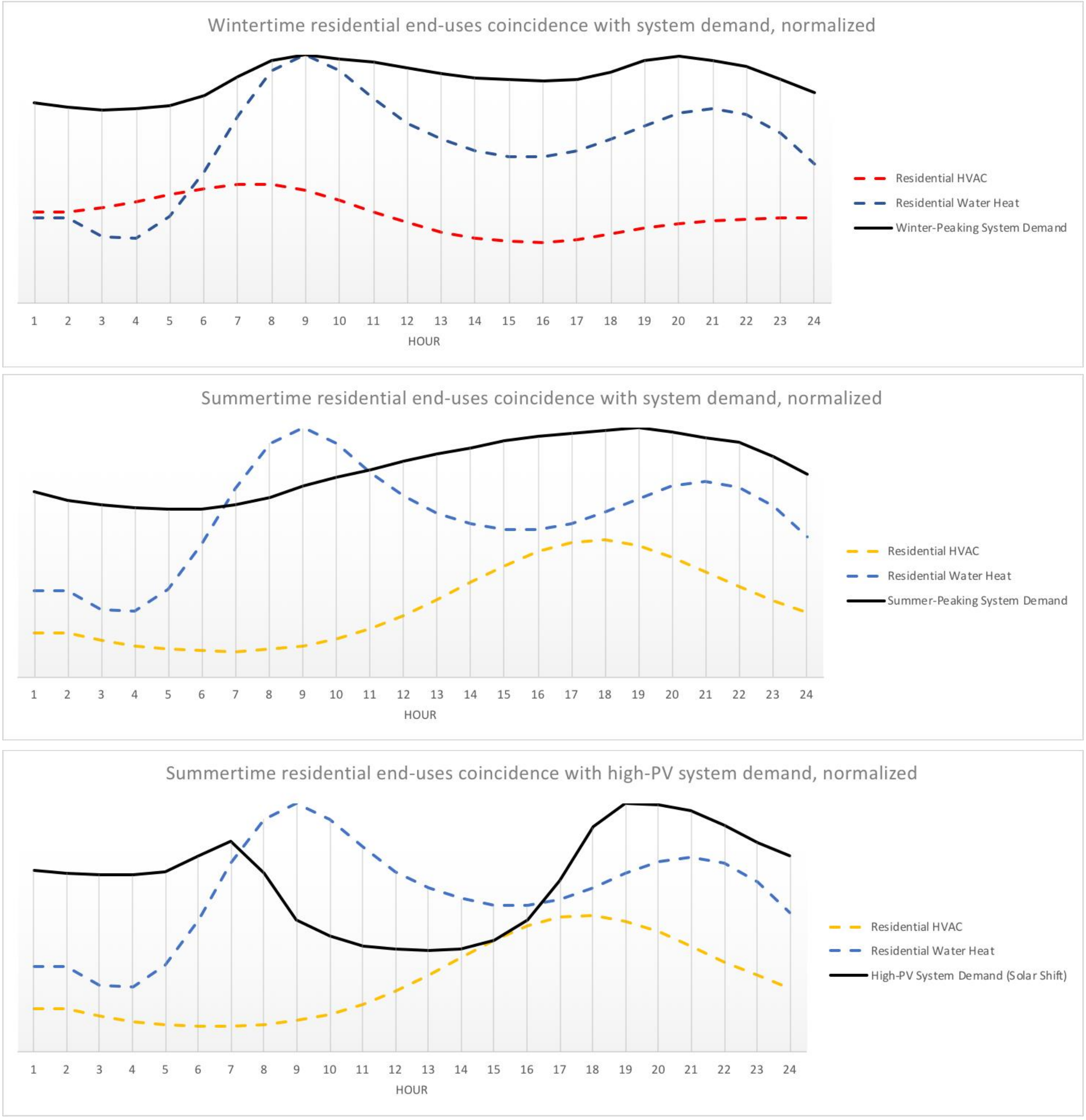

Figure A-2. Normalized residential end-uses' coincidence with system prototypes (average weekday end use load shapes from EPRI, n.d.)