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Perspective

A Perspective of Decarbonization Pathways in Future Buildings in the United States

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Abstract: The commitment of electrification and decarbonization goals in the United States (U.S.) will significantly change the performance of future buildings. To meet these goals, it is critical to summarize the existing research related to building electrification and decarbonization and discuss future research pathways. This paper provides a perspective on decarbonization pathways of future buildings in the U.S. A critical review of the existing research was conducted, which is divided into three closely linked categories: technologies, economic impacts, and code regulations. Technologies support investments and code regulations while marketing affects the design of building codes and standards. In the meantime, code regulations guide the development of technologies and marketing. Based on the review, future potential research directions for building decarbonization are then discussed. Due to the needs of building decarbonization, future research will be multidisciplinary, conducted at a large geographic scale, and involve a multitude of metrics, which will undoubtedly introduce new challenges. The perspective presented in this paper will provide policy-makers, researchers, building owners, and other stakeholders with a way to understand the impact of electrification and decarbonization of future buildings in the U.S.

Keywords: decarbonization; building; technologies; economic; marketing; code regulations

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1. Introduction

Decarbonization has become a critical research topic all over the world. For example, in the United States (U.S.), the transition of buildings, transportation, and other energy sectors from using fossil fuels to appliances, equipment, and vehicles powered by clean electricity is key to meeting the U.S. White House's commitment to 100% clean electricity by 2035 [1].

The U.S. Energy Information Administration (EIA) concluded that buildings accounted for approximately 39% of 2021 U.S. sector energy consumption [2] and approximately 35% of 2021 U.S. sector energy-related CO_2 emissions [3]. Specifically, residential and commercial buildings accounted for 19% and 16% of 2021 U.S. sector energy-related CO_2 emissions, respectively. Electricity was the primary energy source consumed in the residential and commercial sectors comprising 43% and 50%, followed by natural, accounting for 42% and 37%, respectively. Renewable energy resources accounted for a small fraction representing only 7% and 3% in the residential and commercial buildings, respectively [4]. Buildings, as a major energy consumer, are taking an important role in support of decarbonization. Furthermore, buildings contain the potential of improving energy efficiency and the flexibility of shedding and shifting energy consumption, which provides a manner to adjust energy use patterns [5]. Due to increasing distributed energy resources (DERs), e.g., solar power and wind power, the carbon emission factor for electricity generation becomes dynamic [6].

Adjusting energy use patterns potentially changes the CO_2 emissions in buildings, which makes buildings critical in decarbonization. In addition, by adopting behind-the-meter DERs, buildings are not only energy consumers, but also energy generators [7]. Using electricity generated by behind-the-meter DERs will further support decarbonization. Thus, it is important to study building decarbonization.

The U.S. White House has a decarbonization goal [1]. However, there is a lack of a summary by considering all key aspects of decarbonization pathways in future buildings in the U.S. Based on the literature review, especially documents from the U.S. government and national laboratories, we identified three key aspects for the decarbonization pathways in U.S. future buildings: technologies [8], economic impacts [9–11], and code regulations [12–16]. Figure 1 displays the theory for building decarbonization research. Rapid deployment of decarbonization will lead to significant challenges for the electricity grid and its consumers, technically and economically, which should be considered by policy-makers, stakeholders, and industry leaders when they develop possible pathways to the clean electricity target and analyze the impact on people's lives. In addition, current global challenges, such as climate change, energy shortages, and air pollution, greatly affect the decarbonization pathways in future buildings. Thus, building decarbonization is interdisciplinary research and has three aspects, technologies, economic impacts, and code regulations, that need to be considered. In the technologies aspect, building energy efficiency [17], building electrification [18], and grid-interactive efficient buildings (GEBs) [19] are all critical aspects in this research. In terms of economic impacts, cost-effectiveness (investment and payback period) [10,11] is necessary to be studied, which will be one of the motivations for building owners to decarbonize their buildings. Code regulations [12] for both existing buildings and new constructions are required and new policies need to be designed to guide the future of building decarbonization.

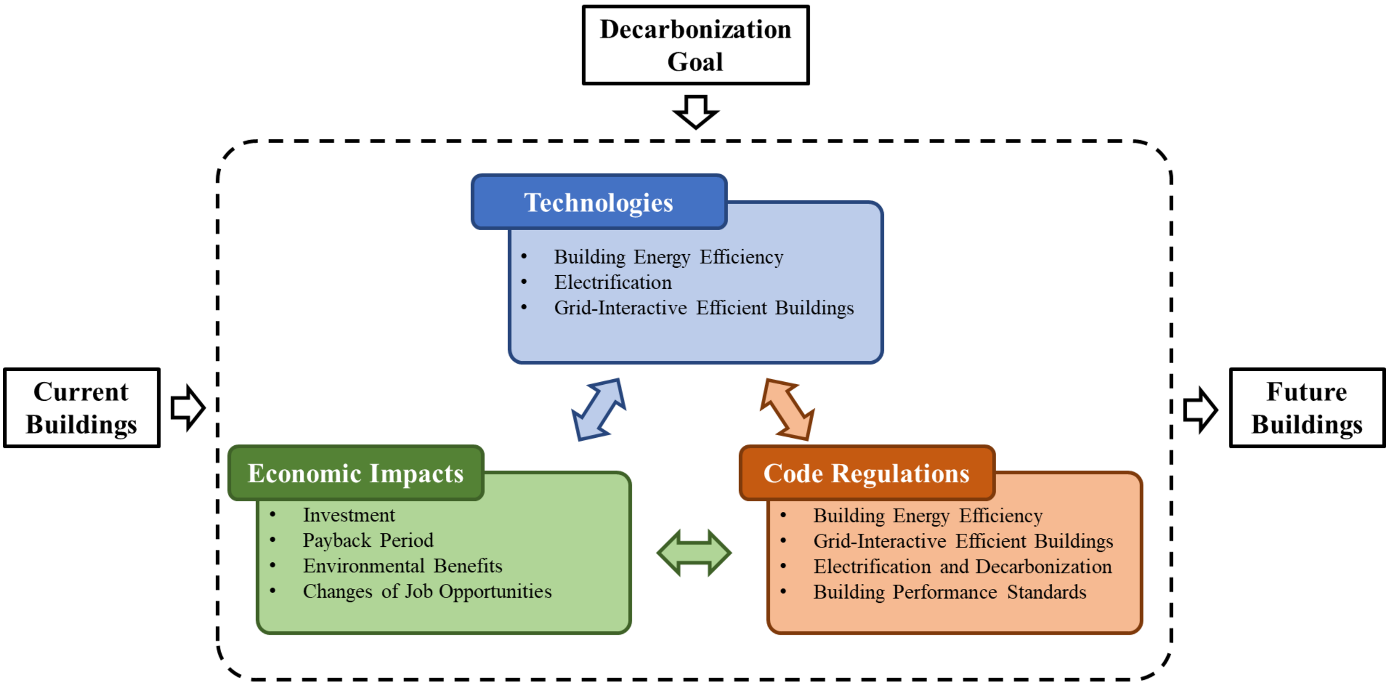


Figure 1. Theory for building decarbonization research.

In support of understanding existing research related to building decarbonization and future research directions, this paper provides a perspective of decarbonization pathways in future residential and commercial buildings in the U.S. This paper is organized as follows: Section 2 introduces technologies for the U.S. building decarbonization, including building energy efficiency, electrification, and GEBs; Section 3 introduces the economic impacts for U.S. building decarbonization, including investment, payback period, environmental benefits, and changes of job opportunities; Section 4 introduces the code regulations for the U.S. building decarbonization, including building energy efficiency, GEBs, electrification and decarbonization, and building performance standards; Section 5 discusses the potential future research directions; and Section 6 is the conclusion.

2. Technologies

To achieve building decarbonization goals, many technologies are being studied and adopted. This section introduces these technologies in three areas: building energy efficiency, electrification, and GEBs. Table 1 summarizes the reported technologies with example measures listed. Sections 2.1–2.3 will detail the technologies for energy efficiency, GEBs, and electrification applications, respectively.

Table 1. Summary of reported technologies suitable for energy efficiency, GEBs, and electrification applications.

Category	Technology (Example Measures)	Efficiency	GEBs	Electrification	References
Envelope	High efficiency glazing (Triple-pane, Argon filled)	√			[16,20–33]
	Dynamic glazing (Electrochromic, thermochromic glazing)	√	√		
	Automated attachment (Blinds, shades, drapes)	√	√		
	Green roofs	√			
	High performance insulation material (Vacuum insulation panel, gas filled panels)	√			
	Tunable thermal conductivity materials (Switchable insulation)	√	√		
	Thermally anisotropic systems	√	√		
	Trombe wall	√			
	Thermal storage (Phase change materials)	√	√		
	Moisture storage and extraction (Phase change humidity control materials)	√	√		
	Variable radiative technologies (Dynamic cool roofs)	√	√		
	Weatherization	√			
	Natural ventilation	√	√		
Heating, Ventilation, and Air Conditioning (HVAC)	Efficient HVAC systems (variable refrigerant flow [VRF], air and ground source heat pump [HP]))	√		√	[34–40]
	Energy recovery ventilators	√			
	Economizer	√			
	Smart thermostats	√	√		
	Controls for HVAC equipment with embedded T-stats		√		
	Liquid desiccant thermal energy storage		√		
	Hybrid evaporative precooling	√	√		
Water Heating	Efficient systems (HP)	√		√	[35,41–44]
	Solar water heater	√	√	√	
	Smart, connected controls	√	√		
	Dual-fuel water heaters		√		
Appliances	Efficient Appliances (ENERGY STAR)	√			[35,45–48]
	Efficient stoves (Electric and induction)	√		√	
	Efficient dryers (HP and Ultrasonic)	√		√	
	Advanced dishwasher and clothes washer controls		√		

Table 1. *Cont.*

Category	Technology (Example Measures)	Efficiency	GEBs	Electrification	References
Lighting	Daylight sensors	√	√		[28,49–52]
	Efficient lighting (LED)	√			
	Advanced sensors and controls	√	√		
	Hybrid daylight solid-state lighting (SSL) systems	√	√		
	SSL displays	√	√		
Behind-the- meter DERs	On-site photovoltaic (PV) (e.g., Rooftop PV)		√	√	[33,53–55]
	On-site battery storage		√		

2.1. *Building Energy Efficiency*

Energy efficiency is a key component of decarbonizing the energy sectors including the built environment. Considerable efforts have been devoted to enhancing energy efficiency in order to minimize the carbon footprint of buildings. There have been numerous studies that have evaluated the energy saving potential from energy efficiency measures (EEMs) in an effort to reduce the energy consumption of residential and commercial buildings [56,57]. Numerous EEMs have been proposed and promoted to be effective in enhancing energy efficiency as well as indoor environmental quality (IEQ) of the built environment. New buildings have a wide range of opportunities to achieve net zero energy building (nZEB) designs since they can easily adopt most of the EEMs. Recently, a large number of existing studies have focused on providing the best guidelines for nZEBs when designing residential and commercial buildings [41,58]. Furthermore, the existing building stock plays a crucial role in the ambitious goals for decarbonization that most states have adopted [59,60]. While existing buildings offer significant energy saving opportunities as they represent a large share of the building stock, special attention should be paid when considering energy efficiency retrofits for historic buildings to reduce energy use and maintain thermal comfort while preserving their heritage value [28].

There are a rich set of energy efficiency measures that have been reported in the literature, as listed in Table 1. Enhancing the performance of the building shell has been one of the earliest remedies considered to reduce energy consumption. Examples of popular envelope energy efficiency measures include increasing insulation levels, thermal mass, and air tightness, especially for shell-dominated structures [22,56]. Some of the proposed envelope EEMs can be easily implemented in existing buildings while others require deconstructive means. Moreover, a lot of emphasis has been given to enhancing the efficiency of HVAC systems since space heating, ventilation, and cooling comprise a large share of total residential and commercial energy consumption. The energy efficiency measures could be at the system, component, or control levels [36,61]. Lighting and equipment are major energy consumers, especially in commercial buildings. Their energy efficiency aspects focus on improving the efficiency of the systems and developing control strategies that can reduce the time of usage [46,51,52]. For instance, numerous studies revealed that the use of light emitting diode (LED) lamps can significantly reduce energy use compared to other lighting types. Furthermore, occupancy behavior is a critical factor that influences energy consumption in buildings. To improve energy efficiency, it is essential to integrate both behavioral change interventions, such as raising awareness and providing feedback on energy use, and technological solutions such as the use of occupancy sensors [62]. Studies have shown that utilizing occupancy-based sensors in building energy management can effective in reducing energy use [63].

2.2. *Electrification*

In the U.S., natural gas is the source of 23% and 20% of the total energy consumption in the residential and commercial sectors, respectively [64]. Almost half of U.S. homes use natural gas as the primary source for space and water heating. Electrifying the building sector in conjunction with decarbonizing the power sector is one of the key elements to achieving carbon neutrality targets. Electrifying the building sector means moving away from using fossil fuels (e.g., natural gas and oil) to electricity for operating building energy systems such as space and water heaters. Electrification enables long-term reductions of greenhouse gas (GHG) emissions, improves indoor and outdoor air quality and reduces carbon monoxide (CO) risks, as well as facilitates smart technology adoption [65]. California has been a leader in the U.S. in its commitment to decarbonization. The recently published Building Electrification Technology Roadmap (BETR) for the state of California outlines the technical status, identifies key barriers, and charts a course for progress in residential and commercial buildings [66]. For electrification to be deemed advantageous, it must satisfy at least one of three requirements without negatively impacting the other two. Those requirements include offering monetary savings for consumers, improved grid management, and minimizing detrimental environmental impacts [67]. Furthermore, the main technologies driving electrification include air and ground source heat pumps (HPs) for space heating and cooling, efficient electric and HP water heating solutions, induction stoves for cooking, as well as ultrasonic and HP for clothes drying. Electrification also unlocks opportunities for GEBs applications that relieves stress on the grid and improves occupants' experience through demand-side management (DSM) strategies.

2.3. Grid-Interactive Efficient Buildings

In the U.S., both supply and demand sides of the power grid evolve quickly. The sources of fuels used in generating electricity are shifting towards natural gas and renewable energy, including wind and solar. Further, a portion of the buildings' electricity demand is met by DERs such as solar photovoltaics (PV) that can also deliver excess electricity to the grid. The grid experiences periods of high demand that necessitates big investments to build new power plants [68]. Demand-side management offers strategies that can reduce, shift, or shed building loads while preserving adequate levels of service and comfort [69]. Stabilizing power systems is another aspect that buildings need to consider. GEBs can be defined as "energy efficient buildings with smart technologies characterized by the active use of DERs to optimize energy use for grid services, occupant needs and preferences, climate mitigation, and cost reductions in a continuous and integrated way" [19]. The benefits of utilizing DSM include reduced utility costs for the building owner and increased system reliability for the utility. Demand response (DR) can be dispatchable or non-dispatchable depending on who initiates the response action [19]. Non-dispatchable DR is activated at the building owner's discretion based on price signals (e.g., time of use electricity tariffs) while dispatchable DR responds directly to signals initiated by the grid operators or third part aggregators during peak events. Given the growing prevalence of GEBs, it is crucial to proactively address both passive (e.g., physical faults) and active (e.g., cyber attacks) threats associated with using control sensors and connected devices [70,71].

The most well-established and mature DSM resources are energy efficiency and demand response. Table 1 lists technologies suitable for GEB applications [25,35,51]. Examples of market-available dynamic envelope technologies that have high potential for GEB applications are dynamic windows, automated attachments, and thermal storage. Although these technologies can offer savings potential when applied individually, combining selective dynamic envelope technologies can further enhance their grid service capabilities (e.g., tunable thermal conductivity and thermal storage) [25,72]. Furthermore, other technologies, including separate sensible and latent space conditioning, as well as smart controls of water heaters, lighting, and HVAC have high potential to enable grid services with market-available technologies.

3. Economic Impacts

When implementing the technologies introduced in Section 2, the economic impacts need to be studied. This section introduces economic impacts from four areas, namely investment, payback period, environmental benefits, and changes of job opportunities.

3.1. Investment

Investment consists of two parts: initial investment and operation costs. Initial investments for decarbonization can include investments in electric equipment and infrastructure, including heat pumps, electrical panel upgrades, smart thermostats and controls, and more [73]. One study [73] estimated an incremental initial cost increase of $1000–$1700 for a single-family home. The same study also determined that an all-electric home was cheaper to construct by about $7500–$8200 than a mixed-fuel home because of the removal of fossil-fuel infrastructure. Energy efficiency upgrades, such as building envelope and HVAC system retrofits, can also reduce carbon emissions related to the building operation [57,74]. Buildings may invest in rooftop photovoltaics and/or battery energy storage systems, which can lower electricity costs [75] and lessen reliance on the grid [76]. There are associated operation costs with these systems in addition to the initial investment, such as taxes, insurance, maintenance, and more [77]. Financial incentives, such as tax credits, feed-in tariffs, investment subsidies, etc., can help offset some of these costs and promote investments [76]. Finally, beyond investments in buildings, larger scale infrastructure for renewable energy generation, electricity transmission and distribution are needed. One study [78] estimated annual average investments of $6.2 trillion per year until 2030 for low-carbon infrastructure in the U.S.

3.2. Payback Period

The payback period on investments in building decarbonization is an important consideration for building operators. There are several metrics for payback period calculations. First is the simple payback period, which is the time that savings, as a result from the investments, equal the initial investments [79]. Various studies have applied these metrics to building decarbonization studies. Depending on the scenario and investment, the payback period can range from less than a year to over 10 years [79,80]. Another metric is return on investment (ROI), which calculates the ratio of savings per initial investment. Lastly, life cycle cost analyses are commonly used to determine total costs including the initial investments and recurring costs for replacements, maintenance, etc. [81].

3.3. Environmental Benefits

The environmental benefits of building decarbonization are important to mitigating climate change, such as reaching global temperature targets of the Paris Agreement [82]. One study [73] estimated life cycle carbon emission savings of 126 MT CO_2e for an all-electric single-family home. Other studies have shown up to 17% reduction in life cycle carbon emissions for office buildings in Chile using energy efficient measures [83] and a 77% reduction in carbon emissions compared to a “worst case scenario” for buildings in China [84]. These studies demonstrate the significant potential of carbon emission reduction from buildings. Decarbonization of building energy systems can improve air quality and also lead to a reduction in other pollutants [85,86]. Finally, policies may incentivize the reduction in carbon emissions as well. For example, a carbon tax may push building operators to be more environmentally conscious and reduce their emissions [87].

3.4. Changes to Job Opportunities

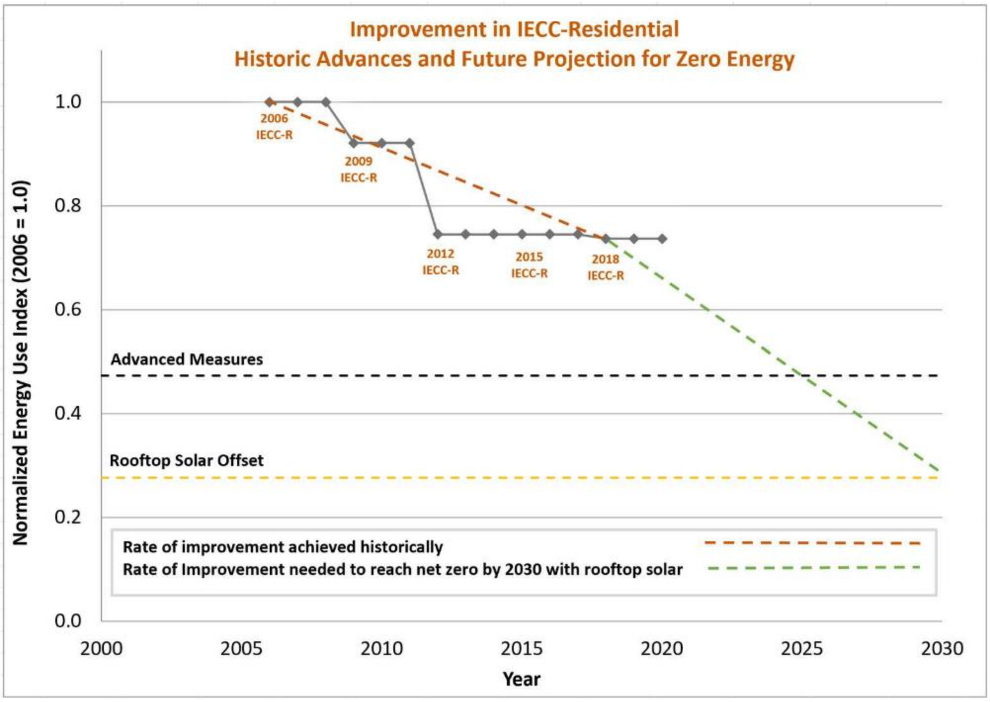
Building decarbonization will create new job opportunities, such as jobs related to developing and operating new energy infrastructure (e.g., more renewable energy jobs) [9]. Solar energy-related construction and installation show significant potential for providing new job opportunities. Additionally, many operation and management jobs will be needed for renewable wind energy infrastructure. There will be some jobs removed from the workforce as buildings and other infrastructure move towards decarbonization. This is expected to, at worst, create a small loss of jobs, but an expected net increase in jobs in the longer term. Overall, it is expected to have a less than 1% net change in total jobs in the current market.

4. Code Regulations

Due to the U.S. White House's commitment, building decarbonization has become more popular and affects building standards and codes that start to consider not only energy efficiency but also other factors, such as GEBs, electrification, and decarbonization. This section introduces the code regulations for four aspects, specifically building energy efficiency, GEBs, electrification and decarbonization, and building performance standards.

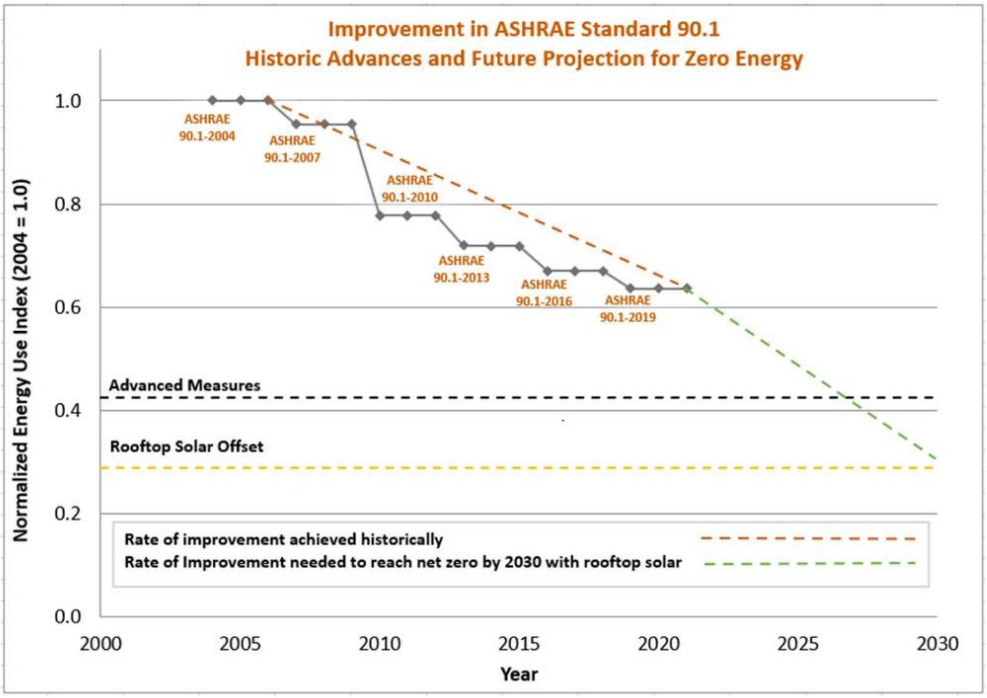
4.1. Building Energy Efficiency

Energy efficiency is one of the traditional criteria for evaluating the performance of buildings. Energy use intensity (EUI) reflects the annual energy consumption per area in buildings and is one of the key metrics to evaluate building energy efficiency. Building assets (e.g., envelope; lighting; heating, ventilation, and air-conditioning (HVAC) system; and service water heating (SWH) system) are the main contributors to building energy efficiency [88–90]. When evaluating a building's energy efficiency, we need to eliminate the impacts of unrelated aspects, e.g., location/weather, building geometry, unregulated loads such as high-performance computing sources, and building operation. Thus, normalized EUI is often used to evaluate building energy efficiency. Certain building energy codes and standards are used to regulate building designs to improve building energy efficiency. The ANSI/ASHRAE/IES Standard 90.1 [91] and International Energy Conservation Code (IECC) [92] are two popular building energy codes of this kind. In addition, there are advanced codes, which provide higher requirements, such as the ANSI/ASHRAE/IES Standard 189.1 [93] and Advanced Energy Design Guides [94]. Figure 2 displays historical and needed advances to achieve zero energy buildings for both residential and commercial buildings in the U.S. [13]. Policy-makers continue to push building energy efficiency improvements in newer editions of related building energy codes and standards.



(**a**) Residential buildings

Figure 2. *Cont.*



(**b**) Commercial buildings

Figure 2. Chronological estimate of the performance of various codes [13]. Reproduced with permission from Battelle Memorial Institute, 2022.

4.2. Grid-Interactive Efficient Buildings

GEBs are regulated in building codes and standards. Buildings have significant power flexibility to make contributions to grid-side optimization. Figure 3 displays the building flexibility load curves (efficiency, load shed, load shift, and modulate) [19]. With the development of DERs, e.g., PV and battery, power systems face new challenges, such as the duck curve issue, which is caused by the imbalance between the peak demand and renewable energy generation [95]. Building flexibility load curves provide one solution to solve or relieve these challenges.

In the current code regulation process, electricity tariffs are commonly used to regulate operations in buildings [96]. Time-of-use rates are one of the popular electricity tariffs. Different electricity unit retail prices are designed for time periods. Electricity unit retail price is high during the critical-peak or on-peak period while it is low during the off-peak period [33,96], which provides motivations for building operators to regulate building operations. The U.S. utility rate database provides more details: https://apps.openei.org/USURDB/ (accessed on 7 March 2023).

4.3. Electrification and Decarbonization

Due to the U.S. White House's commitment to 100% clean electricity by 2035 [1], there will be rapid deployment of electrification in the U.S. Figure 4 provides estimates of generation across the suite of scenarios by fuel type [97]. The usage of renewable energy, e.g., solar and wind, will be significantly increased in 10 years if we pursue the goal for 100% clean electricity by 2035. This process will significantly impact operations for end uses and power systems. To optimize this process, it is necessary not only to study different electrification and decarbonization pathways, but also to regulate the deployment process. Code regulations will play an important role in regulating existing buildings' retrofits, new construction development, and building operations in the future. Due to the needs of the energy source changes, future code regulations will provide requirements and recommendations for future building energy systems and take deeper consideration of GHG emissions.

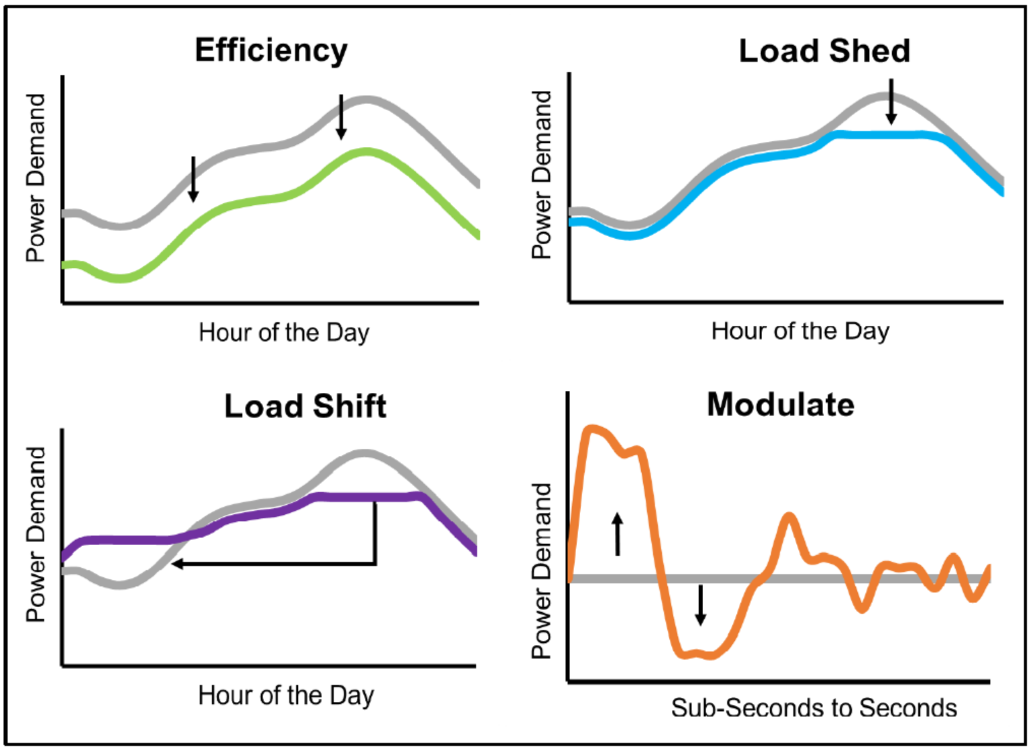


Figure 3. Building flexibility load curves [19]. Reproduced with permission from the U.S. Department of Energy, EERE, 2019.

4.4. Building Performance Standards

Building performance standards (BPS) are emerging outcome-based policy tools for jurisdictions, which aim at reducing the carbon impact of the built environment [15]. BPS require existing buildings to meet increasingly stringent energy and/or GHG emission-based performance targets and to improve their performance throughout their lifetime. In addition, BPS are also able to be combined with other building codes for new constructions and major renovations, which will empower governments to deliver on their energy and carbon goals for the building sector.

To develop BPS, metrics are needed to evaluate building performance and normalization methods are needed to eliminate the impact of factors not related to building performance (e.g., climate and building operation) on the evaluation result [12]. Selecting a suitable metric and a normalization method is important to simplify the evaluation process and obtain a non-biased evaluation result. The U.S. Environmental Protection Agency (EPA) recommended metrics (site EUI and GHG emission) and normalization methods for BPS, which provides a guidance on making suitable selections [98].

Figure 5 displays the status of BPS in the U.S. The green color means that the state/local government adopted BPS by using GHG emissions as the metric; the blue color means that the state/local government adopted BPS by using energy as the metric; the yellow color means that the state/local government is developing BPS; and the red color means that the state/local government considers adopting BPS. Besides different performance metrics, the BPS in these states and cities include different building types, scope expectations, compliance options, implementation timelines, and emission reduction goals. The details are displayed in [99].

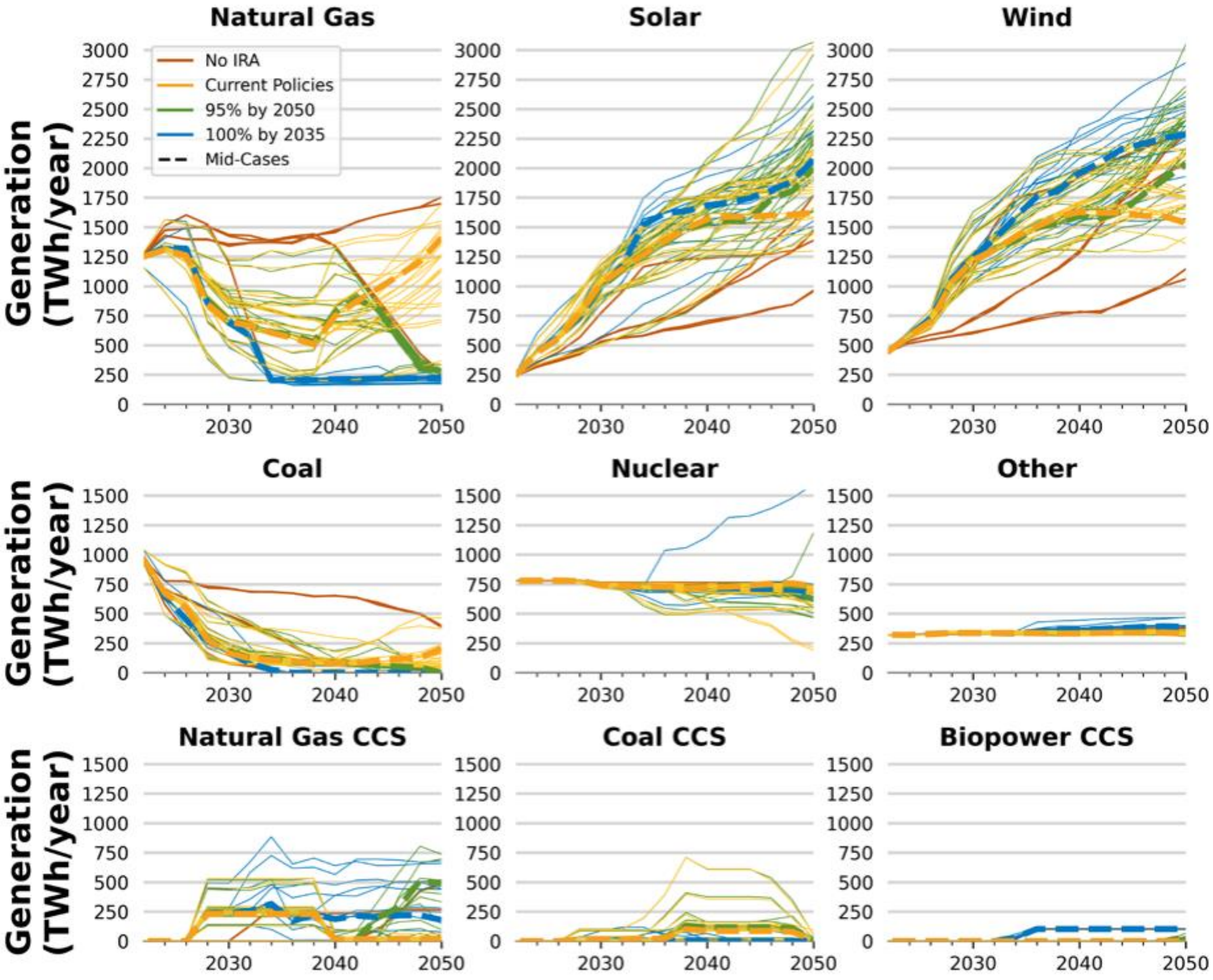


Figure 4. Generation across the suite of scenarios by fuel type [97]. Reprinted with permission from the National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy23osti/84327.pdf (accessed on 7 April 2023).

There are tools and resources that are useful for BPS studies [100]. Data sources include benchmarking data (e.g., ENERGY STAR score [101]), audit data, tax assessor data, and survey data (e.g., CBECS [102] and RECS [103]). ENERGY STAR Portfolio Manager [89] is one example of the tools that can be used for BPS. This tool provides benchmarking for evaluating building performance and ENERGY STAR score as the performance metric. Physics-based building energy modeling approaches are also useful for the BPS studies in support of policy design. For example, ComStock [104] and ResStock [105] can develop county/city/state-scale stock building energy models. DOE Commercial and Residential Prototype Building Models [106] provide detailed building energy models for different building types and climate zones. These models can be used for normalization and study of the electrification/decarbonization retrofits to meet the BPS targets.

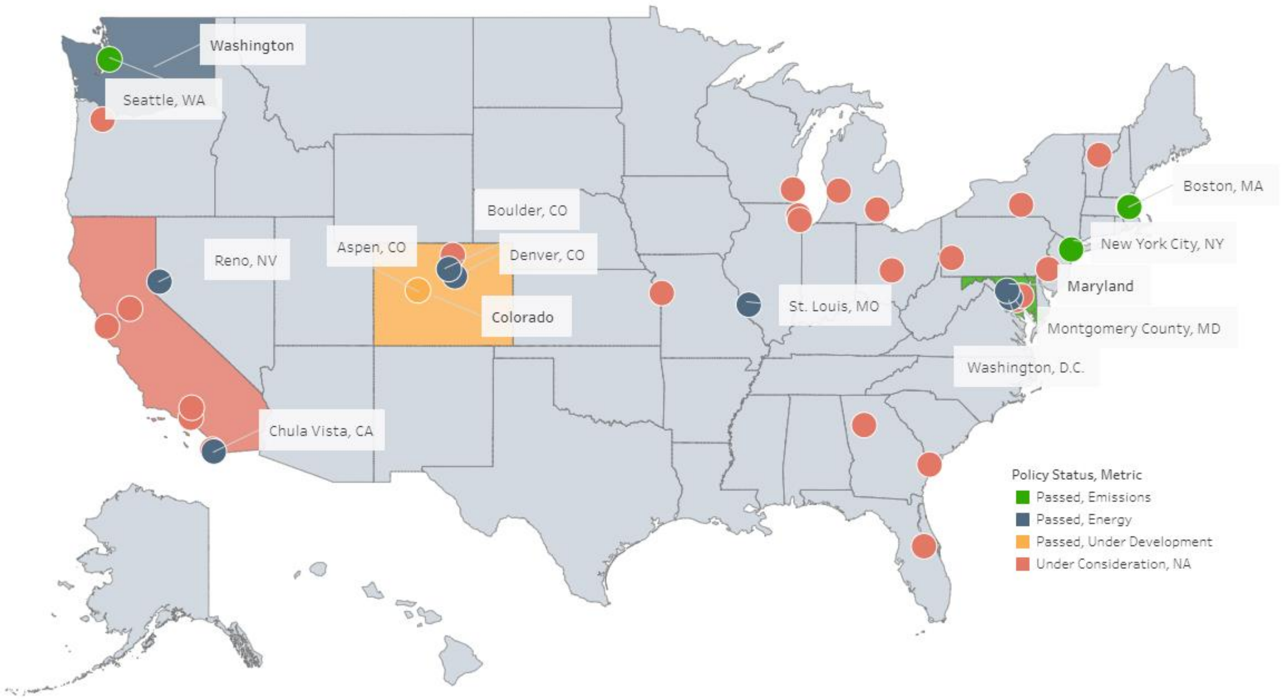


Figure 5. BPS status in the U.S. [99]. Reproduced with permission from Battelle Memorial Institute, 2022.

5. Discussion

This paper studies the existing research on the decarbonization pathways in future buildings in the U.S. from three aspects: (1) technologies, (2) economic impacts, and (3) code regulations. Based on this study, this section provides a perspective about potential future research directions of building decarbonization:

Future research will make more effort on a large geographic scale, such as the community-scale, urban-scale, and nationwide studies. Studies at a device level or whole building level focus on improving the performance of a specific device or building. However, future research will consider the aggregated impact of a set of buildings and optimize a whole system including buildings, power grid, and other sectors. For example, a connected community study will conduct optimization at a community level and energy will be shared between buildings, which optimizes the aggregated load profile [107]. Building–grid integration research optimizes the aggregated load profile for buildings, which improves the performance of both building and grid sides [7,19]. Studying how buildings within a community share energy with each other, for example selling green energy from one building to another, can improve energy load management. However, there are associated uncertainties with this energy sharing, so assumptions about the availability of building resources need to be made to assess this scenario.

The future research will be multidisciplinary. There will be more connections between the building stock sector and other sectors (e.g., transportation sector and industry sector) in the future. For example, the transportation sector heavily researches electric vehicles (EV) [108–110]. As EV chargers are installed in buildings, the optimization of electricity consumption for EV chargers needs to be studied in buildings. In addition, behind-the-meter DERs are installed in buildings. Buildings are not only energy consumers, but also energy generators, which may impact grid operation strategies [111]. Thus, building–grid integration also needs to be studied. Furthermore, future climate changes will affect building resilience, and microclimate studies need to be considered in future building decarbonization research. In addition, other aspects, such as economic and environmental impacts, also need to be studied.

Future research will generate a systematic way to evaluate the overall performance of buildings by considering multiple metrics. In the current building performance evaluation process, energy consumption (e.g., energy use intensity) and GHG emission/CO_2 emission are the two popular metrics [98]. Cost-effectiveness and indoor environmental quality are often considered in this process as well. To evaluate future building performance, other metrics, such as energy equity and changes in job opportunities, also need to be considered. In addition, due to multiple metrics, a systematic way to evaluate the overall performance of future buildings becomes a critical research direction.

Future research will face new challenges. The first challenge is about collaborations between different domain experts. It is necessary to determine who needs to take charge of a certain part and how to connect different parts together. For example, the following questions need to be answered: (1) Is EV studied by building energy or transportation experts? (2) Are behind-the-meter DERs studied by building energy or power system experts? And (3) How can the whole system be optimized, including different end-use sectors and power grid? The second challenge is to determine suitable modeling approaches, which are able to balance between efforts for modeling/simulation and accuracy of the simulation results. A system modeling approach needs to be designed [112]. The last challenge is to evaluate the overall performance by considering multiple aspects and based on multiple metrics.

6. Conclusions

This paper conducts a perspective on decarbonization pathways in U.S. future buildings based on a review of existing research. This review consists of three aspects: (1) technologies, (2) economic impacts, and (3) code regulations. Based on the review, this paper discusses the future potential research directions for building decarbonization in the U.S., which will be large-scale and multidisciplinary research, consider multiple metrics, and face new challenges. This paper will support policy-makers, researchers, building owners, and other stakeholders to understand the impact of electrification and decarbonization to future buildings on the U.S.

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