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Grid-interactive, efficient buildings: expanding value streams through optimised control of flexible building technologies

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Grid-interactive, efficient buildings: expanding value streams through optimised control of flexible building technologies

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Keywords

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Abstract

Energy efficient buildings can operate at lower loads, but without optimised systems, they are limited in terms of dynamically responding to grid signals to adjust demand to best meet grid and occupant needs. If enabled with intelligent controls, buildings' efficiency and flexibility features can become resources with value in electricity markets. As a result, grid-interactive efficient buildings could reduce and shift electricity consumption to the mutual economic benefit of building owners and grid operators, relieve system stress, better integrate variable renewable energy generation, and better meet building occupant expectations for optimised comfort, cost, and resilience. This paper describes how a new class of grid-interactive efficient buildings (GEBs) can both reduce net demand and benefit the grid through more flexible loads.

This research provides a new taxonomy for flexible building technologies: flexible timing, flexible efficiency, flexible fuel source, and flexible frequency/voltage regulation. Each of these flexibilities is linked to grid services recognised by electricity markets and analysed in terms of technical potential and optimisation requirements. This paper demonstrates an estimated 1.7 exajoules (XJ) of summer season energy savings from the technical potential of efficiency and flexibility in building cooling equipment. By targeting high-value electricity, these strategies could bring an estimated €28 billion in cost savings and over 60 million metric tons (Mt) in CO_2 emission savings.

Introduction

Breakthroughs have made building technologies increasingly smarter, more connected, and more efficient. When these technologies can more flexibly react to changing conditions, new opportunities will emerge for both building occupants and the electric grid. The grid can benefit from reduced power generation and delivery costs. Building occupants can gain greater control over and value from their building assets, while also benefiting from a cleaner, less expensive, and more resilient electrical system. Buildings are the main consumers of electricity, representing about 75 % of all demand in the U.S. (EIA (Energy Information Administration) 2017). Residential buildings are also the main driver of hourly peak demand, largely due to summer air conditioning needs (Mims, Eckman, and Goldman 2017). As such, buildings possess tremendous potential to impact the electricity system through both net and time-dependent shifts in demand.

Historically, grid operators have maintained load-resource balance through predictive analytics and supply-side control. However, advances in connected devices have expanded the potential of demand-side control, or demand response (DR). While DR has existed for decades, for a long time it was largely limited to manual intervention at industrial facilities. By 2016, almost 10 million American electricity customers were enrolled in DR programs, providing 35.9 GW of capacity; however, only 11.8 GW were successfully deployed, primarily due to customer opt-outs (EIA 2017; Burger and Luke 2017).

In the future, smart and connected technologies in grid-interactive efficient buildings (GEBs) will empower building owners and occupants to interact with the grid in a manner that is mutually advantageous and supportive of greater *energy flexibility*, or a building's "ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements" (Østergaard Jensen et al. 2017). In GEBs, occupant preferences can be integrated with real-time pricing to deliver autonomous, model predictive control that reduces the need for real-time user intervention. This enables grid operators to more confidently deploy DR signals that will deliver reliable grid services. The vision is for GEBs to act as hubs that manage system flexibilities offered by distributed energy resources (DERs) including distributed generation, storage, and now building loads.

This paper synthesises highlights from a literature review of flexible building technologies to outline a framework for considering how these technologies influence load shape. We begin by providing background information on the types of grid services recognised by energy markets to which building technologies can be responsive. Next, a new taxonomy for flexible building technologies is introduced, followed by a quantitative analysis linking the flexibility potential of efficient cooling technologies with grid services deployed at national scale. We conclude with a discussion and a view of future research opportunities.

The U.S. Department of Energy's (U.S. DOE's)[1] Scout Tool is used to assess the technical potential of optimised flexibility and efficiency of these technologies. Scout offers estimates of energy and carbon impacts of various energy conservation measures (ECMs) on the U.S. residential and commercial building sectors (U.S. DOE 2019). U.S. DOE's Building Technologies Office (BTO) primarily uses Scout to inform its technology research and development investment strategy by identifying impactful technology areas. Recently, new computational abilities have been added to Scout that allow it to assess not only efficiency measures but also various building technology flexibility scenarios. Scout draws energy use baselines out to the year 2050 from the EIA Annual Energy Outlook reference case (U.S. EIA 2018), applying user-defined energy conservation measures (ECMs) to these baselines to determine national energy use, operating cost, and emissions impact potentials. In order to enable time-sensitive valuation of energy efficiency, Scout distributes annual EIA electricity use estimates across the hours, days, and seasons using end use load shapes from the Electric Power Research Institute (EPRI 2018). Hourly electricity use estimates[2] are assigned costs and emissions using 50th percentile time-of-use (TOU) electricity pricing from the U.S. Utility Rate Database (URDB) (NREL 2018) and marginal emissions factors from Siler-Evans, Azevedo, and Morgan (2012).[3]

1. This paper was not funded by and is not an official product of the U.S. Department of Energy.

2. Electricity use estimates in this paper are based on *source* energy, which sums delivered (site) electricity use and electricity generation, transmission and distribution losses.

3. Additional details about Scout's time-sensitive valuation approach are available: https://scout-bto.readthedocs.io/en/latest/analysis_approach.html#time-sensitive-adjustment-of-total-energy-co2-and-cost

Types of Grid Services

Portions of the U.S. electric grid are separately controlled and coordinated through a collection of independent system operators (ISOs) and regional transmission organisations (RTOs). They facilitate the delivery of electricity to U.S. consumers through three major types of electricity markets – capacity, energy, and ancillary services.

Capacity markets are designed to ensure adequate grid resources are available at all times through multiyear power delivery contracts (R Street 2016).[4] In contrast, both energy and ancillary services markets are short-term (e.g., day-ahead, real-time). Most electricity market transactions take place in energy markets, which use locational marginal pricing (LMP) to reflect marginal energy cost, transmission losses, and transmission congestion when conducting short-term bulk energy transactions. When electricity demand is high, LMP can increase significantly from transmission constraints and the required use of more expensive energy resources. Electricity demand and high LMP tend to coincide between 14:00 and 20:00 during the summer season (Macdonald, Cappers, and Callaway 2012). The smallest of the three markets, and where much of this research is focused, is the ancillary services market. Products in this market include system frequency regulation and operating reserves (i.e., spinning, non-spinning, and supplemental) (Cetin 2016).

There are a variety of actions buildings can take to benefit the grid in electricity markets. Each action, or "grid service," has different characteristics. Table 1 explains these grid services and their properties.

Taxonomy for Building Energy Flexibility

To logically and simply connect building technology capabilities to grid services, this paper defines a new schematic. Alstone et al. (2017) developed a schematic for managing electric loads from the grid perspective: shape, shave, shift, and shimmy. However, this framework has drawbacks when trying to concretely link building technologies to these services. Mainly, the framework is grid-centric in approach, which makes it more challenging to weigh impacts on building occupants, technology lifecycles, and other externalities, such as alternate fuel consumption. This paper's schematic focuses on technology flexibility actions and links them to grid services recognised in electricity markets. This new schematic can be used alongside the existing one to create better mutual understanding between electricity grid management and building operators.

There is a wide array of building technologies that enable loads to be more responsive to grid conditions. This responsiveness is referred to as "load flexibility," and it is useful to distinguish flexible technology behaviours. The schematic defines four flexibilities: flexible efficiency, flexible regulation, flexible power source, and flexible power timing. Many building technologies can be flexible in more than one way. For instance,

4. Not all ISO/RTOs have structured capacity markets, but instead have competitive retail power markets with higher energy price caps, such as in Texas, or one-year bidding processes in California (Kelly-Detwiler 2018).

Table 1. Types of Grid Services from Buildings and Corresponding Avoided Costs.

Grid Service	Load Change	Response Time	Avoided Cost
Ancillary Service Market Products			
Frequency Regulation (Up, Down, and Combined)	Modulate power demand in response to 4-second signals from the grid operator to balance electricity supply and demand. Maintain grid frequency at 60 Hz.	~4 seconds	Power plant fuel, operation, maintenance, and opportunity costs associated with providing frequency regulation (e.g., not selling power in order to be ready for up-regulation).
Distribution Voltage Support/ Solar Integration	Modulates rate of active and/or reactive power draw to control distribution system voltage.	~4 seconds	Avoided costs for distribution voltage control equipment (e.g. capacitor banks, transformer tap changes); reduced costs for distributed solar hosting capacity (Nistor et al. 2015).
Operating Reserves (spinning, non-spinning, & supplemental)	Reduce power demand within 10-30 minutes of a signal from the grid operator to make up for a shortfall in electricity supply.	10–30 minutes	Power plant fuel, operation, maintenance, and opportunity costs associated with providing operating reserves.
Capacity Market Cost Reduction			
Reduced Peak Generation Capacity Costs	Reduce or shift demand during generation annual peak demand period(s).	Years	Fixed operation and maintenance costs for power plants and capital costs for new generating facilities
Reduced Generation Operating Costs	Reduce or shift electricity demand during high-cost periods. Improve utilisation of low-cost generation.	Years	Power plant fuel, operation, maintenance, and start-up and shutdown costs.
Reduced Transmission Upgrade Costs	Reduce or shift demand at a time that reduces local transmission delivery constraints.	Years	Capital costs for transmission equipment upgrades.
Reduced Distribution Upgrade Costs	Reduce or shift demand at a time that reduces local distribution delivery constraints.	Years	Capital costs for distribution equipment upgrades.

electrochemical batteries can offer both flexible regulation and flexible power timing, depending on the response specified by system controls. These are broadly defined in Table 2 with some example technologies.

These distinctions provide a logical framework based on the varying impacts technology flexibilities have on resultant load shapes. A technology's ability to deliver grid services is defined by how quickly it can respond to grid signals and the resultant load shape it is able create in response to grid signals. This is helpful for research and development prioritisation to advance flexible building technologies based on potential to deliver grid services while meeting occupant needs. Figure 1 shows basic illustrations suggesting the impact each of these flexible technology categories may have on a building's load shape.

Technologies that reduce generation capacity costs and defer upgrade costs through non-wires alternatives will deliver longer-term efficiency and reduce demand, lessening grid constraints. Efficient building technologies with flexible efficiency and flexible energy sources have the ability to reduce grid-operating costs. Voltage control and frequency regulation are best delivered by building technologies offering flexible regulation services. With better-enabled flexibility through control strategies, a vast array of building technologies can be optimised to serve building occupant needs as well as deliver a spectrum of grid services.

Types of Control

One of the key enabling technologies for realising grid-interactive, efficient buildings is advanced technology control. Control systems can dramatically impact how reliably building technologies provide services such as flexibility, which are vital to their inclusion in ancillary service markets. Background on types of technology control systems will help for understanding the modelling assumptions and mechanics of integrating flexible building technologies. The most common current and emerging control methods used in buildings can be broadly divided into three types: rule-based and on-off control; proportional-integral-differential (PID) feedback control; and model-predictive control.

Rule-based and on-off control use simple if-then control logic. The simplest example is a common thermostat installed in a residential building: in cooling mode, if the temperature exceeds a certain threshold, the air conditioner turns on, if it falls below a threshold, the air conditioner turns off (Ogata 2010). PID control is a common method of control used in building automation systems and uses continuous measurements of the output that is trying to be controlled (e.g., temperature) to continuously tune the appropriate position for an actuator (e.g., ventilation damper). Model-predictive control is an emerging control method that uses a physical or empirical model of the system being controlled (e.g., the building) to predict how it will respond to changes, rather than simply

Table 2. Linking building energy technologies based on flexibility type and primary grid services.

Flexibility Type	Load Change	Response Time	Example Technologies	Primary Grid Services
Flexible Efficiency	Adjustable efficiency performance allowing technologies to improve efficiency when electricity LMP is high (within occupant preferences).	~30 minutes	Dynamic facades, Smart/"eco-mode" appliances, Dimmable LEDs	Operating Reserves, Capacity Market Cost Reduction
Flexible Regulation	Adjustable power flow in response to 4-second grid signals to balance supply and demand.	~4 seconds	Electronically commutated motors (ECMs), variable frequency drives (VFDs), electrochemical storage, solar inverters	Frequency regulation, Voltage control
Flexible Power Source	Backup power supply for avoiding electricity when costs are high.	~10-30 minutes	Dual-fuel heat pumps, micro-combined heat and power (mCHP)	Operating Reserves, Capacity Market Cost Reduction
Flexible Power Timing	Capacity to pre-charge via energy storage or delay-start via appliances to coordinate power timing when controls suggest electricity is cheap.	~4 hours	Thermal storage, electrochemical storage, delay-start appliances	Operating Reserves, Capacity Market Cost Reduction

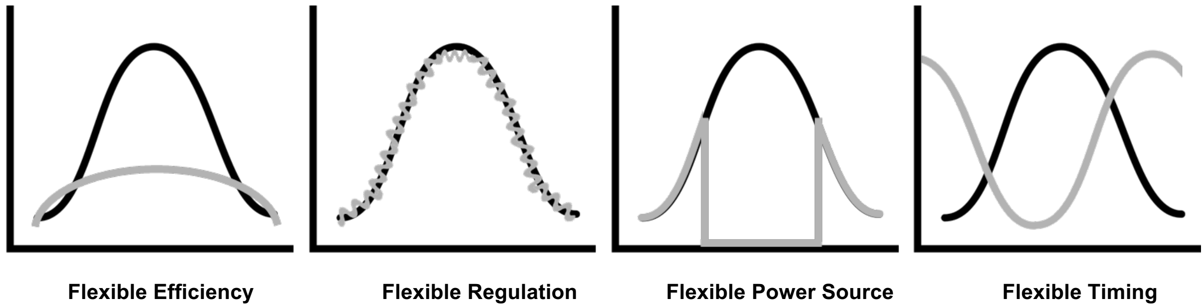

Figure 1. Illustrative impact of various flexible building technology flexibilities (grey) on a load shape (black).

observing the output and adjusting the input in real-time (Seborg et al. 2016; Forbes et al. 2015; Mayne 2014; Morari and Lee 1999). The main advantage of model predictive control over rule-based and PID control is that it explicitly anticipates how a system will respond to control actions, and plans future control actions with that in consideration. Rule-based and PID-control only observe how a system is reacting to control actions in real-time.

The optimal GEB will monitor and control electrical loads not just on the whole-building level, but on individual circuits, outlets, or devices to best integrate occupant preferences within the control methodology. Within all types of control strategies, it is important that the preferences of building occupants always define the parameters for comfort and energy cost. Optimised control, at its core, must deliver services of comfort, cost reduction, peace of mind, feelings of control, and feelings of contribution to social and environmental wellness to building occupants in order for GEBs to be deployed and their services delivered to the grid. In this way, flexible buildings with best-fit control strategies can bring enhanced experiences to building occupants while grid services operate in the background. If financial and other incentives are not delivered downstream to consumers, then the many benefits of these control strategies will be difficult to realise.

The analysis conducted through Scout uses various assumptions for control type when modelling the impact of optimised control strategies for flexible building technologies. For certain use cases, a specific kind of control is assumed: for instance, flexible regulation with variable speed heating, ventilation, and air conditioning (HVAC) is optimised with PID control, whereas flexible power timing with thermal storage requires model-predictive control for optimal performance. Control assumptions are stated for each analysis.

Scout Analysis of Specific Building Technology Flexibility Potential

To show examples of the technical potential of various flexible building technologies to offer grid services within GEBs across the United States, we conducted analyses in U.S. DOE's Scout Tool. Studies by Rocky Mountain Institute (RMI) have begun exploring the technical and economic potential of demand flexibility through building technologies in the U.S. (Goldenberg and Dyson 2018; Dyson et al. 2015). The 2018 study explores the potential impact and value of demand flexibility in Texas. When simulating a Texas power system with high penetration of variable energy supply, demand flexibility helped to raise revenues by 36 %, lower peak net demand by 24 %, lower the average magnitude of multi-hour ramps by 56 %, and avoid €1.7 billion in annual generator costs. This was accomplished through simple, technical potential modelling of flexible end-use loads, including residential and commercial electric water heaters, space heating and cooling, and residential plug loads (Goldenberg and Dyson 2018). Our analysis takes a different approach by categorising types of technology flexibilities and researching examples of how their flexibilities impact the grid and building occupants at a national scale.

For this analysis, we suppose immediate adoption of a highly efficient, variable-speed, intelligently controlled electric cooling technology across residential and commercial buildings in the U.S. First, we use Scout to estimate the energy, cost, and emissions savings attributable to just the higher efficiency performance of this technology. Then, we show how this technology could be used to provide each of the flexibility types defined above. We explore the technical potential, associated benefits to both consumers and the grid, and potential problems or barriers to optimised use. For some of these flexibilities, other building technologies may have higher potential than the theoretical cooling technology analysed here. We chose this technology based on its ability to provide some service across these categories rather than a belief it is the best-fit solution for each. This analysis helps illustrate the potential in each of these areas and sets a framework for exploring the potential among other building technologies.

TECHNICAL POTENTIAL OF ENERGY EFFICIENCY THROUGH HIGH-EFFICIENCY COOLING

To separate the benefits of a high-efficiency cooling technology from the benefits of its flexible capabilities, we begin by analysing the energy, cost, and emissions savings from the efficiency gains of the technology alone. We assume instantaneous adoption across residential and commercial buildings that already have air conditioning. No intelligent controls are assumed. The change in national summer load shape for the months of May through September for residential and commercial buildings is shown in Figure 2.

Installed electric cooling systems across the U.S. have a typical seasonal energy efficiency ratio (SEER) of 10 to 13 in residential buildings and a typical energy efficiency ratio (EER) of 11.2–11.6 or full-load coefficient of performance (COP) 1.2–1.6 in commercial buildings depending on equipment type (EIA 2018). We apply instantaneous adoption of SEER 18 cooling in residential buildings, EER 13 cooling in small and medium size commercial buildings, and part-load COP 4.1–11.5 chillers in large commercial buildings, depending on best available by type (EIA 2018). These ECMs result in 31 % cooling energy savings in residential buildings and 22 % energy savings in commercial buildings, saving a total of 240 Terawatt hours (TWh) (0.86 XJ), 38 $MtCO_2$, and €9.6 billion when using median TOU rates from the URDB. The savings potential from improved efficiency performance of cooling technologies in U.S. buildings is therefore large even before building flexibilities are considered; these savings would directly add value to capacity markets by reducing needed investments in capacity generation.

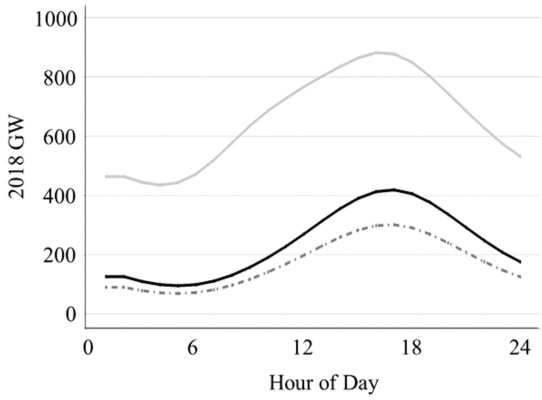

Figure 2. May–September load shape with 2018 curve and technical potential of high-efficiency cooling. May–Sept. building electricity load shape (grey), 2018 cooling load shape (black), efficient cooling ECM (dashed line).

TECHNICAL POTENTIAL OF FLEXIBLE EFFICIENCY

Flexible efficiency technologies give controls the ability to adjust performance due to occupant preferences dependent on electricity price points. In this way, a collection of building technologies could respond quickly to a request for operating reserves if they have programmed logic based on comfort and cost levels. This analysis assumes building occupant willingness to opt-in to wider temperature bands when LMP is high. For simplicity sake, daily summer peaking hours – 14:00 to 20:00 between May and September – are used as a proxy for assumed relatively higher LMP. Therefore, during this time range we assume full adoption of increased temperature bands within the PID control systems save 25 % of cooling energy in commercial buildings and 15 % of cooling energy in residential buildings (Hoyt, Arens, and Zhang 2014; Lawrence Berkeley National Laboratory 2018). This flexibility results in the load shape change shown as a dashed line in Figure 3.

Adding such flexible efficiency to high-efficiency cooling to reduce daily peaking throughout the summer in the U.S. could reduce electricity consumption by an additional 46 TWh during key hours, resulting in a total seasonal savings of 288 TWh. This flexibility also increases estimated cost savings by €2.3 billion to roughly €11.8 billion between May and September. This analysis does not consider the potential benefit of high-efficiency cooling during other seasons and provides a conservative cost savings estimate due to the summer average daily peak being less extreme than overall system peak. By adjusting the performance of high-efficiency cooling in response to grid signals, this flexibility could contribute an additional 7 $MtCO_2$ emission reductions between May and September.

It is possible that flexible efficiency strategies result in some temporary occupant discomfort, particularly if complementary ventilation, air circulation, and thermal performance strategies are not undertaken. Studies have shown, however, that most occupant discomfort can be avoided if fans and window shades are coordinated to increase comfort (Hoyt, Arens, and Zhang 2014; Hoyt et al. 2009). More field validation studies are needed to show the impact autonomous control strategies have on occupant perception of comfort, particularly if they are unaware their system is acting to offer operating reserves.

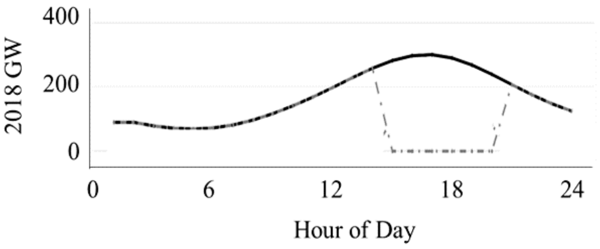

Figure 3. May–September load shape with 2018 curve and technical potential of high-efficiency cooling with flexible efficiency during daily peak hours. May–Sept. efficient cooling ECM (black), flexible efficiency strategy (dashed line).

TECHNICAL POTENTIAL OF FLEXIBLE REGULATION

Technologies with flexible regulation capabilities can provide frequency regulation or voltage control in the ancillary services market when building occupants will not be negatively impacted by rapid fluctuations in power draw. Newer motor and electronic technologies such as variable frequency drives (VFDs) and electronically commutated motors (ECMs), enabling heat pumps and other HVAC to run at various speeds. VFDs are typically used with three-phase alternating current (AC) induction motors, while ECMs are used with brushless direct current (DC) motors (Goetzler, Sutherland, and Reis 2013). Estimates suggest motors consumed 10.1 XJ of primary energy in 2013 in just the U.S. commercial and residential building sectors (Goetzler, Sutherland, and Reis 2013). The relationship between power draw and speed of AC induction motors with VFDs is non-linear, meaning that a 10 % reduction in speed often results in a 30 % reduction in power draw (Goetzler, Sutherland, and Reis 2013). By enabling variable speeds, VFDs and ECMs help motorised equipment save energy and quickly respond to grid signals.

The way that loads operate to meet building occupant set points can be adjusted to provide frequency and voltage regulation services without noticeably impacting the quality of energy services delivered to building occupants. For example, the instantaneous speed of a ventilation fan can be modulated on a second-by-second basis to provide frequency regulations, but still deliver the amount of conditioned air required to meet ventilation standards and maintain occupant comfort.

Optimal control of variable speed HVAC technologies to deliver frequency regulation requires PID control to allow for response to 4-second grid signals and maintenance of occupant comfort. If able to participate in a transactive market with the grid, variable speed HVAC could be leveraged to provide frequency regulation and voltage control. Today, the market is relatively small and most frequency regulation is covered by regulating reserve generators. Throughout the United States, the system requirements for frequency regulation represents 2.5–3.8 GW annually, or less than 1 % of U.S. peak demand (Tacka 2016; Denholm et al. 2015). In 2010 and 2011, the regulation market across four ISO/RTOs (serving roughly 150 million customers nationwide) was €271 million and €299 million, respectively (Macdonald, Cappers, and Callaway 2012). While currently representing a relatively small portion of electricity markets, VRE deployment will likely grow this market and thus the potential for building technology participation (Macdonald, Cappers, and Callaway 2012).

Without controls capable of responding to rapid grid signals, flexible regulation technologies are not able to participate in real-time ancillary services markets. Additionally, ISO/RTO rules may specify bidding technologies be able to meet other specific requirements in terms of response speed and run time (Zhou, Levin, and Conzelmann 2016). Research is needed to assess the impact of utilising automated controls on variable speed HVAC, as this could cause much faster wear and tear on machinery, and therefore may be better fit for electrochemical battery technologies. Further, automated control modulation of variable speed HVAC machinery may cause unexpected comfort issues for building occupants, even if systems comply with ventilation standards, such as noise disturbances from fan speed modulation. Therefore, flexible regulation may be better served by electrochemical battery technologies (Navigant Consulting 2017).

TECHNICAL POTENTIAL OF FLEXIBLE POWER SOURCING

Technologies with flexible power sourcing capabilities allow for fuel switching, which can be enabled during periods of low or expensive electricity supply. Through this, users or automated controls can choose between available energy resources based on efficiency, cost, or pollution-related preferences. When combined with efficiency practices, flexible energy sourcing can be a good option for a building's remaining energy needs that are not easily shifted or reduced. However, technologies that enable flexible energy sources are subject to more volatility in energy price as compared to technologies that fundamentally reduce energy load overall. If a technology's backup power source is too expensive, then it may switch away from electric energy only rarely.

Two major building technologies capable of fuel switching are micro-combined heat and power (mCHP) and dual fuel heat pumps. From the grid's perspective, these technologies are capable of quickly reducing electricity demand at high value moments. From the building occupant perspective, these technologies offer backup energy supply requiring fuel input costs and additional in-building infrastructure. One study found dual-fuel heat pumps could be used to provide most heat with electrical energy, while "topping off" with gas during periods with higher electricity costs (Carter, Lancaster, and Chanda 2017).

This analysis assumes that the high efficiency HVAC analysed in this paper also has dual-fuel capabilities. For optimal control, this technology requires either rule-based control to allow for rapid fuel switching based on price signals or PID control for fuel switching based on occupant comfort and temperature thresholds. This results in reduced electricity usage to minimise electricity demand when LMP is high. It is assumed that 100 % of the cooling loads between 14:00 and 20:00 from May to September is shifted to an in-building natural gas fuel supply.

Flexible power sourcing of high efficiency cooling in buildings has the technical potential to reduce electricity demand by an additional 258 TWh, yielding a cost reduction of €12.7 billion, and an electricity emissions reduction of 40 $MtCO_2$. These savings, however, must be balanced against the increased consumption of on-site fuel sources. Increased consumption of fuel – here, assumed to be natural gas – during these periods would cause increases of 300 PJ in energy consumption, €2.4 billion in

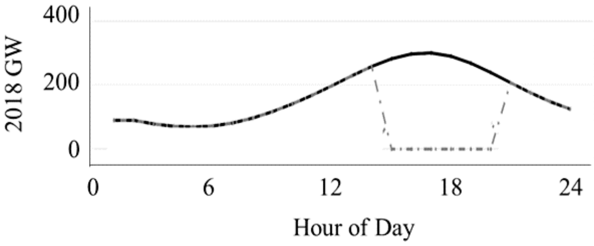

Figure 4. Dual fuel HVAC deployment in 100 % of buildings causing switch from electricity to natural gas for cooling 14:00–20:00. May–Sept. building efficient cooling ECM (black), flexible power source strategy (dashed line).

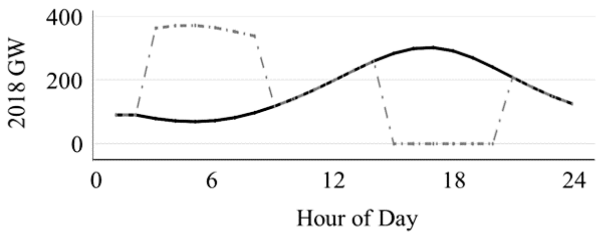

Figure 5. 12-hour shift of cooling consumption on May through September residential and commercial building load shapes. May–Sept. building efficient cooling ECM (black), flexible timing strategy (dashed line).

costs to building occupants, and 16 $MtCO_2$ of emissions. Thus, the net system benefit of efficiency plus flexible energy sourcing is 412 TWh energy reduction, €19.7 billion cost savings, and 62 $MtCO_2$ emissions savings between May and September.

Flexible power sourcing for HVAC can offer building occupants benefits when active heating or cooling is necessary by potentially reducing operating costs. However, if both electricity and fuel prices are high, these benefits are minimal compared to efficiency strategies that reduce the need for active heating and cooling overall. Additionally, with wide deployment this equipment should be cooperatively controlled across a region to minimise instantaneous demand spikes as they all suddenly react to the same price or grid signals.

TECHNICAL POTENTIAL OF FLEXIBLE POWER TIMING

Technologies enabling flexible timing of electricity use are able to shift their consumptive periods either by charging storage devices in advance or employing delay-start functionality in appliances. In buildings, storage can take shape as on-site energy electrochemical battery or thermal sinks that can be charged when electricity is cheap and discharged when expensive. Unlike electrochemical battery storage, thermally stored energy batteries do not store electrical energy and cannot discharge energy back to the grid. Their flexibility does not lie in their ability to act as electricity sources, but rather to time shift when electricity demand for heating and cooling occurs. Flexible power timing requires model-predictive control to allow for pre-cooling or pre-heating of thermal sinks before electricity prices are expected to increase. With enough communications and planning capabilities, though, devices offering flexible timing can shift when grid electricity is consumed with little to no impact on building occupants.

Energy storage has traditionally played a relatively minor role in grid operations, but as VRE deployment expands, storage will need to take a more prominent role. It is estimated that meeting about 80 % of U.S. demand with wind and solar will require about 12 hours' worth of energy storage (roughly 5.4 TWh), and meeting 100 % of demand will require several weeks' worth (Shaner et al. 2018).

When paired with an electrochemical battery, high-efficiency cooling technology in buildings can run off the battery when LMP is high if it has pre-charged overnight. The technical potential of storage could allow for shifted energy consumption to flatten the overall demand curve and minimise reliance on expensive generation. In this analysis, it is assumed that 100 % of cooling load can be shifted by 12 hours with negligible associated losses from use of electrochemical batteries. More research is needed to determine the potential for thermal storage to provide similar flexible timing benefits without significant thermal losses. The resultant load shape for building cooling is shown in Figure 5.

Although this flexible timing strategy would not affect the amount of energy used, it would still result in an increase of €5.5 billion in cost savings compared to the benefits of efficient cooling alone, due to the relatively low night-time costs of energy under the examined TOU rates. This strategy is modelled to save a total of €15.1 billion for cooling in buildings. Implemented nationally today, this strategy would result in 31 $MtCO_2$ marginal emissions savings, which is 6 Mt lower than efficient cooling alone due to the relatively higher emissions of U.S. base load nighttime power compared to peaking capacity power plants. This, however, is dependent on the particular electricity source mix within the ISO/RTO. Further, as VRE penetration increases, this flexibility strategy could not only avoid relatively high LMP, but also shift electricity consumption toward time periods of high VRE energy output, and thus contribute to emissions savings. If storage systems are not optimally controlled, associated cost and emissions benefits are highly variable and could result in increased costs and emissions. Buildings and thermal storage systems may result in higher losses than what is modelled here, as a building utilising space conditioning thermal storage with poor envelope performance will suffer significant energy losses.

Control systems must allow for time shifts across buildings that are coordinated to avoid new demand peaks caused by precooling and pre-heating. Additionally, if TOU price signals are not employed with flexible timing technologies, little to no benefit will reach the consumer and therefore deeply minimise the scope of deployment.

A summary of the quantitative results from these analyses is shown in Table 3.

Discussion and Future Research Opportunities

The distinctions between different types of flexibilities leveraging building technologies are important because it helps grid operators, planners, and decision-makers determine which strategies will best deliver specific results. Many ECMs on their own will not have as targeted of an impact on reducing demand during high LMP. If decision-makers seek strategies to deliver

Table 3. Seasonal energy, cost, and emissions savings estimates for efficiency and flexibility measures. Each of the flexibility strategies are in addition to the first savings measure, "Improved Cooling Efficiency Performance."

Savings Measure/ Flexibility Strategy	Technologies Required	Estimated Energy Savings (May–Sept.)	Estimated Cost Savings (May–Sept. TOU rates)	Estimated Emissions Savings (marginal emissions)
Improved Cooling Efficiency Performance	SEER 18 (res.); EER 13 (sm. comm.); part-load COP 4.5–11.1 (lg. comm.)	240 TWh	€9.6 B	38 $MtCO_2$
Flexible Efficiency	PID controls or model-predictive controls & grid interoperability	+ 48 TWh	+ €2.3 B	+ 7 $MtCO_2$
Flexible Regulation	PID controls & grid interoperability	+ 0 TWh	+ ~€0.3 B	+ 0 $MtCO_2$
Flexible Power Source	Rule-based or model-predictive controls, grid interoperability, dual fuel capability	+ 172 TWh	+ €10.1 B	+ 24 $MtCO_2$
Flexible Timing	Model-predictive controls, grid interoperability, battery storage	+ 0 TWh	+ €5.5 B	+ (-8 $MtCO_2$)

value streams to building owners, flexible power source and flexible power timing may be able to deliver significant impact. On the other hand, flexible efficiency and flexible regulation require less capital investment for building owners to participate in ancillary services markets. When considering emissions factors for the grid today, flexible power sourcing may reduce emissions, while flexible power timing may increase them; however, given the unique grid mix within a specific ISO/RTO, this relationship may also change.

In addition to the high-efficiency cooling technologies considered in this analysis, many other building technologies and systems can provide flexibility benefits to occupants and the grid (Cetin 2016). However, additional research and development is still needed to quantify this potential. With research, device-embedded and standalone thermal storage can benefit from improved energy densities, charge/discharge rates, storage mediums, and minimised self-discharge. Dynamic envelope features could allow envelope efficiency performance to vary responsively, such as through anisotropic heat transfer materials, dynamic window glazing, and motorised window attachments. Advanced lighting systems could modulate power and spectrum when LMP is high, depending on daylight and how spaces are used. Continued improvements in variable speed motor performance could allow clothes dryers and HVAC systems to provide flexible regulation without increased wear and tear on machinery. Both resilience and flexibility can be enhanced through better dual-fuel technologies. Additional research is also needed to understand the possible confounding factors and trade-offs that may be present when endeavouring to deliver multiple flexibility services from a single system or from multiple systems in a single building. To be adopted, these flexibilities must be achieved in ways that do not adversely impact product values, lifetimes, maintenance requirements, or operational requirements.

The potential of GEBs grows when considering increased adoption of newer variable electrified products like electric vehicles (EVs) and distributed solar photovoltaics. This increased grid complexity may accelerate the timeline for GEBs becoming hubs for multiple connected technologies. Such a reimagining of the building as a hub for integrated demand-side management technologies requires a new paradigm – one that combines insights from building scientists, architects, electrical and mechanical engineers, and smart grid professionals.

Continued development of interoperable control systems is critical for GEBs to successfully take on the role of being smart energy hubs. Controls will need to use common communication standards and protocols to ensure interoperability between building technologies and grid operators. Model-predictive controls will require real-time data feeds to make informed and trusted decisions. Additionally, they will need to undergo rigorous testing and validation in order to prove they can effectively manage multiple variables and competing objectives. For instance, control systems will need to manage the HVAC demands of solar heat gain against daylighting for occupant comfort, or modulate the load of EVs connecting or disconnecting from the grid around rush hour windows. Control systems will also need to consider economic and market conditions, changing fuel sources at certain price points, or responding to utility price signals for a demand response or other grid events. Finally, control platforms must deliver this functionality in a way that is fully cyber secure.

Ultimately, GEBs will only reach their full potential if utilities have confidence in them as reliable grid resources, owners experience increased building performance alongside energy bill savings, and occupants do not experience any reduction in comfort or usability. Advances in building energy modelling (BEM) will help demonstrate the value GEBs bring to various stakeholders through the incorporation of more realistic controls and presenting outcomes with enhanced temporal and spatial resolutions. Either in aggregate or through urban-scale modelling software, BEM can help quantify the net flexibility of the building stock. These tools can inform building design activities, green certifications, codes development, integrated resource planning, and more. Finally, human behaviour in GEBs must also be well understood. Further research is needed to understand how building occupants will interact with GEB technologies in real-world environments.

Conclusion

Increased flexibility of building technologies may be enabled through deployment of efficient systems with intelligent controls that effectively meet building occupant needs. These flexibilities have the potential to deliver significant electricity market services, provide new value streams to building owners, and added control for occupants. As the electric grid mix and load shape changes over time, these flexibility services may become more valuable in ancillary and capacity markets. This analysis suggests that when energy efficiency and load flexibility are co-optimised in buildings, they can provide tens of billions of Euros in benefits to U.S. consumers. Beyond assessing technical potential with U.S. DOE's Scout, continued research on technology adoption potential can enable more strategic decision-making among researchers and planners. This paper sets the framework for assessing the technological needs for buildings to deliver grid services, and quantifying the system-wide benefits that GEBs can deliver to building occupants, grid operators, and other stakeholders.

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