sustainability

MDPI

Review

Interactive Buildings: A Review

Zahra Fallahi [1,*,†] **and Gregor P. Henze** [1,2,†]

[1] Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder, Boulder, CO 80309, USA
[2] National Renewable Energy Laboratory, Golden, CO 80401, USA
* Correspondence: zahra.fallahi@colorado.edu
† These authors contributed equally to this work.

Received: 10 June 2019; Accepted: 19 July 2019; Published: 23 July 2019

Abstract: Buildings are widely regarded as potential sources for demand flexibility. The flexibility of thermal and electric load in buildings is a result of their interactive nature and its impact on the building's performance. In this paper, the interaction of a building with the three interaction counterparts of the physical environment, civil infrastructure networks and other buildings is investigated. The literature review presents a wide variety of pathways of interaction and their associated potential impacts on building performance metrics such as net energy use, emissions, occupant comfort and operational cost. It is demonstrated that all of these counterparts of interaction should be considered to harness the flexibility potential of the buildings while maintaining other buildings performance metrics at a desired level. Juxtaposed with the upside potential for providing demand flexibility, numerous implementation challenges are identified that are associated with the evaluation and financial valuation of the capacity for demand flexibility, the aggregated flexibility potential, as well as the control and communication to facilitate the interactions.

Keywords: interactive buildings; demand flexibility; demand response; grid services; microgrids

---

1. Introduction

Historically, buildings were expected to provide shelter from the elements along with an acceptable level of comfort for the occupants. In more recent history, energy efficiency has been a central driver for improving building design and operation. Motivated by the desire for utility cost savings, efficient buildings aim primarily at reducing the total amount of energy procured to operate the buildings on an annual basis. Commonly, energy efficiency measures do not consider the time-varying value of energy, except, for example, the peak electric demand impacts of select measures such as daylight dimming control and their focus lies on reducing the cumulative energy use during operation.

Although energy efficiency is an essential foundation for good design, it alone cannot address the needs of future buildings. The value of energy and resource delivery to the buildings varies across different time scales. The temporal variation of energy cost depends on the complete supply chain of energy in which the demand, availability of resources and network constraints affect energy costs to varying extents. These variations affect the energy market on seasonal, diurnal, hourly and sub-hourly time scales. For example, in the electricity production market, the active generators vary their output in response to changes in location-specific demand at any given time. With a sustained and increasing trend towards electrification, the electric grid needs to evolve to be able to provide electricity to all existing and emerging consumers. As a result of grid modernization, system operators will be able to provide more options for electricity production and lower production costs while increasing the resiliency and reliability of the electric grid system. Increasing penetration of renewable energy resources in the future electric grid increases the uncertainty and variability associated with power production because of the intermittency of wind and solar resources. Therefore, future grids rely on storage and reserve capacities as well as demand-side resources to address these increasing levels of uncertainty and variability in supply and demand.

Buildings are responsible for about 75% or electricity consumption in the United States [1]. Buildings and their electric loads strongly affect the electric generator unit commitment and dispatch but they can also be viewed as a novel resource to provide grid services. Building energy consumption depends on many factors such as primary use type of the building, operational schedules, design and construction, selected building systems and equipment and weather conditions. Today's buildings may also benefit from onsite generation and storage facilities that transform them from consumers of energy to prosumers. Due to the factors impacting the buildings' consumption and production of energy, their load profile is not merely variable but may also be flexible.

Buildings interact with their environment, various infrastructure networks and other buildings within the context of an urban district. The interaction of buildings with these counterparts affects their operation and may offer different forms of flexibility. Building flexibility is the ability to change thermal and electrical consumption and production of the building and at the same time sustaining or improving other building performance metrics. The flexibility potential of the buildings is affected by their interactions. Conversely, buildings also affect their counterparts of interaction: Changing the ambient temperature in an urban context, emissions production of the buildings, influencing the electric grid load profile, the evolution of water and transportation networks and the development of microgrids are some of the ways buildings affect their counterparts.

In this paper, we evaluate the ways buildings and their counterparts of interaction impact and influence each other, refer to Figure 1. To that end, we offer an overview of the design, equipment and control techniques that facilitate these interactions and summarize the methods by which building load can be viewed or actively made flexible. We believe that building demand flexibility will prove immensely beneficial to the grid and that demand side management serves as an important resource to the grid for increasing the resiliency and reliability of electricity production.

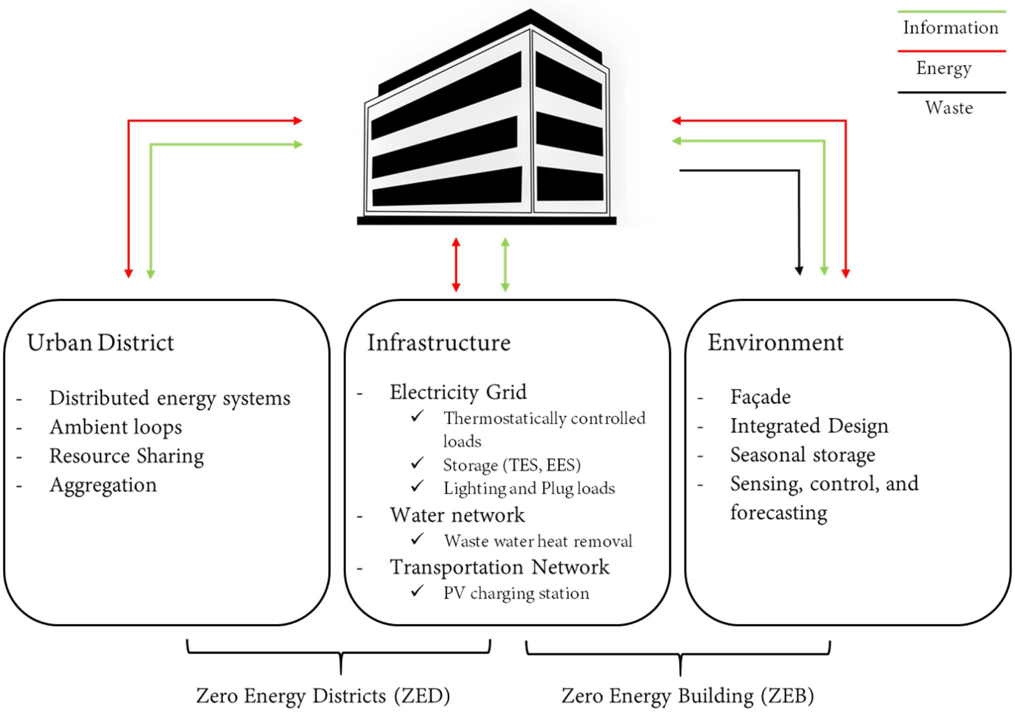

Figure 1. Overview of buildings interactions with its counterparts: Physical environment, infrastructure and other buildings in an urban district. There are energy and information exchanges through these interactions. Buildings environmental impacts is shown as waste.

Further, we discuss the challenges involved in the estimation, characterization and control of flexible loads in buildings. Proper estimation and characterization of buildings' load flexibility allows for future grid planning. An accurate estimation of the amount of flexibility will allow buildings to participate in electric grid dispatch. Identification of different time scales in load variability will allow assigning proper grid services to the respective flexible load. Moreover, control strategies ensure that the predicted amount and time scale of load flexibility is actually achieved. Finally, we discuss how building interactions are important in the design of zero energy buildings, zero energy districts and zero carbon districts. Benefiting from the control enabled flexibility allows future buildings to be beneficial to the environment, the electric grid, water and transportation systems, as well as the community they support.

2. Physical Environment

The built environment provides shelter from the elements and therefore, buildings need to be designed in a way that is suitable for and responsive to their surroundings. Outdoor conditions impact the amount of energy use, such as for heating, cooling, lighting and energy production, for example, photovoltaic production. Buildings establish an indoor environment, with which occupants and their behavior interact, thus affecting building operation. Building operation determines the occupant's comfort and occupant decisions are becoming increasingly important in the performance of the building [2]. Buildings interact with their physical environment through their façade, their architecture and design and their ability to use the environment to store energy. All these interactions are possible through design, forecasting, control systems and occupant decisions. Future buildings will not only harvest the cooling and heating resources available in their environment but also contribute to the improvement of their surroundings, indoor air quality and occupant comfort [3]. Table 1 overviews the technologies or the actors of interactions within buildings and the physical environment. In the context of the physical environment as the counterpart for interaction, the delivery of flexibility may pertain to how a dynamic façade can adjust its characteristics in response to changes in environmental conditions.

Table 1. Building interactions with the environment.

Actors of Interaction	Interaction Technologies	Interaction Timescale
Facade	Actively controlled façade: Shading [4], dynamic insulation [5], BIPV [6,7], RASF [7]	Hours to minutes
	Interactive façade design: Glazing [8], construction material and envelope surface properties [9–12]	Diurnal, seasonal, and life cycle
Integrated design	Passive design: Green roof [13], phase change materials [14,15], passive PV cooling [16,17], thermally activated building systems [18]	Diurnal
Storage	Ground source heat pumps [19], low-exergy heat pumps [20]	Seasonal
Sensing and control	Control strategy: operating cost, temperature, sun angle, comfort [7,21–24] Sensing: weather forecasting, occupant sensing	Seasonal to minuets

2.1. Building Façade

The façade of the building most directly interacts with prevailing local climatic conditions including wind, temperature, humidity and solar irradiation. The implementation of dynamic systems or the integrated design of the envelope can be beneficial in terms of energy use reduction and occupant comfort. Active façades can change their functionality depending on the outdoor or indoor conditions, while their response time depends on the control architecture that is used to operate them. Other façade parameters such as the construction and the design respond to seasonal or diurnal changes in the environment.

Automated shading systems can provide the desired indoor illuminance for the occupants by interacting with the available solar irradiation [25] and can change the solar gain of the building and therefore affect the air conditioning load of the structure. Façade retrofitting is one of the methods of increasing energy efficiency in buildings [26].

Saretta et al. encourage considering building integrated photovoltaic (BIPV) for any façade retrofitting project [6]. They argue that the potential of BIPV can be predicted by using data sets for solar availability and the use of proper building energy modeling software [6]. They conclude that a geographic information system (GIS) based environment is widely used for modeling façade interactions with the environment and that physical building energy modeling software is preferred to statistical models for façade analysis [6]. Reflective adaptive solar façade (RASF) technology, as shown in Figure 2, uses reflective shading panels that can move using an actuator and control systems [27]. RASF can interact with the solar irradiation by different modes of operation: (1) scattering or simply creating shade for the building, (2) redirecting to surrounding buildings to be used for space heating or electricity generation and (3) redirecting to solar panels for heat and electricity generation [27]. Powell et al. show that redirecting the solar arrays in a concentrated manner is beneficial for concentrated photovoltaic (CPV) and therefore accurate actuator control is important in this mode of operation [27].

In the absence of active systems, façades still interact with their environment. Façade design should consider the climatic context of the buildings and occupant well-being. Façades designed for optimum daylighting performance result in lower electricity consumption of the building for lighting energy use. Yi et al. provide parameters for the design of the façade based on the climate and the aesthetic preferences of the clients in order to optimize the design of the façade for daylighting [28], as shown in Figure 3. Façade surface properties affect the need for air conditioning and energy use of the building. Hawila et al. identified effective parameters for thermal comfort in a school in France [29]. Since the glazing properties of the glass façade affect the mean radiant temperature of the building, they performed a statistical analysis to optimize the design of the glass façade in an effort to keep the predicted mean vote (PMV) within the comfortable range [29].

Surface properties of the building not only affect energy use and occupant comfort but they also affect the micro-climate of the building. Reflective glazed façades and pavement material both significantly contribute to the micro-climate [8]. Reflective properties cause the surface temperature around the building to be different from the temperature measured on the roof or at the airport weather station. During the summer, the increased temperature of the micro-environment increases the need for air conditioning [8], the well-known urban heat island (UHI) effect. It is important to consider the micro-climatic effect on the performance of the building not only regarding energy use but also with respect to construction material preservation. For example, Charisi et al. take into account the micro-climate parameters as well as the architectural features of the façade to predict the spatiotemporal surface temperatures and moisture content of the façade [30].

The construction materials selected for the building envelope also affect the interactions of the building with the environment. Gunawardena et al. simulate and test different envelope materials for two locations in London to capture their effect on heating and cooling energy use as well as contribution to the UHI effect [9]. They find that the common practice of replacing heavy envelope material with lightweight insulated envelopes increases the need for air conditioning by 2.5% to 9.6%, which also contribute to UHI because higher air-conditioning needs lead to increased amounts of heat rejected from the buildings [9].

In the context of life cycle analysis, selection of envelope material is important both for energy use and environmental impacts. Gevaudan et al. compared alkali-activated cement-based concrete (AAC) and ordinary Portland cement concrete to capture their performance in energy use intensity (EUI) of the building and life-cycle energy use of the material [10]. The replacement of envelope material in an office building in several climates showed that the operational EUI change is negligible. However, the novel AAC concrete shows a reduction in the required material quantity because of its lower thermal conductivity values and therefore, the embedded energy use of construction is lower [10].

A dynamic façade can interact with the environment by changing the heat transfer properties of the envelope. Park et al. simulated a single family house with dynamic envelope material in three different climates. The proposed dynamic envelope can have a range of thermal resistance (0.5 RSI to 2.5 RSI) based on the control settings. They could show an annual reduction of heating (average 10%) and cooling load (average 15%) by two-step (day and night) control of the dynamic insulation material [5].

Building materials may also improve air quality. A cradle-to-gate analysis of concrete and concrete substitutes for buildings shows the sequestration rate is not the only important factor. There is a need to study both life-cycle emission of materials as well as their carbon dioxide sequestration potential towards the goal of net zero carbon buildings and structures [11]. Materials used in the building can also be important in the removal of pollutants to achieve better indoor air quality. Some modern building materials contribute to the increase of indoor pollutants such as NO_2 [31]. As a building defense mechanism, a photocatalytic surface containing titanium dioxide (TiO_2) degrades the NO_2 that is mixed in the air [32]. It is shown that air flow characteristics, velocity and flow velocity distribution on the surface affect the pollutant removal rate [12]. Montoya et al. experimentally studied the flow characteristics by using a multi-orifice fan called a synthetic jet actuator (SJA). Changing the SJA settings, which are fan speed and distance to the wall, showed the importance of optimum flow characteristics in removal of NO_2 from the air within the experimental chamber [12]. Facilitation of the interactions through the buildings material and the environment not only affect the indoor air quality and the occupant's comfort but also it affects the energy use of the buildings and consequently the environmental impacts of buildings' operation.

Figure 2. Example of reflective adaptive solar facade (RASF), adapted from Reference [27].

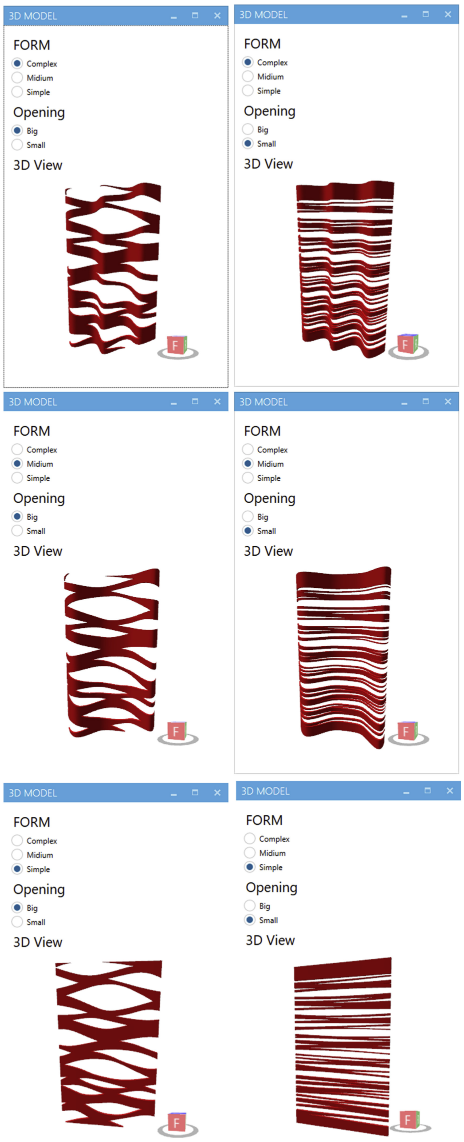

Figure 3. Envelope design for optimum daylighting and aesthetics, adapted from Reference [28]. The form is decided based on the owners preferences.

2.2. Integrated Building Design

The purposeful design of a building structure includes technologies that dampen the effect of diurnal temperature fluctuations in the environment and benefit from them. Passive cooling design commonly includes three modes of harnessing natural heat sinks: (1) Evaporative cooling has historically been used in arid areas to provide air-conditioning in the building. In an example involving a water-to-air heat exchanger, passive evaporative cooling in green roofs removes the heat from the building during the day and maintains the temperature at night time to dampen the effect of outdoor temperature fluctuation on the indoor temperature. Also, circulating irrigation water provides storage of coolth for later use in the building [13]. (2) Nocturnal radiative cooling is another mode of passive cooling that enhances the heat transfer from the building to the outer sky during night time [16]. In other words, the building radiative properties, such as glazing, envelope transmittance and window-to-wall ratio (WWR) can be optimized during the design phase to provide benefits in terms of heating, cooling and life-cycle energy use [4]. (3) The use of phase change materials (PCM) can maintain the indoor temperature by harnessing the high latent heat of fusion of phase change materials at appropriately chosen transition temperatures.

PCMs act as thermal energy storage and can balance the diurnal and nocturnal energy demand by latent heat transfer [33]. Thermal energy storage (TES) can be used to enhance the operation of building integrated photovoltaics (BIPV) systems. The efficiency of a solar panel is affected by the temperature of the panel, with an increase of panel surface temperature resulting in a reduction in the panel efficiency of around 0.5% K [34]. Using PCM can provide passive cooling for the BIPV panels during operating hours [35]. Hamed et al. [7] investigated the effect of channel height on the provided passive cooling for solar panels in the desert climate. They measured an increase in the efficiency and electricity output of the panel due to the reduced temperature by 5–10 K on average compared to zero cooling mode operation.

PCM material could be integrated into the envelope of the building. Pomianowski et al. showed that thermally activated building systems (TABS) and PCM micro-encapsulated concrete, as shown in Figure 4, affect the heat gain of the structure and the effectiveness of the cooling systems [18]. PCM infused gypsum board acts as thermal energy storage in the envelope and does not allow for fast temperature fluctuations due to outdoor conditions [14]. Marin [15] investigated gypsum PCM with a melting point of 25 °C in different climate conditions based on the world map of Köppen–Geiger climate classifications. The climate conditions determine the effectiveness of PCM TES in balancing energy use and thermal comfort. In very humid climates, for example, added thermal energy storage did not have any benefits for free-floating temperature and the areas that have dominant snow coverage and tropical locations see minimal energy savings by PCM [15]. Examples of PCM integration in the envelope are depicted in Figure 5, adapted from Reference [14].

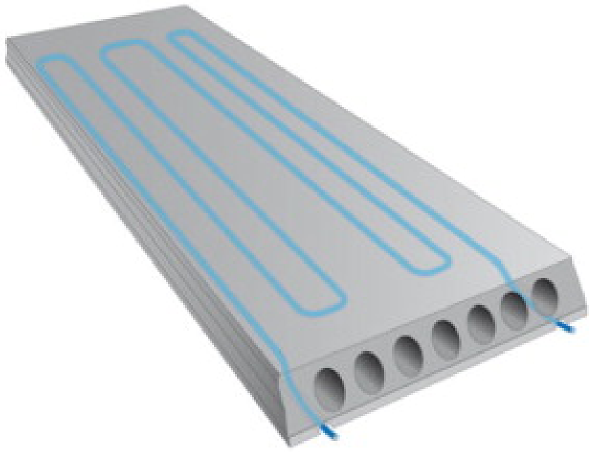

Figure 4. "ThermoMax: prefabricated concrete ceiling deck element", adapted from Reference [18]. The deck can be used for PCM and thermally activated building systems (TABS) integration.

Figure 5. Examples of phase change materials (PCM) integration in envelope, adapted from Reference [14]. (**a**) Electron microscopy of PCM in gypsum plaster, (**b**) Wall finishing for gypsum plaster, (**c**) PCM micro-capsules.

2.3. Seasonal Thermal Energy Storage

Storage of energy in the ground is another way buildings interact with their physical environment. Ground temperature varies at different depths. The relatively constant temperature of deep soil makes it a resource for the operation of heat pumps. By using the temperature at two different depths, the B35 building project in Zürich operates a low-exergy heat pump system during the winter to provide space heating and hot water. Meggers et al. show that the borehole can be regenerated during the summer through solar irradiation [19]. A solar thermal collector providing heat to regenerate the borehole and hot water is another example of how buildings interact with their surroundings. Ground source heat exchangers (GSHE) are used as active or passive storage systems that can provide supply air or water to the building. The use of GSHE alongside other RES technologies are attractive options for zero energy buildings [20].

2.4. Control Strategies

Control strategies facilitate the building interactions with the environment. Sensing and forecasting technologies enable planning and operation of the controllers. Detecting the presence of occupants and their behavior and proper sensing of the indoor conditions are requirements for occupant aware control that allows the building to provide load flexibility without sacrificing occupant comfort [36]. Access to spatiotemporally finely resolved occupancy information is necessary for occupant-driven controls and challenging due to occupant stochastic behavior [37]. Sensing technologies are improving to provide information about the temporal and spatial resolutions of occupancy and the knowledge about the occupant behavior [38]. A wide range of algorithmic approaches have been investigated and are currently refined for the purpose of improving the accuracy of building occupancy detection [39].

3. Infrastructure Systems

In urban environments, buildings are connected to network systems such as the water network, natural gas network and the electricity grid. These networks' design, improvement and planning are affected by building consumption trends. At the same time, buildings' interaction with the infrastructure system can be beneficial in the management of resources and minimizing risks. In the context of infrastructure systems as the counterpart for interaction, the delivery of flexibility may pertain to how a building energy system operation is changed in an effort to provide electric grid services such as ancillary services including contingency and frequency regulation.

3.1. Electric Grid Services

In the United States, residential and commercial building sectors are major consumers of electricity with 38.5% and 36.2% of total electricity use respectively [1]. Because of this large share, the building sector affects the peak for electricity demand and the shape of the demand profile for the grid. Therefore, grid expansion and planning efforts should consider the interactions with the buildings they serve.

Also, enabled by grid modernization and increasing penetration of renewable resources, the grid is facing new complexities such as variability of resources, increased uncertainty, steep ramps and loss of inertia. Electricity generation cost is affected by several factors and represented in different markets. By harnessing load flexibility, the built environment can participate in several markets and provide grid services for cost-effective electricity production.

1. **Generation Services**: Supply of electricity must always meet the instantaneous demand which varies based on daily fluctuations as well as the seasonal and annual trends. Generation cost is affected by the type of generating plants and their fuel, the operation and maintenance costs, start-up and shut-down costs and the capital cost for expansion of the grid. These factors affect the energy and capacity market of electricity generation. Buildings can affect the demand and the

energy market by energy efficiency measures [40]. Also, optimized operation of the buildings based on the dynamic and time-of-use (TOU) pricing can provide opportunities for the system operators to dispatch cheaper power plants. Also, building participation in demand response can reduce the peak loads and therefore reduce the need for grid capacity expansion [41]. Today, peak demand reduction with demand response is being utilized by several independent system operators (ISO) such as PJM [42], NYISO [43], MISO [44] and New England ISO.

2. **Non-Wire Services**: Electricity transmission and distribution systems need to be upgraded in order to ensure delivery of electricity. Upgrades in the transmission system are needed as the load profile changes in various locations' consumption. Strategic load management of buildings through energy efficiency and demand response helps avoid these location-specific upgrades to the transmission and distribution systems. Buildings compete with distributed energy resources to provide grid services [45].
3. **Ancillary Services**: Reliable production of electricity involves services that enable corrections for (1) electrical imbalance and frequency changes due to short term changes, (2) contingencies due to equipment failure and (3) steep changes in the demand that lead to ramping complexities [46,47]. These ancillary services have a small share of the electricity generation but due to the uncertainties involved, fast-responding buildings are well positioned to provide short term demand changes [48].

3.2. Building-to-Grid Integration

Grid operators ensure that the supply of electricity meets the demand at all times. Demand side management (DSM) assists grid operation at different time scales to overcome the complexities of maintaining said balance under grid stress scenarios [49]. Figure 6, adapted from Reference [50], shows how different building load management scenarios can provide grid services at different temporal resolutions. The type of building, occupancy and the equipment determines the load profile and limits the levels of interaction with the grid and the type of available demand response (DR). Also, the location and the time of electricity generation affect the grid's need for DR. DR events are categorized based on their effect on the load profile and the time scale of the event. Table 2 overviews the DR services characteristics provided by buildings.

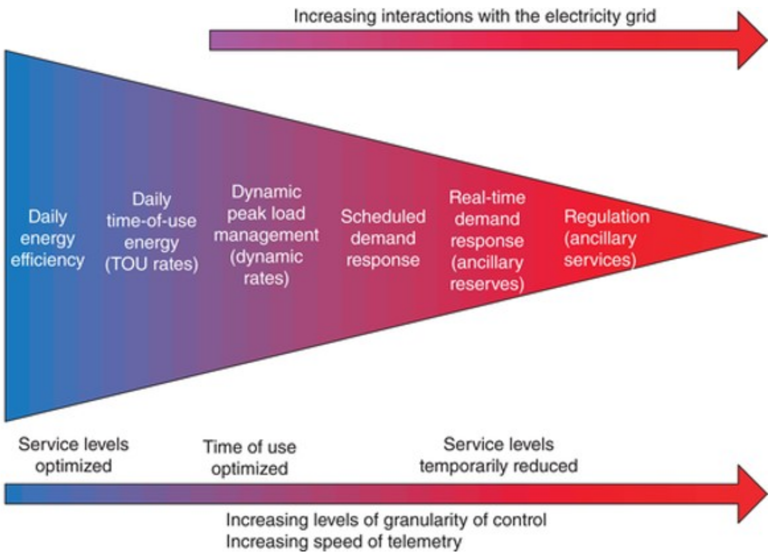

Figure 6. Different time scales of building and grid interactions [50].

- **Energy efficiency** measures aim to reduce the annual energy consumption of the building. These measures have a long term effect, seasonal or annual, on the electricity use of the buildings. Through energy efficiency measures in buildings, the grid can avoid some capacity expansion [51].

- **Load shed** is a service to the grid at peak hours and also during emergencies to provide contingency. Load shedding has a shorter time scale (hours) and assist the grid by substituting for reserve capacity. A survey commissioned by the Federal Energy Regulatory Commission (FERC) 2018 shows that the buildings have the potential of reducing the peak demand by about 70% through DR [52].
- **Load shape**: This type of DR changes the load profile of the building relative to the baseline and the grid desired profile. Load shaping DR changes the daily load profile and assists with complexities such as forecasted renewable generation output [53].
- **Modulate**: On a shorter time scale, load modulation DR changes the building load, increase or decrease, to provide grid ancillary services. The amount of change in the demand is relatively small but the participants of this kind of DR should be able to modulate the load on short time scales (seconds to minutes) [54].

A building's ability to respond to grid signals determines the type of services that can be provided. Factors such as the capacity for load interventions, the time of the event and the effect of the event on energy efficiency or cost of the operation characterize the flexibility of the building [55]. Flexibility characteristics of the building help determine the factors above. Junker et al. [56], identify these characteristics based on the received signal from the grid and the corresponding response of the building. Figure 7 offers an overview of these characteristics for a load shed event. τ represents the time lag between receiving the grid signal and the actual start of the event in the buildings. Participants for grid ancillary services should have small values for τ. Area A, which is affected by α, Δ and β shows the amount of load reduction provided by the building and is important for load shed DR events. Area B which represents the amount of increase in the load, due to inefficiencies and rebound effect [57]. These values also help determine if a building should participate in a load shaping event.

Buildings can be prosumers of energy, which means they consume energy at certain times and produce it during others. The amount of on-site generation also affects the load profile of the building and its ability to respond. The use of smart inverters assists with the flexibility of behind the meter generation and consequently the flexibility characteristics of the whole building [58].

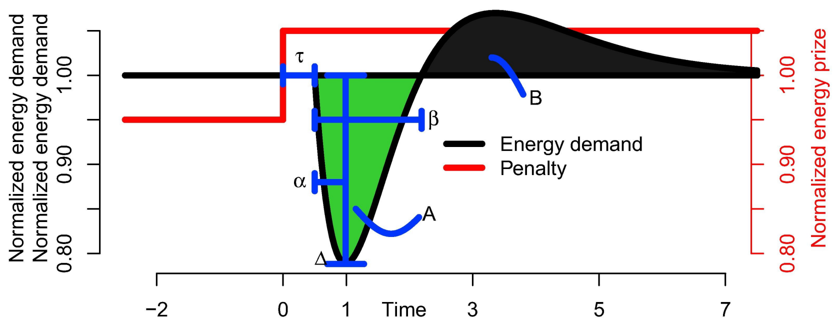

Figure 7. Characteristics of response that determine the flexibility of a building [56].

3.3. Actors of Grid Interactions

Building-to-grid interactions are possible because of load flexibility provided by the equipment and interaction of the building with its environment. The actors of interaction facilitate the building flexibility and responsiveness by changing the load profile of the building in response to a utility signal while maintaining occupant comfort. As shown in Figure 8 the information and energy flows will allow the building to provide flexibility to the electric grid system. The actors can be categorized as (1) thermostatically controlled loads, (2) plug loads and smart appliances, (3) dynamic lighting, and (4) thermal or electric storage systems. Onsite energy production also can facilitate the grid interaction with the building; however, it is shown that the inclusion of renewable energy systems

(RES) in a microgrid context has a larger impact on providing DR services to the grid [59] and is discussed further in the district interactions.

1. **Thermostatically controlled loads**: Depending on the climate and season, the addition or removal of heat from the building is necessary for maintaining thermal comfort. Heating, ventilating and air-conditioning (HVAC) systems meet such building heating and cooling loads to keep the indoor thermal conditions comfortable. HVAC systems are a prime target for electricity use reduction because they are responsible for more than 27% of electricity use in commercial and residential sectors [1]. Since thermostat settings determine the amount of heating and cooling needed for a space, adjustments in the temperature band impacts the operation of the HVAC and causes changes to the gas and electricity use of the building [60]. In order to respond to temperature set point changes, the operations of variable components of the HVAC systems such as heat pumps [61], fans [62,63], electric heaters [64], compressors and chillers, change. These devices have various response times and therefore the resulting changes in electricity use may be utilized to provide various services to the grid.
   Occupant thermal comfort determines the amount of HVAC system flexibility. Various factors such as building operation, occupant activity level, clothing and occupants' metabolic rates are important in the determination of acceptable ranges for indoor temperature and humidity [65]. It is important to note that the temporal rate of temperature changes also affect the occupant comfort levels and should be studied for DR purposes [66]. Nonetheless, standards for thermal comfort allow for some variability in temperature set point to provide flexibility. The use of thermal storage systems would allow the building to remain within comfort conditions with larger variability in temperature settings. Building thermal mass provides passive thermal energy storage to the buildings. In larger or passive buildings the efficacy of HVAC demand response is higher due to the amount of available heating and cooling provided by their building thermal mass [67]. Similarly, integrating other forms of thermal energy storage such as phase change materials with the HVAC system increases the available flexibility for DR.
   Another example of thermostatically controlled loads are domestic hot water (DHW) heaters. Heat pump DHW systems use electricity to provide thermal energy to water. Hot water storage tanks enable DHW systems to provide flexibility to the grid [68]. Similar to HVAC loads, the DHW heater's operation is affected by the outdoor temperature, season and time of day. Also, the storage tank size and the interactions of the DHW system with the environment and other buildings systems are important in the operation and responsiveness of DHW systems [69,70]. At the same time, occupant water use behavior is important in the amount of available flexibility [71]. Sensitivity and uncertainty analysis is needed to capture the effect of the occupant behavior pattern on the operational schedule of the DHW systems [72]. Consideration of all these factors is important for engaging the DHW systems in electricity markets.
2. **Building lighting systems**: Both electrical and natural lighting provide visual comfort for the occupants. Lighting systems account for roughly 19% of global electricity use [73]. Researchers perform whole building analysis to capture the interactions of energy efficiency and operation of the lighting system in the building [74]. A common retrofitting measure for lighting systems is to use solid state (LED) fixtures for lighting [75]. While LED light sources are an energy efficiency measure that reduce the building's electricity demand, daylighting and smart shading systems can also provide energy savings and services to the grid.
   As seen in Section 2, interaction of the building shading system with the environment not only affects the illuminance levels within the space but also changes the building's thermal load and the HVAC energy consumption of the building. Dynamic control of lighting systems can provide grid services by changing the lighting or HVAC energy use of the building. Dynamic shading systems also provide flexibility in the operation of BIPV systems [76]. Utilization of dynamic PV shading devices (PVSD) [77] can provide grid services by adjusting the amount of onsite generation.

Considering occupant comfort, such as adjusting the workplane illuminance, for example, by light dimming, is another way buildings can participate in short time scale grid services. However, due to the complexity of dynamic shading adjustment in buildings [78], the amount of potential flexibility is limited. When evaluating the lighting systems for the capacity of offered flexibility, their effect on the internal gains of the building should be considered [79]. Another limiting factor in the flexibility of lighting systems is the occupant visual comfort. Comfort measures such as Daylight Glare Probability approximation (DGP) and vertical illuminance constrain the operation of dynamic lighting and shading systems [80].

3. **Plug loads and smart appliances**: Changing the operational schedule of appliances results in changes in the load trend of the building. It is possible for the residential appliances and other plug loads to participate in day-ahead and real time electricity markets for load shifting purposes [81]. On a day-ahead scale, load shaping by appliances is possible by developing a home energy management system that can respond to hourly pricing or peak load limits [82]. The participation of smart appliances in load shifting and peak load reduction depends on their energy use and the uncertainties regarding their operating time. Uncertain operating times affect the appliances' ability for response during the day. It is shown that although clothes dryers have a higher capacity for load shifting, a refrigerator's potential for response is more predictable and uniform during all hours of the day [83]. Technological advancements such as the Internet of Things (IoT), smart plugs and smart appliances are expected to facilitate the responsiveness of plug loads [84].
4. **Energy storage**: Energy storage in buildings also provides demand flexibility. Storing energy can be in the forms of thermal energy storage (TES) or electrical energy storage (EES). In both cases, the energy is stored in the battery in times of excess onsite generation or when the price of electricity is low, to reduce the cost of operation [85]. Availability of storage systems increases the flexibility of the building and its responsiveness to grid signals. The provided flexibility depends on battery characteristics such as capacity, charge and discharge rates and efficiency of storage.

As discussed earlier, PCMs are a type of latent thermal energy storage for buildings and depending on the climate and the building application, coolth or heat can be stored in TES systems. Latent heat storage provides flexibility of operation to the HVAC system so that the HVAC demand is less affected by weather conditions. This allows the equipment to operate close to their nominal capacity to increase the coefficient-of-performance and also allows for providing grid services with less risk to occupant thermal comfort. Also, TES integration with primary HVAC systems allows for peak demand reduction [86]. For example, an ice storage tank can enable the chiller demand to change rapidly while preventing an excessive increase in the space temperature [87]. Lizana et al. investigates the load shaping ability of a heat pump operation with PCM storage system for DHW [88].

Electrical energy storage systems, such as Lithiom-ion batteries, may provide building responsiveness, higher efficiency and lessen environmental impacts of the building [89]. This type of storage can be used regardless of the HVAC operation of the building and can accompany different end uses of electricity. Especially in locations without net metering, storage of excess onsite electricity generation potentially reduces the levelized cost of electricity (LCOE) of the building [90]. In case of two-way grid communications, electricity storage systems allow the building to participate in electricity market during the high price hours. Researchers have shown the benefits of harnessing the storage capacity of electric vehicles in buildings. EV charging accommodated by smart plugs can control the time of charge so that is beneficial to the grid [91].

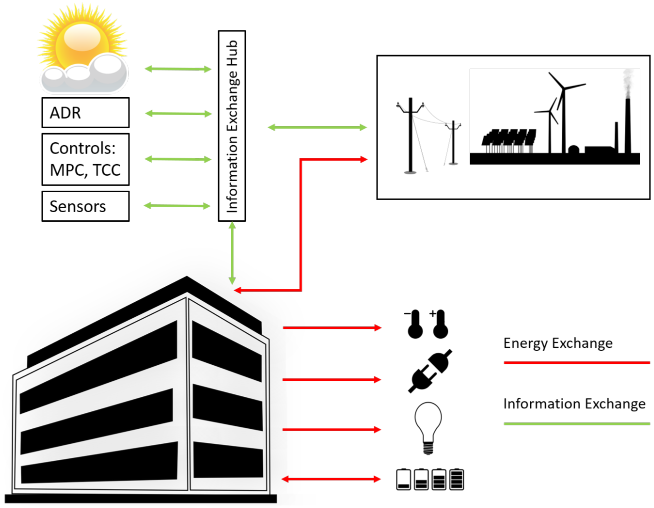

Figure 8. Building interactions with electricity grid. Actors of flexibility provide responsiveness through energy and information flow.

Table 2. Time scales of flexibility provided by interaction actors [50,92]. Frequency of event is High if it 2–4 times a day and if it demands continuous modifications during the bidding period. Moderate Frequencies are ≤2 event per day. Short event duration is within 30 min. Medium duration is ≤2 h. Long duration events last for ≥2 h.

Actor of Response	Flexibility Mode	Response Time	Frequency	Event Duration	Grid Services	Remarks
Envelope insulation	Energy efficiency	NA	NA	NA	Energy Capacity	
Construction material thermal mass	Energy efficiency	NA	NA	Diurnal	Energy Capacity	
Equipment efficiency	Energy efficiency	NA	NA	NA	Energy Capacity	
Day lighting and SSL	Energy efficiency	NA	NA	Diurnal	Energy Capacity	
Commercial HVAC	Shed and Shape	Minuets	High	Long	Energy Capacity Renewable curtailment Non-wires Solutions	Thermal load of the buildings can be adjusted through temperature setpoint, dynamic insulation, dynamic shading, and use of ground source energy storage resources
Residential HVAC	Shed and Shape	Minuets	High	Medium	Energy Capacity Renewable curtailment Non-wires Solutions	Residential buildings have smaller thermal mass and equipment so the duration of the event provided by the residential sector is smaller than commercial.
Dynamic lighting	Modulate	Seconds	High	Short	Ancillary services	Dynamic dimmer and smart shading systems allow for fast response to the grid without comfort compromise.
Smart plug loads	Shed and Shape	Seconds to minutes	High	Medium	Energy Renewable curtailment Contingency	Optimized scheduling of plug loads and appliance programming provides flexibility to the buildings energy consumption.
Thermal and Electrical Storage	Shape and Shed, and Energy efficiency	Minuets	Moderate	Medium to Long	Energy Capacity Renewable curtailment Non-wires Services	Thermal and Electrical storage can opt-in for HVAC energy use or plug loads of the building in the time of load shed signals. Load shaping is also possible by optimizing the charge/discharge rates. Also, storage integrated with HVAC operation will increase the efficiency as it allows for the equipment to work on optimum capacity.
Water Heating	Shape	Minuets	Moderate	Medium to Long	Renewable curtailment Energy	Ability to preheat and use the storage in hot water tanks to provide load shift and shaping.
Onsite generation	Modulate	Seconds to minuets	High	Short to Medium	Ancillary services	Behind the meter generation control.

Consumers can integrate DR measures on a manual (using labor intensive manual adjustments to decrease the load), semi-automated (by benefiting from pre-programmed control strategies) and fully automated (by using external operating signals) basis [93].

There are three main logic architectures for automated DR (ADR). (1) Enabling the onsite energy management control system (EMCS) to receive signals and convert these to DR strategies. (2) DR logic integration in the load itself enables smart devices to operate based on the DR signal. And (3), cloud based DR control enables third parties to control loads for each DR event. Implementation of ADR requires efficient communication between the grid operators and consumers. Standards such as OpenADR offer a common language to connect producers and consumers of energy for DR implementation [94].

Supporting an increasing level of interaction, transactive control and coordination (TCC) strategies allow the participants to consider several markets to provide services [95]. Voltron [96] is a communication protocol for the implementation of TCC and is shown to enable agents, applications and end users, to participate in financial, energy and operational transactions [97].

Building participation in multiple electricity markets, in particular day-ahead energy and frequency regulation ancillary service markets, was investigated by Pavlak et al. in which a model predictive control framework is proposed to determine optimal operating strategies in consideration of energy use, energy expense, peak demand, economic demand response revenue and frequency regulation revenue [98].

3.4. Building Interactions with Water and Transportation Networks

Buildings are connected to water and sewer networks. Fresh water is provided to the building while the latter delivers gray and black water to the sewer system. Waste water heat recovery systems (WWHRS) utilize the waste heat in the water rejected from the building to provide space heating or hot water to the building. Although this practice reduces the energy use and emission for heating, the cost of utilization is currently not competitive at the scale of a single residential building [99]. Bertrand et al. [100] show the possibility of improvement in the cost and energy savings of domestic WWHRS by considering various streams of grey water specifying their temperature and thermal load levels on an urban scale. Recent work shows that the use of building information management (BIM) concepts are also valuable for the demand and supply of water [101]. Integration of GIS, smart metering, smart appliances and BIM is useful for locational optimization of water demand [102].

Buildings and their interactions with the electric grid and the environment affect the transportation energy consumption [103]. The authors of Reference [103] show how the location of the building and mobility pattern of the occupants affect the transportation energy consumption. Another important factor in transportation networks are the increasing number of electric vehicles (EV). Buildings, commercial and residential, provide charging stations for EVs and therefore, are important in the mobility patterns of occupants [104]. Also, the storage capacity of EVs can be utilized in buildings for other applications. The ability of smart parking lots to provide flexibility depends on the location of the buildings and the amount of their onsite electricity generation [105].

Successful NZEBs provide environmental, occupant and economic benefits; therefore, the design and operation of zero energy buildings needs to account for building interactions with the physical environment and the energy infrastructure [106], see Figure 1. Marique et al. [107] provided an interactive tool that evaluates building energy efficiency measures and transportation energy consumption to showcase the effect of building's location on NZEB performance. The next step after reaching energy efficient design for NZEBs is to harvest their energy flexibility [108]. Load flexibility is created when the temporal occurrence between demand and supply is decoupled through either electrical storage or building active and passive thermal energy storage systems. And, optimizing demand flexibility allows for the integration of more renewable resources in the energy use of NZEBs [109].

4. Urban District Context

The idea of a building's interactions with other buildings within a district evolves from the concept of resource sharing. Resource sharing involves considering the building as a system situated within the context of an ensemble or cluster of buildings. The system of systems perspective provides potential in waste heat management, distributed energy resource design and operation optimization and aggregated grid services [109]. The biggest challenge in building cluster interaction is the control and aggregation of resources. Several methods such as game theory, block chain technology and transactive control schemes are studied in the literature to tackle the challenges. In the context of urban districts as the counterpart for interaction, the delivery of flexibility may include diversity effects in district energy systems, resource sharing such as community PV systems or cogeneration systems operating in either heat or power priority modes.

With advancements of energy systems, buildings are acting as prosumers of energy to further transform the energy market [108]. Both production and consumption of energy allows them to interact with energy systems and other buildings. Extending from individual NZEBs, optimized operation of buildings and DER within a district served by a micro-grid is essential for designing net zero energy districts (NZEDs) [110]. Evaluation of interactions within a micro-grid allows for more successful use of a district's electricity generation as well as district heating resources, which can ultimately result in 100 % renewable energy systems [111]. Cluster level interactions provide more opportunities in management of shared resources, such as DER, because of the potential for higher energy efficiency, aggregated load uniformity and more storage capability [112]. Also, integrating smart building technologies in a cluster of buildings benefits from economies of scale to reduce the investment and adaptation costs [113]. Therefore, the emergence of cluster interactions is shown in several cases such as Smart Neighborhood in Alabama, BedZED eco-community in London, Hammarby in Stockholm and Vauban in Freiburg [113,114].

Pavlak et al. explores the potential for synergistic effects that may exist through communal coordination of commercial building operations. A framework is presented for diurnal planning of multi-building thermal mass and HVAC system operational strategies in consideration of real-time energy prices, peak demand charges and ancillary service revenues. Optimizing buildings as a portfolio achieved up to seven additional percentage points of cost savings over individually optimized cases, depending on the simulation case study [115].

An important step in identifying the interaction potential within a district is the evaluation of the district's temporal energy consumption and production. Top down, bottom up and statistical models are used in the literature to provide energy trends within groups of buildings [116]. For example, Hedegaard et al. provide a bottom up modeling approach using Bayesian calibration techniques to evaluate the space heating DR potential in a residential group of buildings in Denmark [117]. Kazmi et al. show the use of deep reinforcement learning for optimum control of hot water systems for 32 houses [118]; in their energy efficiency optimization, inclusion of a hot water storage tank coupled with a heat pump result in 20% hot water energy use reduction for the group of buildings [118].

In addition to the benefits of intra-district interaction for the buildings and the environment, the aggregation of demand flexibility in building clusters can provide grid services such as peak shaving and load shaping [119]. It is shown that individual building participation in peak shaving under scenarios of dynamic and time-of-use pricing can have an adverse aggregate effect on aggregate load shaving. Therefore, in group level participation in DR, coordinated control schemes should evaluate the benefit of each building's participation and remove the useless ones to avoid unintended peak forming and extra energy consumption [120]. Campus level interactions with both the water network and the district heating network shows potential in heating load flexibility. In a price induced demand response scheme for a district heating network in a university campus, substations participated by changing their inlet water temperature while monitoring the occupant's thermal comfort [121].

- **Distributed Energy Systems**: With recent advancements in transactive energy and economy, microgrids may provide solutions in providing services to the power grid in general and the distribution systems in particular. The output of distributed generators and utilization of distributed energy storage systems are scheduled by a microgrid central controller (MCC) [122]. District heating is one way that buildings benefit from a distributed energy source and their complementary loads to reduce their aggregated energy consumption. For example, utilizing a GSHP for a district is economically viable and more efficient as it can increase the COP of the heat pump [123]. Hybrid heat pump systems allow for heat generation in a flexible manner. Coupling of auxiliary generators, such as a gas boiler [124] and storage facilities, [125], with a HP provides detachment of the building's load and electricity consumption for heating that results in higher flexibility of the load. District heating systems and using cogeneration for district heating is shown to be beneficial in terms of fuel efficiency and economics [126]. With greater renewable penetration, however, individual heat pumps may become more economical depending on the location of district heating network [126]. Cogeneration can adjust its production based on price signals and participate in energy markets [127]. Buildings also provide flexibility within a microgrid to mitigate the uncertainties involved with renewable generation. Jin et al. show the ability of a microgrid participating in DR in two different time scales [128]. They employ the office building energy storage capacity and EV storage capacity controls in the microgrid to be able to dispatch the resources at different time scales [128]. Brahman et al. evaluate the role of scheduling in a residential energy hub that is equipped with combined cooling heating and power systems (CCHP), PV, TES and EV charging stations and found that both load flexibility and storage capacity should be utilized for maximum energy cost reduction [129].
- **Ambient Loops**: Traditionally, the use of district heating systems utilizing cogeneration has been popular because of economies of scale [130]. The higher efficiency provided by these central plants leads to reduced environmental impacts compared to individual heating systems for buildings [130]. Advancements in district heating has led to the use of low-temperature networks for delivering space heating and air conditioning to the buildings [131]. The use of low-exergy heat pumps benefiting from the low-temperature environments to provide space heating and domestic hot water is discussed in the literature [132]. Fourth-generation district heating and cooling systems (4GDHC) focus on reducing the supply temperature in order to reduce the exergy requirements and distribution losses [133]. Fifth-generation district heating and cooling systems (5GDHC) lower the supply temperature even more than 4GDHC and utilize buildings' wast heat for simultaneous heating and cooling purposes [134]. 5GDHC systems show resilience in interacting with variety of energy supply temperatures and other conditions such as the user needs and the facilities efficiency as demonstrated in Anergy network in Zürich [134,135]. The flexibility of operation makes 5GDGC systems a solution to waste heat absorption [136].
  Bidirectional systems use the same network for heating and cooling. The performance of bidirectional systems depends on the district density and network losses. Buildings in low-temperature bidirectional networks can participate in thermal energy markets to trade waste heat [137]. Currently, the control of 5GDHC systems is challenging. It is shown that regulating the agent temperatures in 5GDHC systems by optimization can improve energy savings in the district [138].
- **Resource Sharing**: Resource sharing in commercial or residential districts allows for improved utilization of onsite energy resources, better allocation of resources to avoid network transmission losses and more economical solutions for energy savings. In contrast to individual buildings in which the optimum rooftop PV area depends on their individual load and storage capacity, resource sharing allows for trading PV generation within different buildings. In this case, evaluation of self-sufficiency of the buildings group depends on (1) relative load and generation, (2) time resolution of model and data and (3) the number of aggregated buildings to remove stochastic fluctuations of load and generation [139]. For a case study of office buildings in

California, it is shown that benefiting from the maximum available rooftop area in smaller buildings allows for excess generation that can be used in larger buildings in the district [140]. Also, adding electrical storage for the district is less expensive than allocating battery packs for individual buildings. The addition of the electrical storage facility allows for improved savings of the district's generation and self sufficiency to reduce the peak load of the district [141]. Thermal energy sharing also allows for better use of waste heat resources. In a retail complex, Syed and Hachem show the use of commercial building refrigeration compressor waste heat for a neighboring greenhouse results in site energy use reduction [142].

- **Portfolio Aggregation**: One of the main challenges in capturing the potential benefits of district interactions is the aggregation and control of resources. Optimizing the individual building level operations is computationally expensive. Huang uses a hierarchical coordinated scheme to evaluate and control a group of buildings flexibility potential for peak shaving. It reduces the computational load compared to traditional independent DR control [143]. A common practice for energy management system aggregators (EMSA) is to be seen as agents representing virtual load or production trends. It is important for the EMSA to implement proper contracts with the end users and the operating systems to ensure the implementation of load and production modifications [144].

District Management

Management of district interactions or, in other words, microgrid management means controlling the microgrid operation, DG schedule and charge and discharge rates of the ESS. Scheduling the load, for example, HVAC operation of individual buildings, is a challenge for district control systems. A central control system optimization is computationally expensive and has privacy issues; therefore, decentralized optimization using dual decomposition is studied in the literature [145]. Liu et al. propose a district management system that pursues load balance by communicating price signals to DG and home energy management systems to provide intelligent control that ensures privacy and autonomy for the costumers [146]. Buildings as prosumers of energy may practice resource sharing (both energy production and storage) in the paradigm of peer to peer (P2P) markets [147]. P2P markets enable not only energy transactions within agents in a district but also participation of the district in existing market structures [147]. The increasing number of peer-to-peer interactions as well as inclusion of various energy markets suggest that blockchain technology can be a solution to control the energy and economic transactions and smart contracts [148]. However, in peer-to-peer microgrids, realization and readiness of blockchain technology should incorporate several aspects such as (1) Technological, (2) Economic, (3) Social, (4) Environmental and (5) Institutional dimensions [149].

5. Conclusions

In this paper, interaction of the buildings with three main counterparts is investigated. A review of literature for interactions with environment, infrastructure and other buildings within a district shows how building's performance is affected by several factors. It is discussed that buildings' interactions should be considered for evaluation of building's thermal and electric load flexibility and responsiveness. Consideration of the system of interactions allows for occupant satisfaction, better use of onsite resources, providing services to the infrastructure and reducing uncertainties involved with supply and demand of energy. Knowledge of the potentials and challenges of interactions allows for better planning and design of high performance buildings with optimized use of the resources. In other words, design of zero energy buildings and districts is only possible when system of buildings are evaluated in the context of their interactions with the grid, the environment and other buildings. However, the complexity of the system provides challenges in planning and control of building interactions. The challenges and opportunities regarding building responsiveness can be categorized as the following:

1. *Evaluation of the amount and type of flexibility and the technologies participating in demand responsiveness.* Grid services only can count on buildings for providing demand side resources if they have a knowledge about the amount of potential flexibility. The flexibility potential should provide information about the amount of desired load change and the inevitable effects of a DR event, such as the kickback effect. Also, the knowledge of the reaction time of the building to a grid signal is important in grid planning and time of dispatch for the resources. It is important to note that building interactions both with the environment and the grid drive the characteristics of flexibility.
2. *Finding the value of demand flexibility by buildings.* The value of demand response helps the infrastructure with the creation of price signals for the buildings. For example, how should the pricing scheme for high and low consuming costumers differ [150]? How are the effects of participation in load flexibility for the buildings, such as effects on envelope, equipment efficiency, complexity of control, considered? All these research questions determine the proper price signals for a DR event and evaluate the willingness of different buildings to participate.
3. *Control and management of flexible resources on an aggregated level.* It is challenging to evaluate the potential of buildings flexibility on an aggregated level. Understanding the exchange of resources within buildings group is necessary for evaluating the district constraints and fabricating the proper contracts. Wang et al. suggest that coupling data driven models with network representative models may be a solution in understanding the district transactions [151].
4. *Evaluation of actions and interaction on building's energy use and occupant comfort considering different time scales.* It is important to evaluate different timescales to capture the effect of the interactions on the building's metrics. The interaction time scale defines the type of flexibility a building can provide. In interaction with the environment for example, seasonal or longer term time scales affect the grid planning. It is challenging to evaluate the combined effect of the interaction time resolutions on actions for retrofitting or flexibility harvest of the building.

Funding: This research was funded by the National Renewable Energy Laboratory (NREL) grant number APUP UGA-0-41026-124.

Acknowledgments: The authors gratefully acknowledge and appreciate the efforts of Amy Allen, P.E. in reviewing and critiquing the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2019 with Projections to 2050*; U.S. Energy Information Administration: Washington, DC, USA, 2019.
2. Yousefi, F.; Gholipour, Y.; Yan, W. A study of the impact of occupant behaviors on energy performance of building envelopes using occupants' data. *Energy Build.* **2017**, *148*, 182–198. doi:10.1016/j.enbuild.2017.04.085. [CrossRef]
3. Wang, N.; Phelan, P.E.; Gonzalez, J.; Harris, C.; Henze, G.P.; Hutchinson, R.; Langevin, J.; Lazarus, M.A.; Nelson, B.; Pyke, C.; et al. Ten questions concerning future buildings beyond zero energy and carbon neutrality. *Build. Environ.* **2017**, *119*, 169–182. doi:10.1016/j.buildenv.2017.04.006. [CrossRef]
4. Harkouss, F.; Fardoun, F.; Biwole, P.H. Passive design optimization of low energy buildings in different climates. *Energy* **2018**, *165*, 591–613. doi:10.1016/j.energy.2018.09.019. [CrossRef]
5. Park, B.; Srubar, W.V.; Krarti, M. Energy performance analysis of variable thermal resistance envelopes in residential buildings. *Energy Build.* **2015**, *103*, 317–325. doi:10.1016/j.enbuild.2015.06.061. [CrossRef]
6. Saretta, E.; Caputo, P.; Frontini, F. A review study about energy renovation of building facades with BIPV in urban environment. *Sustain. Cities Soc.* **2019**, *44*, 343–355. doi:10.1016/j.scs.2018.10.002. [CrossRef]
7. Hamed, T.A.; Alshare, A.; El-Khalil, H. Passive cooling of building-integrated photovolatics in desert conditions: Experiment and modeling. *Energy* **2019**, *170*, 131–138. doi:10.1016/j.energy.2018.12.153. [CrossRef]

8. Mehaoued, K.; Lartigue, B. Influence of a reflective glass façade on surrounding microclimate and building cooling load: Case of an office building in Algiers. *Sustain. Cities Soc.* **2019**, *46*, 101443. doi:10.1016/j.scs.2019.101443. [CrossRef]
9. Gunawardena, K.; Kershaw, T.; Steemers, K. Simulation pathway for estimating heat island influence on urban/suburban building space-conditioning loads and response to facade material changes. *Build. Environ.* **2019**, *150*, 195–205. doi:10.1016/j.buildenv.2019.01.006. [CrossRef]
10. Gevaudan, J.P.; Srubar, W.V. Energy Performance of Alkali-Activated Cement-Based Concrete Buildings. In Proceedings of the AEI 2017, Oklahoma City, OK, USA, 11–13 April 2017; pp. 311–323. doi:10.1061/9780784480502.026. [CrossRef]
11. Souto-Martinez, A.; Arehart, J.H.; Srubar, W.V. Cradle-to-gate CO2e emissions vs. in situ CO2 sequestration of structural concrete elements. *Energy Build.* **2018**, *167*, 301–311. doi:10.1016/j.enbuild.2018.02.042. [CrossRef]
12. Montoya, L.D.; Mauney, D.C.; Srubar, W.V. Investigation of efficient air pollutant removal using active flow control. *Build. Environ.* **2017**, *122*, 134–144. doi:10.1016/j.buildenv.2017.06.012. [CrossRef]
13. Berardi, U.; Roche, P.L.; Almodovar, J.M. Water-to-air-heat exchanger and indirect evaporative cooling in buildings with green roofs. *Energy Build.* **2017**, *151*, 406–417. doi:10.1016/j.enbuild.2017.06.065. [CrossRef]
14. Saffari, M.; de Gracia, A.; Ushak, S.; Cabeza, L.F. Passive cooling of buildings with phase change materials using whole-building energy simulation tools: A review. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1239–1255. doi:10.1016/j.rser.2017.05.139. [CrossRef]
15. Marin, P.; Saffari, M.; de Gracia, A.; Zhu, X.; Farid, M.M.; Cabeza, L.F.; Ushak, S. Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions. *Energy Build.* **2016**, *129*, 274–283. doi:10.1016/j.enbuild.2016.08.007. [CrossRef]
16. Panchabikesan, K.; Vellaisamy, K.; Ramalingam, V. Passive cooling potential in buildings under various climatic conditions in India. *Renew. Sustain. Energy Rev.* **2017**, *78*, 1236–1252. doi:10.1016/j.rser.2017.05.030. [CrossRef]
17. Agathokleous, R.; Barone, G.; Buonomano, A.; Forzano, C.; Kalogirou, S.; Palombo, A. Building façade integrated solar thermal collectors for air heating: Experimentation, modelling and applications. *Appl. Energy* **2019**, *239*, 658–679. doi:10.1016/j.apenergy.2019.01.020. [CrossRef]
18. Pomianowski, M.; Heiselberg, P.; Jensen, R.L. Dynamic heat storage and cooling capacity of a concrete deck with PCM and thermally activated building system. *Energy Build.* **2012**, *53*, 96–107. doi:10.1016/j.enbuild.2012.07.007. [CrossRef]
19. Meggers, F.; Ritter, V.; Goffin, P.; Baetschmann, M.; Leibundgut, H. Low exergy building systems implementation. *Energy* **2012**, *41*, 48–55. doi:10.1016/j.energy.2011.07.031. [CrossRef]
20. Gao, J.; Li, A.; Xu, X.; Gang, W.; Yan, T. Ground heat exchangers: Applications, technology integration and potentials for zero energy buildings. *Renew. Energy* **2018**, *128*, 337–349. doi:10.1016/j.renene.2018.05.089. [CrossRef]
21. Vanaga, R.; Blumberga, A.; Freimanis, R.; Mols, T.; Blumberga, D. Solar facade module for nearly zero energy building. *Energy* **2018**, *157*, 1025–1034. doi:10.1016/j.energy.2018.04.167. [CrossRef]
22. Johra, H.; Filonenko, K.; Heiselberg, P.; Veje, C.; Dall'Olio, S.; Engelbrecht, K.; Bahl, C. Integration of a magnetocaloric heat pump in an energy flexible residential building. *Renew. Energy* **2019**, *136*, 115–126. doi:10.1016/j.renene.2018.12.102. [CrossRef]
23. Clauß, J.; Stinner, S.; Sartori, I.; Georges, L. Predictive rule-based control to activate the energy flexibility of Norwegian residential buildings: Case of an air-source heat pump and direct electric heating. *Appl. Energy* **2019**, *237*, 500–518. doi:10.1016/j.apenergy.2018.12.074. [CrossRef]
24. Liu, Z.; Li, Y.; Xu, W.; Yin, H.; Gao, J.; Jin, G.; Lun, L.; Jin, G. Performance and feasibility study of hybrid ground source heat pump system assisted with cooling tower for one office building based on one Shanghai case. *Energy* **2019**, *173*, 28–37. doi:10.1016/j.energy.2019.02.061. [CrossRef]
25. Nielsen, M.V.; Svendsen, S.; Jensen, L.B. Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. *Sol. Energy* **2011**, *85*, 757–768. doi:10.1016/j.solener.2011.01.010. [CrossRef]
26. Belussi, L.; Barozzi, B.; Bellazzi, A.; Danza, L.; Devitofrancesco, A.; Fanciulli, C.; Ghellere, M.; Guazzi, G.; Meroni, I.; Salamone, F.; et al. A review of performance of zero energy buildings and energy efficiency solutions. *J. Build. Eng.* **2019**, *25*, 100772. doi:10.1016/j.jobe.2019.100772. [CrossRef]

27. Powell, D.; Hischier, I.; Jayathissa, P.; Svetozarevic, B.; Schlüter, A. A reflective adaptive solar façade for multi-building energy and comfort management. *Energy Build.* **2018**, *177*, 303–315. doi:10.1016/j.enbuild.2018.07.040. [CrossRef]
28. Yi, Y.K. Building facade multi-objective optimization for daylight and aesthetical perception. *Build. Environ.* **2019**, *156*, 178–190. doi:10.1016/j.buildenv.2019.04.002. [CrossRef]
29. Hawila, A.A.W.; Merabtine, A.; Troussier, N.; Bennacer, R. Combined use of dynamic building simulation and metamodeling to optimize glass facades for thermal comfort. *Build. Environ.* **2019**, *157*, 47–63. doi:10.1016/j.buildenv.2019.04.027. [CrossRef]
30. Charisi, S.; Thiis, T.K.; Stefansson, P.; Burud, I. Prediction model of microclimatic surface conditions on building façades. *Build. Environ.* **2018**, *128*, 46–54. doi:10.1016/j.buildenv.2017.11.017. [CrossRef]
31. Uhde, E.; Salthammer, T. Impact of reaction products from building materials and furnishings on indoor air quality—A review of recent advances in indoor chemistry. *Atmos. Environ.* **2007**, *41*, 3111–3128. doi:10.1016/j.atmosenv.2006.05.082. [CrossRef]
32. Maggos, T.; Bartzis, J.; Leva, P.; Kotzias, D. Application of photocatalytic technology for NO_x removal. *Appl. Phys. A* **2007**, *89*, 81–84. [CrossRef]
33. Cabeza, L.; Martorell, I.; Miró, L.; Fernández, A.; Barreneche, C. 1—Introduction to thermal energy storage (TES) systems. In *Advances in Thermal Energy Storage Systems*; Cabeza, L.F., Ed.; Woodhead Publishing Series in Energy; Woodhead Publishing: Sawston, UK, 2015; pp. 1–28, ISBN 9781782420880 doi:10.1533/9781782420965.1.
34. Dubey, S.; Sarvaiya, J.N.; Seshadri, B. Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World—A Review. *Energy Procedia* **2013**, *33*, 311–321. doi:10.1016/j.egypro.2013.05.072. [CrossRef]
35. Li, H.; Zhao, J.; Li, M.; Deng, S.; An, Q.; Wang, F. Performance analysis of passive cooling for photovoltaic modules and estimation of energy-saving potential. *Solar Energy* **2019**, *181*, 70–82. doi:10.1016/j.solener.2019.01.014. [CrossRef]
36. Day, J.K.; Futrell, B.; Cox, R.; Ruiz, S.N. Blinded by the light: Occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies. *Build. Environ.* **2019**, *154*, 107–121. doi:10.1016/j.buildenv.2019.02.037. [CrossRef]
37. Labeodan, T.; Zeiler, W.; Boxem, G.; Zhao, Y. Occupancy measurement in commercial office buildings for demand-driven control applications—A survey and detection system evaluation. *Energy Build.* **2015**, *93*, 303–314. doi:10.1016/j.enbuild.2015.02.028. [CrossRef]
38. Balvedi, B.F.; Ghisi, E.; Lamberts, R. A review of occupant behaviour in residential buildings. *Energy Build.* **2018**, *174*, 495–505. doi:10.1016/j.enbuild.2018.06.049. [CrossRef]
39. Saha, H.; Florita, A.R.; Henze, G.P.; Sarkar, S. Occupancy sensing in buildings: A review of data analytics approaches. *Energy Build.* **2019**, *188–189*, 278–285. [CrossRef]
40. Holmes, C.; Mullen-Trento, S. *Technical Update: State Level Electric Energy Efficiency Potential Estimates*; EPRI: Palo Alto, CA, USA, 2017.
41. Alstone, P.; Potter, J.; Piette, M.A.; Schwartz, P.; Berger, M.A.; Dunn, L.N.; Smith, S.J.; Sohn, M.D.; Aghajanzadeh, A.; Stensson, S.; et al. *2025 California Demand Response Potential Study—Charting California's Demand Response Future: Final Report on Phase 2 Results*; Technical Report; Demand Response Research Center, Energy Technologies Area, Berkeley Lab: Berkeley, CA, USA, 2017.
42. *Analysis of the 2021/2022 RPM Base Residual Auction: Revised*; Monitoring Analytics: Eagleville, PA, USA, 2018.
43. New York Independent System Operator (NYISO). *Annual Report on Demand Response Programs*; New York Independent System Operator: New York, NY, USA, 2018.
44. Midcontinent Independent System Operator (MISO). *2018/2019 Planning Resource Auction Results*; Midcontinent Independent System Operator: Carmel, IN, USA, 2018.
45. Xu, Y.; Li, F.; Kueck, J.D.; Rizy, D.T. Experiment and simulation of dynamic voltage regulation with multiple distributed energy resources. In Proceedings of the 2007 iREP Symposium—Bulk Power System Dynamics and Control—VII. Revitalizing Operational Reliability, Charleston, SC, USA, 19–24 August 2007; pp. 1–7. doi:10.1109/IREP.2007.4410576. [CrossRef]
46. Ela, E.; Milligan, M.; Kirby, B. *Operating Reserves and Variable Generation*; National Renewable Energy Laboratory: Golden, CO, USA, 2011.

47. California Independent System Operator (CAISO). *Q4 2018 Report on Market Issues and Performance*; California Independent System Operator: Folsom, CA, USA, 2019.
48. Denholm, P.; Eichman, J.; Markel, T.; Ma, O. *Summary of Market Opportunities for Electric Vehicles and Dispatchable Load in Electrolyzers*; National Renewable Energy Laboratory: Lakewood, CO, USA, 2015.
49. Palensky, P.; Dietrich, D. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. *IEEE Trans. Ind. Inform.* **2011**, *7*, 381–388. doi:10.1109/TII.2011.2158841. [CrossRef]
50. Kiliccote, S.; Olsen, D.; Sohn, M.D.; Piette, M.A. Characterization of demand response in the commercial, industrial, and residential sectors in the United States. *Wiley Interdiscip. Rev. Energy Environ.* **2016**, *5*, 288–304. doi:10.1002/wene.176. [CrossRef]
51. Mims, N.; Eckman, T.; Goldman, C. *Time-Varying Value of Electric Energy Efficiency*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2017.
52. Federal Energy Regulatory Commission. *Assessment of Demand Response and Advanced Metering*; Staff Report; Federal Energy Regulatory Commission: Washington, DC, USA, 2018.
53. Mayhorn, E.; Parker, S.; Chassin, F.; Widder, S.; Pratt, R. *Evaluation of the Demand Response Performance of Large Capacity Electric Water Heaters*; Pacific Northwest National Laboratory: Washington, DC, USA, 2015.
54. MacDonald, J.; Kiliccote, S. Commercial Building Loads Providing Ancillary Services in PJM. In Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 17–22 August 2014.
55. Østergaard Jensen, S.; Marszal-Pomianowska, A.; Lollini, R.; Pasut, W.; Knotzer, A.; Engelmann, P.; Stafford, A.; Reynders, G. IEA EBC Annex 67 Energy Flexible Buildings. *Energy Build.* **2017**, *155*, 25–34. doi:10.1016/j.enbuild.2017.08.044. [CrossRef]
56. Junker, R.G.; Azar, A.G.; Lopes, R.A.; Lindberg, K.B.; Reynders, G.; Relan, R.; Madsen, H. Characterizing the energy flexibility of buildings and districts. *Appl. Energy* **2018**, *225*, 175–182. doi:10.1016/j.apenergy.2018.05.037. [CrossRef]
57. Han, X.; You, S.; Bindner, H. Critical kick-back mitigation through improved design of demand response. *Appl. Therm. Eng.* **2017**, *114*, 1507–1514. doi:10.1016/j.applthermaleng.2016.09.053. [CrossRef]
58. Smith, J.W.; Sunderman, W.; Dugan, R.; Seal, B. Smart inverter volt/var control functions for high penetration of PV on distribution systems. In Proceedings of the 2011 IEEE/PES Power Systems Conference and Exposition, Phoenix, AZ, USA, 20–23 March 2011; pp. 1–6. doi:10.1109/PSCE.2011.5772598. [CrossRef]
59. Shariatzadeh, F.; Mandal, P.; Srivastava, A.K. Demand response for sustainable energy systems: A review, application and implementation strategy. *Renew. Sustain. Energy Rev.* **2015**, *45*, 343–350. doi:10.1016/j.rser.2015.01.062. [CrossRef]
60. Fallahi, Z.; Smith, A.D. A Comparison of Commercial Building Retrofits Using Energyplus. In Proceedings of the ASME 2016 International Mechanical Engineering Congress and Exposition, Phoenix, AZ, USA, 11–17 November 2016; pp. 1–10. doi:10.1115/IMECE2016-67615. [CrossRef]
61. Kim, Y.; Fuentes, E.; Norford, L.K. Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump. *IEEE Trans. Power Syst.* **2016**, *31*, 3090–3099. doi:10.1109/TPWRS.2015.2472497. [CrossRef]
62. Zhao, P.; Henze, G.P.; Brandemuehl, M.J.; Cushing, V.J.; Plamp, S. Dynamic frequency regulation resources of commercial buildings through combined building system resources using a supervisory control methodology. *Energy Build.* **2015**, *86*, 137–150. doi:10.1016/j.enbuild.2014.09.078. [CrossRef]
63. Rotger-Griful, S.; Jacobsen, R.H.; Nguyen, D.; Sørensen, G. Demand response potential of ventilation systems in residential buildings. *Energy Build.* **2016**, *121*, 1–10. doi:10.1016/j.enbuild.2016.03.061. [CrossRef]
64. Fabietti, L.; Gorecki, T.T.; Qureshi, F.A.; Bitlislioğlu, A.; Lymperopoulos, I.; Jones, C.N. Experimental Implementation of Frequency Regulation Services Using Commercial Buildings. *IEEE Trans. Smart Grid* **2018**, *9*, 1657–1666. doi:10.1109/TSG.2016.2597002. [CrossRef]
65. ASHRAE. *ANSI/ASHRAE 55 Standard: Thermal Environmental Conditions for Human Occupancy*; Technical Report February; ASHRAE: Atlanta, GA, USA, 2013.
66. Aghniaey, S.; Lawrence, T.M. The impact of increased cooling setpoint temperature during demand response events on occupant thermal comfort in commercial buildings: A review. *Energy Build.* **2018**, *173*, 19–27. doi:10.1016/j.enbuild.2018.04.068. [CrossRef]
67. Panão, M.J.O.; Mateus, N.M.; da Graça, G.C. Measured and modeled performance of internal mass as a thermal energy battery for energy flexible residential buildings. *Appl. Energy* **2019**, *239*, 252–267. doi:10.1016/j.apenergy.2019.01.200. [CrossRef]

68. Balint, A.; Kazmi, H. Determinants of energy flexibility in residential hot water systems. *Energy Build.* **2019**, *188–189*, 286–296. doi:10.1016/j.enbuild.2019.02.016. [CrossRef]
69. Fischer, D.; Wolf, T.; Wapler, J.; Hollinger, R.; Madani, H. Model-based flexibility assessment of a residential heat pump pool. *Energy* **2017**, *118*, 853–864. doi:10.1016/j.energy.2016.10.111. [CrossRef]
70. Rodríguez-Hidalgo, M.; Rodríguez-Aumente, P.; Lecuona, A.; Legrand, M.; Ventas, R. Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank. *Appl. Energy* **2012**, *97*, 897–906. doi:10.1016/j.apenergy.2011.12.088. [CrossRef]
71. Haines, V.; Kyriakopoulou, K.; Lawton, C. End user engagement with domestic hot water heating systems: Design implications for future thermal storage technologies. *Energy Res. Soc. Sci.* **2019**, *49*, 74–81. doi:10.1016/j.erss.2018.10.009. [CrossRef]
72. Pang, Z.; O'Neill, Z. Uncertainty quantification and sensitivity analysis of the domestic hot water usage in hotels. *Appl. Energy* **2018**, *232*, 424–442. doi:10.1016/j.apenergy.2018.09.221. [CrossRef]
73. IEA. *Light's Labour's Lost: Policies for Energy-Efficient Lighting, Energy Efficiency Policy Profiles*; OECD Publishing: Paris, France, 2006. doi:10.1787/9789264109520-en. [CrossRef]
74. Baloch, A.A.; Shaikh, P.H.; Shaikh, F.; Leghari, Z.H.; Mirjat, N.H.; Uqaili, M.A. Simulation tools application for artificial lighting in buildings. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3007–3026. doi:10.1016/j.rser.2017.10.035. [CrossRef]
75. Nardelli, A.; Deuschle, E.; de Azevedo, L.D.; Pessoa, J.L.N.; Ghisi, E. Assessment of Light Emitting Diodes technology for general lighting: A critical review. *Renew. Sustain. Energy Rev.* **2017**, *75*, 368–379. doi:10.1016/j.rser.2016.11.002. [CrossRef]
76. Jayathissa, P.; Luzzatto, M.; Schmidli, J.; Hofer, J.; Nagy, Z.; Schlueter, A. Optimising building net energy demand with dynamic BIPV shading. *Appl. Energy* **2017**, *202*, 726–735. doi:10.1016/j.apenergy.2017.05.083. [CrossRef]
77. Taveres-Cachat, E.; Lobaccaro, G.; Goia, F.; Chaudhary, G. A methodology to improve the performance of PV integrated shading devices using multi-objective optimization. *Appl. Energy* **2019**, *247*, 731–744. doi:10.1016/j.apenergy.2019.04.033. [CrossRef]
78. Al-Masrani, S.M.; Al-Obaidi, K.M.; Zalin, N.A.; Isma, M.A. Design optimisation of solar shading systems for tropical office buildings: Challenges and future trends. *Sol. Energy* **2018**, *170*, 849–872. doi:10.1016/j.solener.2018.04.047. [CrossRef]
79. Christantoni, D.; Oxizidis, S.; Flynn, D.; Finn, D.P. Implementation of demand response strategies in a multi-purpose commercial building using a whole-building simulation model approach. *Energy Build.* **2016**, *131*, 76–86. doi:10.1016/j.enbuild.2016.09.017. [CrossRef]
80. Xiong, J.; Tzempelikos, A. Model-based shading and lighting controls considering visual comfort and energy use. *Sol. Energy* **2016**, *134*, 416–428. doi:10.1016/j.solener.2016.04.026. [CrossRef]
81. Harris, A.; Rogers, M.M.; Miller, C.J.; McElmurry, S.P.; Wang, C. Residential emissions reductions through variable timing of electricity consumption. *Appl. Energy* **2015**, *158*, 484–489. doi:10.1016/j.apenergy.2015.08.042. [CrossRef]
82. Christensen, D.T.; Jin, X.; Sparn, B.F.; Isley, S.; Balamurugan, S.P.; Carmichael, S.; Michalski, A.; Sanghvi, A.D.; Martin, M.; Baker, K.A.; et al. *TIP-337 Home Battery System for Cybersecure Energy Efficiency and Demand Response*; Technical Report; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2018.
83. Cetin, K.S. Characterizing large residential appliance peak load reduction potential utilizing a probabilistic approach. *Sci. Technol. Built Environ.* **2016**, *22*, 720–732. doi:10.1080/23744731.2016.1195660. [CrossRef]
84. Good, N.; Ellis, K.A.; Mancarella, P. Review and classification of barriers and enablers of demand response in the smart grid. *Renew. Sustain. Energy Rev.* **2017**, *72*, 57–72. doi:10.1016/j.rser.2017.01.043. [CrossRef]
85. Bianchini, G.; Casini, M.; Pepe, D.; Vicino, A.; Zanvettor, G.G. An integrated model predictive control approach for optimal HVAC and energy storage operation in large-scale buildings. *Appl. Energy* **2019**, *240*, 327–340. doi:10.1016/j.apenergy.2019.01.187. [CrossRef]
86. Kamal, R.; Moloney, F.; Wickramaratne, C.; Narasimhan, A.; Goswami, D. Strategic control and cost optimization of thermal energy storage in buildings using EnergyPlus. *Appl. Energy* **2019**, *246*, 77–90. doi:10.1016/j.apenergy.2019.04.017. [CrossRef]
87. Tang, R.; Wang, S. Model predictive control for thermal energy storage and thermal comfort optimization of building demand response in smart grids. *Appl. Energy* **2019**, *242*, 873–882. doi:10.1016/j.apenergy.2019.03.038. [CrossRef]

88. Lizana, J.; Friedrich, D.; Renaldi, R.; Chacartegui, R. Energy flexible building through smart demand-side management and latent heat storage. *Appl. Energy* **2018**, *230*, 471–485. doi:10.1016/j.apenergy.2018.08.065. [CrossRef]
89. Liu, J.; Chen, X.; Cao, S.; Yang, H. Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings. *Energy Convers. Manag.* **2019**, *187*, 103–121. doi:10.1016/j.enconman.2019.02.080. [CrossRef]
90. Tran, T.T.; Smith, A.D. Thermoeconomic analysis of residential rooftop photovoltaic systems with integrated energy storage and resulting impacts on electrical distribution networks. *Sustain. Energy Technol. Assess.* **2018**, *29*, 92–105. doi:10.1016/j.seta.2018.07.002. [CrossRef]
91. Stadler, M.; Kloess, M.; Groissböck, M.; Cardoso, G.; Sharma, R.; Bozchalui, M.; Marnay, C. Electric storage in California's commercial buildings. *Appl. Energy* **2013**, *104*, 711–722. doi:10.1016/j.apenergy.2012.11.033. [CrossRef]
92. Hummon, M.; Palchak, D.; Denholm, P.; Jorgenson, J.; Olsen, D.J.; Kiliccote, S.; Matson, N.; Sohn, M.; Rose, C.; Dudley, J.; et al. *Grid Integration of Aggregated Demand Response, Part 2: Modeling Demand Response in a Production Cost Model*; National Renewable Energy Laboratory: Lakewood, CO, USA, 2013.
93. Piette, M.A.; Watson, D.; Motegi, N.; Kiliccote, S.; Xu, P. *Automated Critical Peak Pricing Field Tests: Program Description and Results*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2006.
94. Herberg, U.; Mashima, D.; Jetcheva, J.G.; Mirzazad-Barijough, S. OpenADR 2.0 deployment architectures: Options and implications. In Proceedings of the 2014 IEEE International Conference on Smart Grid Communications (SmartGridComm), Venice, Italy, 3–6 November 2014; pp. 782–787. doi:10.1109/SmartGridComm.2014.7007743. [CrossRef]
95. Subbarao, K.; Fuller, J.; Kalsi, K.; Pratt, R.; Widergren, S.; Chassin, D. *Transactive Control and Coordination of Distributed Assets for Ancillary Services*; Pacific Northwest National Laboratory: Washington, DC, USA, 2013.
96. Katipamula, S.; Haack, J.; Hernandez, G.; Akyol, B.; Hagerman, J. VOLTTRON: An Open-Source Software Platform of the Future. *IEEE Electrif. Mag.* **2016**, *4*, 15–22. doi:10.1109/MELE.2016.2614178. [CrossRef]
97. Katipamula, S.; Lutes, R.; Hernandez, G.; Haack, J.; Akyol, B. Transactional network: Improving efficiency and enabling grid services for buildings. *Sci. Technol. Built Environ.* **2016**, *22*, 643–654. doi:10.1080/23744731.2016.1171628. [CrossRef]
98. Pavlak, G.S.; Henze, G.P.; Cushing, V.J. Optimizing commercial building participation in energy and ancillary service markets. *Energy Build.* **2014**, *81*, 115–126. [CrossRef]
99. Spriet, J.; McNabola, A. Decentralized Drain Water Heat Recovery: Interaction between Wastewater and Heating Flows on a Single Residence Scale. *Proceedings* **2018**, *2*, 583. doi:10.3390/proceedings2110583. [CrossRef]
100. Bertrand, A.; Aggoune, R.; Maréchal, F. In-building waste water heat recovery: An urban-scale method for the characterisation of water streams and the assessment of energy savings and costs. *Appl. Energy* **2017**, *192*, 110–125. doi:10.1016/j.apenergy.2017.01.096. [CrossRef]
101. Raouf, A.M.I.; Al-Ghamdi, S.G. Building information modelling and green buildings: challenges and opportunities. *Archit. Eng. Des. Manag.* **2019**, *15*, 1–28, doi:10.1080/17452007.2018.1502655. [CrossRef]
102. Howell, S.; Rezgui, Y.; Beach, T. Integrating building and urban semantics to empower smart water solutions. *Autom. Constr.* **2017**, *81*, 434–448. doi:10.1016/j.autcon.2017.02.004. [CrossRef]
103. Marique, A.F.; Reiter, S. A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale. *Energy Build.* **2014**, *82*, 114–122. doi:10.1016/j.enbuild.2014.07.006. [CrossRef]
104. Barone, G.; Buonomano, A.; Calise, F.; Forzano, C.; Palombo, A. Building to vehicle to building concept toward a novel zero energy paradigm: Modelling and case studies. *Renew. Sustain. Energy Rev.* **2019**, *101*, 625–648. doi:10.1016/j.rser.2018.11.003. [CrossRef]
105. Amini, M.H.; Moghaddam, M.P.; Karabasoglu, O. Simultaneous allocation of electric vehicles' parking lots and distributed renewable resources in smart power distribution networks. *Sustain. Cities Soc.* **2017**, *28*, 332–342. doi:10.1016/j.scs.2016.10.006. [CrossRef]
106. Attia, S. *Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation*; Elsevier Science: Amsterdam, The Netherlands, 2018; Imprint: Butterworth-Heinemann, ISBN:9780128124611.

107. Marique, A.F.; de Meester, T.; Herde, A.D.; Reiter, S. An online interactive tool to assess energy consumption in residential buildings and for daily mobility. *Energy Build.* **2014**, *78*, 50–58. doi:10.1016/j.enbuild.2014.04.016. [CrossRef]
108. D'angiolella, R.; de Groote, M.; Fabbri, M. NZEB 2.0: Interactive players in an evolving energy system. *REHVA J.* **2016**, *53*, 52–55.
109. Péan, T.Q.; Ortiz, J.; Salom, J. Impact of Demand-Side Management on Thermal Comfort and Energy Costs in a Residential nZEB. *Buildings* **2017**, *7*, 37. doi:10.3390/buildings7020037. [CrossRef]
110. Sameti, M.; Haghighat, F. Integration of distributed energy storage into net-zero energy district systems: Optimum design and operation. *Energy* **2018**, *153*, 575–591. doi:10.1016/j.energy.2018.04.064. [CrossRef]
111. Nielsen, S.; Möller, B. Excess heat production of future net zero energy buildings within district heating areas in Denmark. *Energy* **2012**, *48*, 23–31. doi:10.1016/j.energy.2012.04.012. [CrossRef]
112. Vigna, I.; Pernetti, R.; Pasut, W.; Lollini, R. New domain for promoting energy efficiency: Energy Flexible Building Cluster. *Sustain. Cities Soc.* **2018**, *38*, 526–533. doi:10.1016/j.scs.2018.01.038. [CrossRef]
113. Neukomm, M.; Nubbe, V.; Fares, R. *Grid-interactive Efficient Buildings, Overview*; Technical Report April; Office of Energy Efficiency and Renewable Energy: Washington, DC, USA, 2019.
114. Williams, J. Can low carbon city experiments transform the development regime? *Futures* **2016**, *77*, 80–96. doi:10.1016/j.futures.2016.02.003. [CrossRef]
115. Pavlak, G.S.; Henze, G.P.; Cushing, V.J. Evaluating synergistic effect of optimally controlling commercial building thermal mass portfolios. *Energy* **2015**, *84*, 161–176. [CrossRef]
116. Ferrari, S.; Zagarella, F.; Caputo, P.; D'Amico, A. Results of a literature review on methods for estimating buildings energy demand at district level. *Energy* **2019**, *175*, 1130–1137. doi:10.1016/j.energy.2019.03.172. [CrossRef]
117. Hedegaard, R.E.; Kristensen, M.H.; Pedersen, T.H.; Brun, A.; Petersen, S. Bottom-up modelling methodology for urban-scale analysis of residential space heating demand response. *Appl. Energy* **2019**, *242*, 181–204. doi:10.1016/j.apenergy.2019.03.063. [CrossRef]
118. Kazmi, H.; Mehmood, F.; Lodeweyckx, S.; Driesen, J. Gigawatt-hour scale savings on a budget of zero: Deep reinforcement learning based optimal control of hot water systems. *Energy* **2018**, *144*, 159–168. doi:10.1016/j.energy.2017.12.019. [CrossRef]
119. Zhang, L.; Good, N.; Mancarella, P. Building-to-grid flexibility: Modelling and assessment metrics for residential demand response from heat pump aggregations. *Appl. Energy* **2019**, *233–234*, 709–723. doi:10.1016/j.apenergy.2018.10.058. [CrossRef]
120. Shen, L.; Li, Z.; Sun, Y. Performance evaluation of conventional demand response at building-group-level under different electricity pricings. *Energy Build.* **2016**, *128*, 143–154. doi:10.1016/j.enbuild.2016.06.082. [CrossRef]
121. Mishra, A.K.; Jokisalo, J.; Kosonen, R.; Kinnunen, T.; Ekkerhaugen, M.; Ihasalo, H.; Martin, K. Demand response events in district heating: Results from field tests in a university building. *Sustain. Cities Soc.* **2019**, *47*, 101481. doi:10.1016/j.scs.2019.101481. [CrossRef]
122. Vaahedi, E.; Nodehi, K.; Heim, D.; Rahimi, F.; Ipakchi, A. The emerging transactive microgrid controller: illustrating its concept, functionality, and business case. *IEEE Power Energy Mag.* **2017**, *15*, 80–87. [CrossRef]
123. Al-Habaibeh, A.; Athresh, A.P.; Parker, K. Performance analysis of using mine water from an abandoned coal mine for heating of buildings using an open loop based single shaft GSHP system. *Appl. Energy* **2018**, *211*, 393–402. doi:10.1016/j.apenergy.2017.11.025. [CrossRef]
124. Klein, K.; Huchtemann, K.; Müller, D. Numerical study on hybrid heat pump systems in existing buildings. *Energy Build.* **2014**, *69*, 193–201. doi:10.1016/j.enbuild.2013.10.032. [CrossRef]
125. Heinen, S.; Burke, D.; O'Malley, M. Electricity, gas, heat integration via residential hybrid heating Technologies—An investment model assessment. *Energy* **2016**, *109*, 906–919. doi:10.1016/j.energy.2016.04.126. [CrossRef]
126. Lund, H.; Möller, B.; Mathiesen, B.V.; Dyrelund, A. The role of district heating in future renewable energy systems. *Energy* **2010**, *35*, 1381–1390. [CrossRef]
127. Lund, H.; Andersen, A.N.; Østergaard, P.A.; Mathiesen, B.V.; Connolly, D. From electricity smart grids to smart energy systems—A market operation based approach and understanding. *Energy* **2012**, *42*, 96–102. doi:10.1016/j.energy.2012.04.003. [CrossRef]

128. Jin, X.; Wu, J.; Mu, Y.; Wang, M.; Xu, X.; Jia, H. Hierarchical microgrid energy management in an office building. *Appl. Energy* **2017**, *208*, 480–494. doi:10.1016/j.apenergy.2017.10.002. [CrossRef]
129. Brahman, F.; Honarmand, M.; Jadid, S. Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system. *Energy Build.* **2015**, *90*, 65–75. doi:10.1016/j.enbuild.2014.12.039. [CrossRef]
130. Rezaie, B.; Rosen, M.A. District heating and cooling: Review of technology and potential enhancements. *Appl. Energy* **2012**, *93*, 2–10. doi:10.1016/j.apenergy.2011.04.020. [CrossRef]
131. Schluck, T.; Kräuchi, P.; Sulzer, M. Non-linear thermal networks How can a meshed network improve energy efficiency? In Proceedings of the International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale, LESO-PB, EPFL, Lausanne, Switzerland, 9–11 September 2015; Number CONF, pp. 779–784.
132. Knudsen, M.D.; Petersen, S. Model predictive control for demand response of domestic hot water preparation in ultra-low temperature district heating systems. *Energy Build.* **2017**, *146*, 55–64. doi:10.1016/j.enbuild.2017.04.023. [CrossRef]
133. Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.E.; Hvelplund, F.; Mathiesen, B.V. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy* **2014**, *68*, 1–11. doi:10.1016/j.energy.2014.02.089. [CrossRef]
134. Buffa, S.; Cozzini, M.; D'Antoni, M.; Baratieri, M.; Fedrizzi, R. 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renew. Sustain. Energy Rev.* **2019**, *104*, 504–522. doi:10.1016/j.rser.2018.12.059. [CrossRef]
135. ETH. *The Energy of Tomorrow, Energy Concept Anergy Grid ETH Hönggerberg*; Technical Report; ETH: Zürich, Switzerland, 2018.
136. von Rhein, J.; Henze, G.P.; Long, N.; Fu, Y. Development of a topology analysis tool for fifth-generation district heating and cooling networks. *Energy Convers. Manag.* **2019**, *196*, 705–716. doi:10.1016/j.enconman.2019.05.066. [CrossRef]
137. Pass, R.Z.; Wetter, M.; Piette, M. A thermodynamic analysis of a novel bidirectional district heating and cooling network. *Energy* **2018**, *144*, 20–30. doi:10.1016/j.energy.2017.11.122. [CrossRef]
138. Bünning, F.; Wetter, M.; Fuchs, M.; Müller, D. Bidirectional low temperature district energy systems with agent-based control: Performance comparison and operation optimization. *Appl. Energy* **2018**, *209*, 502–515. doi:10.1016/j.apenergy.2017.10.072. [CrossRef]
139. Luthander, R.; Widén, J.; Nilsson, D.; Palm, J. Photovoltaic self-consumption in buildings: A review. *Appl. Energy* **2015**, *142*, 80–94. doi:10.1016/j.apenergy.2014.12.028. [CrossRef]
140. Fallahi, Z.; Smith, A.D. Economic and emission-saving benefits of utilizing demand response and distributed renewables in microgrids. *Electr. J.* **2017**, *30*, 42–49. doi:10.1016/j.tej.2017.10.008. [CrossRef]
141. Roberts, M.B.; Bruce, A.; MacGill, I. Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings. *Appl. Energy* **2019**, *245*, 78–95. doi:10.1016/j.apenergy.2019.04.001. [CrossRef]
142. Syed, A.M.; Hachem, C. Net-zero energy design and energy sharing potential of Retail - Greenhouse complex. *J. Build. Eng.* **2019**, *24*, 100736. doi:10.1016/j.jobe.2019.100736. [CrossRef]
143. Huang, P.; Fan, C.; Zhang, X.; Wang, J. A hierarchical coordinated demand response control for buildings with improved performances at building group. *Appl. Energy* **2019**, *242*, 684–694. doi:10.1016/j.apenergy.2019.03.148. [CrossRef]
144. Carreiro, A.M.; Jorge, H.M.; Antunes, C.H. Energy management systems aggregators: A literature survey. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1160–1172. doi:10.1016/j.rser.2017.01.179. [CrossRef]
145. Zhang, Y.; Gatsis, N.; Giannakis, G.B. Robust energy management for microgrids with high-penetration renewables. *IEEE Trans. Sustain. Energy* **2013**, *4*, 944–953. [CrossRef]
146. Liu, G.; Jiang, T.; Ollis, T.B.; Zhang, X.; Tomsovic, K. Distributed energy management for community microgrids considering network operational constraints and building thermal dynamics. *Appl. Energy* **2019**, *239*, 83–95. doi:10.1016/j.apenergy.2019.01.210. [CrossRef]
147. Sousa, T.; Soares, T.; Pinson, P.; Moret, F.; Baroche, T.; Sorin, E. Peer-to-peer and community-based markets: A comprehensive review. *Renew. Sustain. Energy Rev.* **2019**, *104*, 367–378. doi:10.1016/j.rser.2019.01.036. [CrossRef]

148. Li, Z.; Bahramirad, S.; Paaso, A.; Yan, M.; Shahidehpour, M. Blockchain for decentralized transactive energy management system in networked microgrids. *Electr. J.* **2019**, *32*, 58–72. doi:10.1016/j.tej.2019.03.008. [CrossRef]
149. Ahl, A.; Yarime, M.; Tanaka, K.; Sagawa, D. Review of blockchain-based distributed energy: Implications for institutional development. *Renew. Sustain. Energy Rev.* **2019**, *107*, 200–211. doi:10.1016/j.rser.2019.03.002. [CrossRef]
150. Haider, H.T.; See, O.H.; Elmenreich, W. A review of residential demand response of smart grid. *Renew. Sustain. Energy Rev.* **2016**, *59*, 166–178. doi:10.1016/j.rser.2016.01.016. [CrossRef]
151. Wang, W.; Hong, T.; Xu, X.; Chen, J.; Liu, Z.; Xu, N. Forecasting district-scale energy dynamics through integrating building network and long short-term memory learning algorithm. *Appl. Energy* **2019**, *248*, 217–230. doi:10.1016/j.apenergy.2019.04.085. [CrossRef]