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Review

Review of Adoption Status of Sustainable Energy Technologies in the US Residential Building Sector

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Abstract: In this paper, a review of the adoption status of energy efficiency and renewable energy technologies is presented, specific to US residential buildings. Various technologies are reviewed and categorized as either their relative "higher adoption" or "lower adoption" rates within the US housing stock. More importantly, the review analysis investigates the main factors associated with their high or low adoption rates. Specifically, the paper provides a background of the historical progression of energy efficiency programs as well as sustainability certifications and standards for buildings. The review then analyzes specific building energy efficiency and renewable energy technologies applied to US residential buildings and their adoption rates. The review analysis indicates that building technologies are more frequently adopted for multiple reasons including requirements by codes and standards, incentives through green certifications, low implementation costs, and acceptance and popularity by the public. In contrast, technologies with low adoption rates have higher payback periods, are not required or highly incentivized through codes and certifications, have limited promotion about their benefits, or are not compatible with existing systems. By determining the reasons for the high and low adoption rates, mitigation options can be identified to increase the application of sustainable energy technologies in designing and retrofitting buildings.

Keywords: adoption rate; energy efficiency; green certifications; net zero energy buildings; residential building sector; sustainability

Citation: Schwartz, E.K.; Krarti, M. Review of Adoption Status of Sustainable Energy Technologies in the US Residential Building Sector. *Energies* **2022**, *15*, 2027. https://doi.org/10.3390/en15062027

Academic Editor: Fabrizio Ascione

Received: 15 February 2022
Accepted: 9 March 2022
Published: 10 March 2022

1. Introduction

The United States (US) building sector is responsible for 40% of the national energy demand and 40% of national CO_2 emissions, according to the US Energy Information Administration (EIA) [1,2]. These levels represent the largest energy and CO_2 contributions of any sector. In particular, residential buildings account for 21% of US energy consumption, with over 60% attributed to space and water heating end-uses, as shown in Figure 1 [3]. The high energy demand, in tandem with the growing climate crisis, growth in population, and increase in global access to reliable power, is causing an energy supply crisis [4].

A wide range of efficient and renewable technologies have been developed over the last few decades specifically to enhance the sustainability of the built environment. Some of these sustainable energy technologies have the potential to significantly reduce the energy and carbon impact of the sector on the environment. However, the deployment rates of several technologies are rather limited for both residential and commercial buildings in the US [5].

Similar studies on adoption rates of sustainable technologies have been conducted in different sectors and countries. For the agricultural sector, there have been specific studies carried out for Brazil, Ireland, and Nigeria [6–8]. These studies concluded that adoption rates of sustainable technologies depend on several factors including but not limited to awareness, social norms, education, soil conditions, capital cost, labor costs, and policy. For the water, sanitation and hygiene sector, studies on sustainable technology adoption for gray water and water management indicated that measures such as awareness, satisfaction, affordability, and policies can increase adoption rates [9,10]. For the energy sector, the identified factors causing slow adoption rates of sustainable technologies are market pressure, technology capabilities, procurement experience, certified systems, capital costs, and stakeholder decision making [11,12]. However, no reported analysis has considered specific adoption rates of sustainable energy technologies for the US residential building sector.

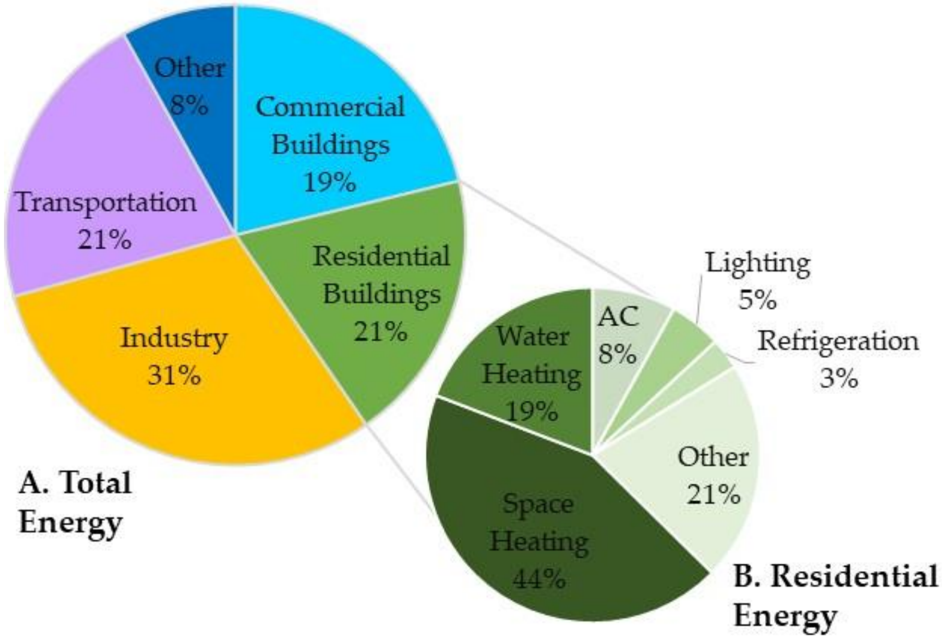

Figure 1. Breakdown of energy usage in the United States (**A**) by sector and (**B**) by end-use for residential buildings. Buildings use 40% of the total energy in the US with residential buildings being responsible for 21%, space heating for 44%, water heating for 19%, air conditioning for 8%, lighting for 5%, refrigeration for 3%, and the other 21% is the total energy used by residential buildings (data source: [3]).

The main goal of the review analysis presented in this paper is to identify the major reasons for the slow adoption in the US residential building sector of available energy efficiency and renewable energy technologies. With a better understanding of the factors and drivers for a technology to be widely accepted, market stakeholders can direct their efforts to target strategies that enhance the adoption of impactful sustainable energy technologies. Table 1 lists the technologies covered in the review analysis summarized in this paper, their rate of adoption, and reasons for their slow or faster penetration in the US market.

Table 1. Sustainable energy technologies considered in the review analysis.

Technology	Adoption Rate	Reasons for Adoption	Reasons Against Adoption	Section
Envelopes/Insulation	~100% [13]	IECC code, certification incentives, financial incentives, social norm	Slow code adoption updates	Section 4.1
Efficient Appliances	~50% [14]	IECC code, certification incentives, financial incentives, social norm	Slow code adoption updates	Section 4.2
Photovoltaics	12.9% [15]	Code, certification incentives, financial incentives, social norm (based on location)	Financial cost, knowledge, accessibility	Section 4.3
Smart Windows	2.4% [16]	Financial incentives	Lack of code, knowledge, financial cost	Section 5.1

Table 1. *Cont.*

Technology	Adoption Rate	Reasons for Adoption	Reasons Against Adoption	Section
Electric Vehicles	1.4% [17]	Financial incentives, environmental morals, electrification	Lack of code, knowledge, financial cost, vehicle charging	Section 5.2
Storage Solutions	1.5% [18,19]	Financial incentives, electrification, resiliency	Financial cost, lack of need	Section 5.3
Heat Pumps	8.7% [20]	Financial incentives, environmental morals, electrification, health	Lack of code, knowledge, financial cost, no social norm, compatibility	Section 5.4
Geothermal Systems	4% [21]	Financial incentives, environmental morals, electrification, health	Lack of code, knowledge, financial cost, no social norm, compatibility	Section 5.5

In this paper, Section 2 discusses the history of sustainable residential technologies, human rationale, and decision-making processes, as well as available policies and programs to foster the construction of high-performance buildings. Section 3 lists energy technologies that are already commonly adopted and the reasons for their fast penetration in US buildings. Section 4 addresses technologies that have limited adoption rates and the main hindrances for their acceptance by US households. Lastly, Section 5 compares the rates of adoption of various energy technologies in US residential buildings and possible pathways for their wider adoption in US residential buildings. The conclusions outlined in Section 5 summarize effective measures such as lower fiscal incentives, brand recognition, and legal requirements, which foster higher adoption rates, as well as common factors such as lack of knowledge, higher initial costs, and fewer historical and legal precedents, which result in lower adoption rates.

2. Materials and Methods

The review analysis conducted for this study relies solely on studies and statistics reported for a specific set of energy efficiency and renewable energy technologies available for US residential buildings. These technologies are listed in Table 1 with their adoption rates in US households based on data reported by the indicated references. The listed technologies are selected based on the availability of data as well as to represent the most promising energy efficiency and renewable energy systems that can reduce the various end-uses of US residential buildings, as illustrated in Figure 1. The analysis includes a brief overview of the history of sustainability in the built environment, human decision-making factors, and existing certifications for residential buildings, as noted in Section 3. Then, the main factors and drivers are identified for each of the higher and lower adopted technologies, as detailed in Sections 4 and 5, respectively. The main findings of the review analysis are summarized in Section 6.

3. Background

3.1. History of Sustainable Buildings

The "green" movement started in the 1950s as a result of the great smog from the UK [22]. However, the main incentive for increased awareness of sustainability and energy efficiency in the building sector can be traced back to the oil crisis of 1973. Indeed, the interest in designing low-energy and passive buildings was initiated during the 1970s [22]. By the 1980s, Building Information Modeling (BIM) technology introduced both passive and active energy-efficient technologies for buildings [18]. As energy efficiency and renewable energy technologies have improved and their costs have lowered, the design and operation of Net Zero Energy Buildings (NZEB) are becoming technically and economically feasible and even required by some standards and building energy efficiency codes [22]. However, several definitions exist for NZEB, depending on the implemented technologies and interactions with the grid.

There are five renewable options, as Wu and Skye [23] prescribe, in order, for homes:

- Option zero: a house design where no energy is needed. This option is also known as a completely passive house design.
- Option one: a house powered by roof-mounted renewable sources.
- Option two: a house powered by onsite renewable energy.
- Option three: a house that is powered by onsite biomass fuel.
- Option four: when a house is connected to a renewable-energy-powered grid.

There are many design approaches to achieve NZEB status, as outlined in Fanney and Healy [24]. The umbrella term of NZEB can encapsulate improving building envelope systems, using energy-efficient appliances, deploying renewable energy generation, or a combination of the three. According to NREL, an "NZEB is a building with greatly reduced operational energy needs" [25]. Regardless of how it is achieved, the building sector must have 62% or more NZEB to offset all carbon dioxide (CO_2) emissions, according to a case study carried out for Boulder, Colorado, US [26,27].

The other current trends in sustainable buildings involve electrification or decarbonization, as well as dynamic grid integrations. By adding renewable technologies onsite and eliminating non-electric fuel sources, buildings can produce their own electricity directly, with any excess power to be supplied to the grid or be stored onsite. Thus, the electrification of buildings requires the use of electric heating systems, as well as the deployment of onsite renewable sources. Electrification is already economically feasible in many US regions, as demonstrated by reported case studies including residential communities in Midland, Texas, US, which has the potential to save 18.35% electricity and 21.33% fuel—a total of USD 52,866 annually [28]—as well as urban districts in Philadelphia, PA, which has the potential to save 14% energy and 18% carbon emissions, lowering the life cycle cost by 3.5% [29].

Today, there are a myriad of energy efficiency and renewable energy technologies that can be incorporated to achieve NZEB and electrification status for buildings. While they are cost-effective, most energy technologies have not been widely deployed due to a wide range of factors, including those related to human behavior and decision rationale.

3.2. Human Behavior and Influences

While Table 1 lists the reported adoption rates of various energy efficiency and renewable energy technologies suitable for US buildings, it is important to discuss the main reasons why these technologies have or have not been accepted by US households. While there is no singular reason, psychology and social norms can be a significant driver for the adoption of sustainable technologies. Psychology is defined as attitudes, beliefs, values, culture, habits, preferences, social norms, awareness, and self-efficacy [30]; social norm is defined as "any of the socially determined consensual standards that indicate (a) what behaviors are considered typical in a given context and (b) what behaviors are considered proper in the context" [31]. Behaviors are extended to actions and purchases. Demographics and behavioral characteristics of households are found to be well-correlated to the adoption level of sustainable solutions. Some of these demographic features include number of people per household [30,31], number of children [30,32], age of users [30,32], educational level [30,32], social and economic status [30,32,33], type of home [30,32,33], energy consumption [32], employment status [33], number of appliances [31,32], and ownership or renting status [33]. For instance, Nie et al. compare renters' and owners' willingness to implement energy-efficient measures (EEMs). The correlation between implementation of EEMs is found to be linked closer to the cost of the EEMs and who pays for the utility bills, rather than the ownership status [34]. The household attributes that most accurately correlate to energy-saving actions are socioeconomic status, square footage of home, and environmental beliefs. Indeed, knowledge of socioeconomic status, size of home, and beliefs facilitates the prediction of whether a household would or would not adopt an efficient technology [34]. The other demographic characteristics have less impact on the adoption rate of EEMs.

Members of households have been assessed by their psychology. Household assessments are performed using various approaches such as:

- Social cognitive theory, pertaining to social influences on choices and behaviors [35];
- Social norms theory, pertaining to social actions and environmental influences [35];
- Theory of reasoned action, pertaining to subjective norms to determine intentions to fulfill a behavior [31];
- Theory of planned behavior, pertaining to subjective norms acting as a perceived behavioral control [31];
- Goal-oriented behavior model, pertaining to achieving a particular goal [31];
- Norm activation theory, pertaining to altruistic and environmentally friendly behaviors [36];
- Self-regulated behavior change theory, pertaining to the changing of an individual's behaviors through four sequential stages [37];
- Achieving events–beliefs–consequences (ABC) theory, pertaining to cognitive behavior therapy, and thought processes of set goals [38].

Similar to the evaluation approaches for identifying the demographic characteristics, these different theories then can help better understand how households and people make decisions, specifically pertaining to energy use, both in terms of type and quantity.

With better understanding of the correlation between demographical and psychological characteristics and decision making, properly designed energy policies and programs can assist in convincing people and households to opt for more sustainable solutions [39]. In order to have effective energy policies to promote sustainable technologies, it is important to use positive (e.g., incentives) or negative (e.g., taxes or fees) influences to draw the intended audience towards pro-environmental behaviors [40]. One means of doing so is policy writers and decision makers promoting pro-environmental actions via the utilization of smart technology so each user knows their energy use and can make educated decisions about which technologies to invest in and how much energy each appliance uses [41]. For instance, if a user knows that a portable air conditioner has high energy consumption levels, they may be more inclined to use less air conditioning. Similarly, if the user's utility has a tiered pricing rate with the cost of electricity being cheaper at nighttime, the user may operate the dishwasher at night, rather than during daytime corresponding to peak hours. To quantify these actions and give feedback to energy users, Source [42] develops a methodical system to rank and weigh options and make sustainable choices more rational. In this way, human behavior can be quantified through usage data.

Another driver for making energy-efficient decisions is social influence, which can come in the form of norms, community examples, and standards. As social creatures, humans are easily influenced by their companions and peers [43]. With an understanding of social norms, this establishes a baseline for changing and influencing energy users towards a new norm of sustainability [43]. By having a better idea of how humans make decisions, it is easier to determine which policies and programs are effective to ensure that sustainable technologies succeed in penetrating the market.

3.3. Sustainability Policies and Programs

Using basic behavioral psychology principles, several organizations are attempting to incentivize the construction of greener buildings using a set of sustainability certifications and rating programs. There are both gubernatorial and non-gubernatorial policies, ranging from carbon goals, to grants, to tax incentives. Table 2 includes a small set of examples for national polices in Western Europe and the US [44]. In the US, individual states set their own policies and incentives, with the number and type of adopted programs varying by state. Figure 2 illustrates the number of enacted policies and incentives promoting sustainable buildings for various US states [45].

Table 2. Policies and incentive programs in US and Europe [44].

Country	Name of Program	Type	Description	Date	Ref.
EU	Energy efficiency directive	Goal	Lower energy usage by 32.5%	By 2030	[46]
EU	EED Article 7	Goal	EEM schemes for distributors and sales to lower 1.5%	2014–2020	[47]
France	Credit energy transition scheme	Tax	30% credit for thermal installation and upgrades	2014–	[48]
France	Interest-free eco-loan (Eco-PTZ)	Loan	EUR 30,000 for EEM refurbishments	2009–	[49]
Germany	Energy-efficiency program	Loan	Homeowners up to EUR 120,000 for CO_2 reduction and EEM	1996–	[50]
Italy	Thermal account (conto Termico)	Grant	65% cost for EEM, renewable thermal energy installation	2013–	[51]
Italy	Energy loan fund (Plafond Casa)	Loan	Purchasing energy-efficiency new homes and EEM	2014–	[52]
Poland	Thermo- modernization fund	Grant	20% of loan for EEM or renewable heating installs	2009–	[53]
Poland	Anti-smog clean air program	Loan	Financing for retrofits and renewable heating installs	2018–	[54]
Romania	Thermal rehabilitation program	Loan	Retrofits and upgrades of heating systems	2006–	[55]
Spain	PAREER- II grant program	Grant	Retrofits and upgrades of heating systems	2018–2020	[56]
Sweden	Tax deduction	Tax	30% of install and labor costs to install EEM	2008–	[57]
Scotland	Home Energy Efficiency	Loan	Interest-free up to EUR 10,000 for EEM	2013–	[58]
N. Ireland	Better Energy Homes Scheme	Grant	Up to EUR 10,000 for EEM retrofit and heating systems	2009–	[59]
UK	Affordable Warmth Scheme	Grant	For low-income households who are energy poor	2014–	[60]
UK	Boiler Replacement Scheme	Grant	For low-income households to replace 15+ year-old boilers	2014–	[61]
US	EnergyStar tax credits	Tax	Credit for builders of energy-efficient homes	2021–	[62]
US	EnergyStar tax credits	Tax	Credit for residential renewable energy products	2023–	[63]
US	DOE federal energy management	Rebate	For EEM. Renewable technology, and water conservation	2008–	[64]

In addition, professional organizations have established rating and labeling programs to encourage designers and owners to enhance the sustainability of buildings, which can result in higher property value or prestige. Different sustainability aspects are covered by these rating programs, ranging from the use of recycled materials, environmental integration, reduced embodied energy, improved indoor quality, to lowered energy demand. Despite the advertised cost savings associated with these programs, Olaussen et al. state that these energy performance certificates and rating programs do not directly correlate to a higher price premium because of the inconsistencies across the various regulations [64]. Moreover, the energy performance of buildings varies significantly, depending on the stringency and prescribed criteria of each certificate and rating system [64]. Figure 3 shows the ranking of the various certifications, codes, and standards ranging from least energy use to most energy use.

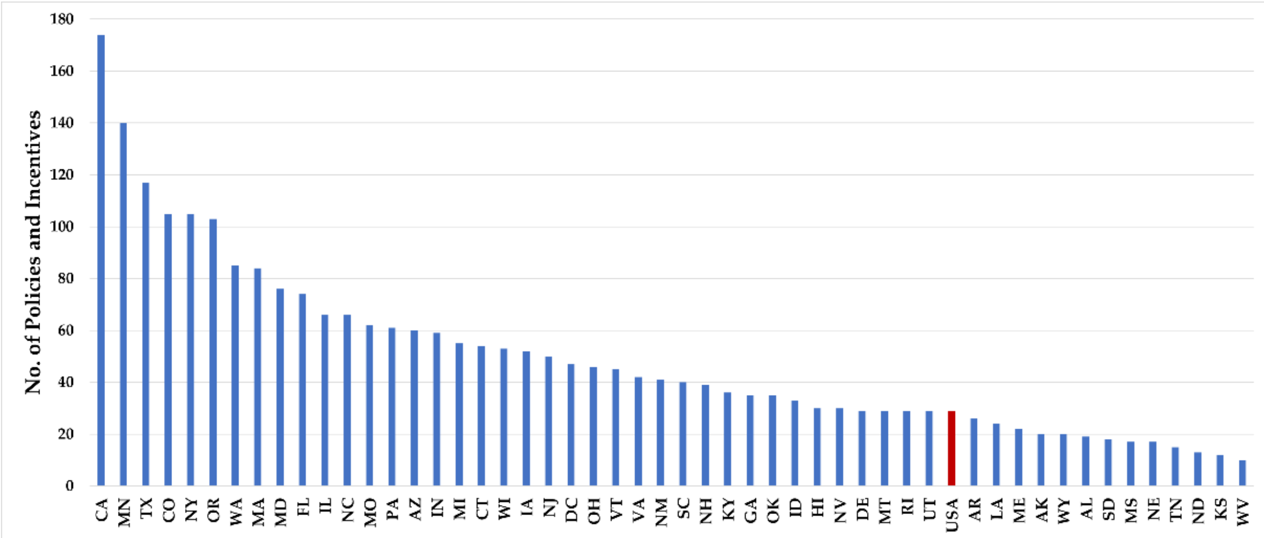

Figure 2. Number of policies and incentives by US state. The enacted policies vary by state, with California having the highest number of policies (176) and West Virginia having the lowest number of policies (10). The federal government, highlighted in red, is ranked 39 with 29 policies (data source: [45]).

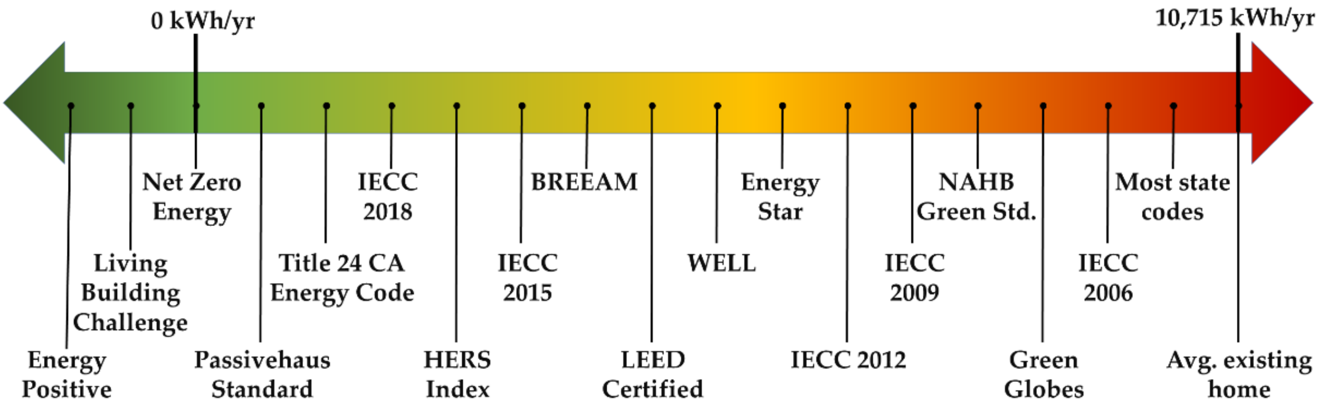

Figure 3. Ranking of energy certificate policies and standards. Each policy/standard is ranked from least energy use potential to most energy use potential. The standards range from energy positive at less than 0 kWh/year to the average US existing home of 10,715 kWh/year (data source: [65]).

Examples of such certificate programs specific to sustainable buildings include:

- Building Research Establishment Environmental Assessment Methodology (BREEAM) (UK) for sustainability rating of master planning projects, infrastructure, and new and renovated buildings with a special focus on environmental life cycle [66].
- EnergyStar (US) a certification given to not only appliances, but buildings based on their energy-efficiency and annual savings [67].
- Green Globes by Green Building Initiative (Canada) using a web-based certification with a focus on energy efficiency [68].
- Home Energy Rating System (HERS) index by Residential Energy Services Network (RESNET) (US) for inspecting and rating a home's energy performance [69].
- Leadership in Energy and Environmental Design (LEED) (US) for renovated and new buildings covering embodied energy, energy efficiency, and resiliency [70].

- Living Building Challenge by the International Living Building Institute for a strict rating on energy and water usage, integration with agriculture, and toxicity levels [71].
- National Association of Home Builders (NAHB-Green) (US) a residential sustainability certification program based on estimation of potential of energy savings [72].
- Passivhaus Institute (Germany) for rating a building's ability to be passive based on its energy performance [73].
- WELL Certificate from the International Well Building Institute (IWBI) for measuring human health and well-being within a structure based on its operation and performance [74].

To meet the criteria set by any of the certification programs described above, buildings must incorporate different energy efficiency and renewable energy technologies. Historically, some of these technologies have been adopted at much faster and higher rates than others, as discussed in the following sections.

4. Highly Adopted Technologies

The technologies that are deemed to be "highly adopted"—that is, deployed by over 10% of the US population—include passive heat retention strategies, energy-efficient appliances, and renewable energy systems. While the list of technologies considered in this section is not exhaustive, it serves as a set of good examples of commonly adopted sustainable technologies by US households.

4.1. Building Envelopes

According to the International Building Code, every US residence must have some amount of thermal insulation in at least exterior walls and roofs to increase the overall energy efficiency of the building [75]. The specific level of thermal insulation depends on the design goal of the building, including meeting only the building code minimum requirement or targeting a special certificate such as those described in Section 3.3. One case study is Healy et al. [24], who describe the construction details of a net zero energy home built in Gaithersburg, Maryland by the National Institute of Standards and Technology (NIST). In particular, the exterior walls were made up of extra sheathing, membranes, and rigid insulation with a total R-value of 45 ft·hr·°F/Btu (7.92 m^2·°C/W). In addition, their windows have an R-value of 5.2 ft·hr·°F/Btu (0.92 m^2·°C/W). Moreover, the home is airtight with an air change rate per hour of 0.09 at 50 Pascals. While most homes do not have such high R-values, building and energy codes are consistently becoming more stringent with higher requirements for thermal insulation levels. Table 3 shows the increase over the last three recent updates in R-value requirements for residential ceilings in various climate zones, as defined by the International Energy Conservation Code (IECC). Figure 4 identifies the US climate zones.

Table 3. Ceiling R-values by climate zone and year required by IECC [75].

Climate Zone	2006–2009 R-Value (ft·hr·°F/Btu)/(m^2·°C/W)	2012–2018 R-Value (ft·hr·°F/Btu)/(m^2·°C/W)	2021– R-Value (ft·hr·°F/Btu)/(m^2·°C/W)
1	30/5.28	30/5.28	30/5.28
2	30/5.28	38/6.69	49/8.63
3	30/5.28	38/6.69	49/8.63
4	38/6.69	49/8.63	60/10.57
5	38/6.69	49/8.63	60/10.57
6	49/8.63	49/8.63	60/10.57
7	49/8.63	49/8.63	60/10.57
8	49/8.63	49/8.63	60/10.57

According to the US Department of Energy (DOE), 11 states follow the 2018 IECC, 28 follow the 2009 IECC version, 4 follow the pre-2009 IECC, and 8 do not have any statewide code standards [13]. However, those eight states, including Alaska, Colorado, Kansas, Missouri, Mississippi, North Dakota, South Dakota, and Wyoming, do have county-specific building energy efficiency codes. For instance, Boulder County in Colorado has a very strict energy code and requires 20% better energy efficiency than IECC 2018 [76]. So, while some states are slower to adopt stricter energy efficiency requirements including higher thermal insulation levels and more airtight building envelopes, all the states have a set of minimum energy efficiency standards for walls, roofs, and windows.

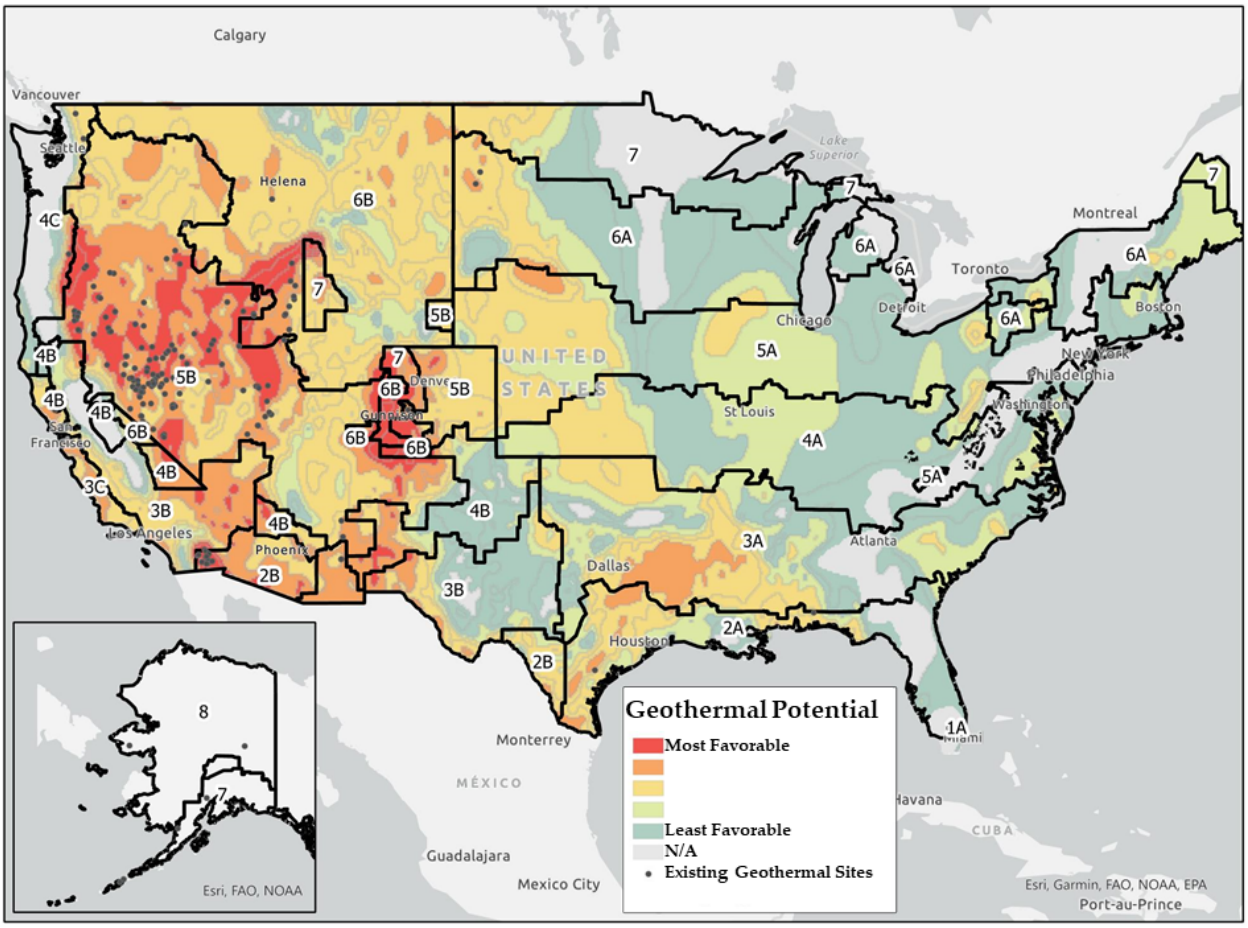

Figure 4. US climate zones and geothermal potential contour map. The color gradient shows the geothermal potential, and each climate zone is numbered, with A pertaining to moist, B pertaining to dry, and C pertaining to marine (data source: [77]).

4.2. Efficient Appliances

The US Environmental Protection Agency (EPA)'s EnergyStar program offers rebates and sets labels to encourage consumers to buy energy-efficient appliances; heating, ventilation, and air conditioning (HVAC) systems; and office equipment [67]. According to the EIA, over 95% of all dehumidifiers, dishwashers, and televisions sold in the US were EnergyStar-rated during the last 10 years [14]. Likewise, over 50% of all sold laptops, room air conditioners, clothes washers, refrigerators, and audiovisual products are EnergyStar-rated [14]. The only listed sold categories that fell below the 50% level are freezers, desktops, and water heaters. It should also be noted that, currently, EnergyStar does not rate electric and tankless water heaters [14]. The EnergyStar rating system enforces the concept of life cycle cost and the premise that reducing energy use means saving money [67]. Generally, EnergyStar-rated appliances benefit from higher rebates and tax incentives, as well as incur lower energy costs. Although some high energy-efficient appliances cost more upfront, older and cheaper models consume more energy and result in higher operation costs.

One major potential for EEM is HVAC. Depending on the climate, HVAC systems can contribute from 23.8% to 72.9% of the overall building's energy demand [26]. With energy-efficient systems such as heat recovery ventilators (HRV), a typical US housing unit can reduce their energy consumption by up to 17.3% to 19.7%. Other energy-efficient HVAC systems can save 1% to 9% of the total energy of buildings [26].

For lower income households that spend a higher percentage of their income on energy costs, energy-efficient appliances are highly cost-effective options that can have significant impacts on improving their living standard [78]. Suitable energy-efficient systems for low-income homes include light emitting diode (LED) lights, EnergyStar-rated appliances, and higher efficiency HVAC equipment. In the US, several retrofit programs are available for low-income households including incentives and rebates to improve the energy performance of their homes [78].

4.3. Photovoltaics

According to the US DOE, as of 2020, there are 97.2 gigawatts (GW) of solar photovoltaic (PV) capacity, or enough to power 18 million (12.9%) of the 139 million homes in the US. This solar capacity includes non-residential PV arrays. Nevertheless, the PV capacity has grown nearly 286 times larger since 2008 when it was only 0.34 GW [15]. US DOE predicts that by 2030, one in seven homes will have rooftop PV system [15].

The adoption of PV both for "early adopters" (pre-2007) and "late adopters" is a prime example of how motivations and reasons to adopt renewable energy technologies have changed over time [79]. Early adopters were mostly interested in the environmental impacts and love for new technology, while late adopters were primarily incentivized by the cost benefits of PV systems. Apart from environmental beliefs and educational levels (i.e., high school diplomas vs. bachelor's or higher degrees), there are no clear correlations between psychological or demographic characteristics and the adoption of PV systems in buildings [79].

In addition to historical data, it is important to consider the benefits of PV systems, including their potential energy and cost savings. While there are several models and tools that can predict the energy performance of PV systems, human behavior is not often considered in the decision making for adopting these systems. Fikru investigated 941 users across four US states, compared the energy and cost savings, and identified potential impactful reasons for adoption including location, leasing vs. buying, and pairing with other EEMs to determine the actual savings from PV. He found that the demographics of occupant count, children, age, income, education, and location have varying influence on the ultimate decision to adopt PV systems for US households [80]. For those that adopted PV, 46% have less than USD 100 k income and 44% have USD 100–200 k income. In addition, 43% did not have a bachelor's and the remaining 57% did have a higher education degree [80].

Furthermore, location and associated cost of electricity impact the adoption of PV systems since their cost–benefit increases and their impact on reducing utilities costs is greater. Location can be a good indicator for the adoption level of PV systems among US households. Indeed, energy costs and incentives for installing PV panels vary greatly from state to state. While the median cost for PV systems (i.e., PV, inverter, and controls) has decreased from about 12.00 USD/Watt in 2000 to USD 3.80 in 2019 and the median size of the PV arrays has increased from 2.5 kW in 2000 to 6.5 kW in 2019, not every state has the same optimal solar radiation conditions [81]. Nevada and Arizona have the lowest cost of energy, including system install and generation price, at 2.30 USD/Watt, and Colorado has the highest at 3.15 USD/Watt [82]. Median size also varies by state, with Washington DC having the smallest PV systems at 7.8 kW total and Florida having the largest systems at 13.4 kW total. It should also be noted that larger PV systems correlate to higher monthly electricity consumption [82]. However, the overall cost across all US states is steadily decreasing and is, on average, 2.75 USD/Watt as of 2020, a 27% drop since 2014 [82].

The PV technology is accessible but is not yet affordable to all US households. According to Lukanov and Krieger, there is one PV array for every 65 residents in California based on a survey conducted in 2019 [83]. In areas where PV is common such as cities, residents only spend 3.5% of their income on utilities, but in rural areas where it is uncommon to install rooftop PV systems and households are poorer, they are spending as much as 14% of their income on utilities. In a way, the lack of PV contributes to poverty, but also causes poorer health conditions since the alternate energy sources often include fuel-based power systems that emit toxic gases. The initial capital cost to install a PV system can be high, even with rebates. While there are subsidies for installing PV systems, the cost of these systems is still not affordable for all US households [83].

5. Lower Adopted Technologies

This section outlines technologies that have lower levels of adoption compared to their lower energy efficiency counterparts. While they do exist on the market, they achieved less than 10% adoption rate. This list is not complete but stands to provide examples and reasons for low adoptions of energy efficiency technologies.

5.1. Smart Windows

Multiple glazing types, such as tinting and reflective, are common and accessible on the market. The global window market was worth approximately USD 153 billion in 2020 [84]. However, even with these glazing types, thermal losses through windows remain significant resulting in as much as 10% to 25% of the home's overall energy loss [85]. Instead, smart windows are equipped with tunable chromogenic glazing types that allow, block, or contain certain radiation wavelengths dependent on if the residence needs heating or cooling. In 2020, smart windows reached a global market value of USD 3.6 billion, 2.4% of the USD 153 billion global window market's worth [16]. The market is growing but is curtailed by the lack of knowledge by the general public, no implementation requirements by codes and standards, and higher initial costs.

Despite the saving potential, the technology has a low adoption rate. The smart windows are currently manufactured using complex processes and, thus, cost more than any non-smart windows. Smart windows need more research and development to bring down the cost, paired with more widespread marketing to educate the general population on their abilities, benefits, and purposes [86].

5.2. Electric Vehicles

According to the US DOE's Alternative Fuels Data Center, 879,320 electric vehicles (EVs) have been sold since 2011, with 241,912 being made in 2019 alone. However, the EV stock represents only 1.4% of the total 16.9 million vehicles sold during 2019 in the US [87]. Figure 5 shows the number of EVs sold each year, by EV automaker. This does not include plug-in hybrid vehicles [17]. While there are more options with higher capabilities at lower prices each year, EVs still remain more expensive and have fewer driving capabilities than their fuel-powered equivalents. EVs are often charged in residential buildings, significantly affecting their overall electrical loads. In addition, some states such as California have added EV charging station requirements to their building code, but other states are slower to enact these mandates [45]. EVs have the potential to lower carbon emissions as well as help offset peak loads and reduce the disparities between power production and demand.

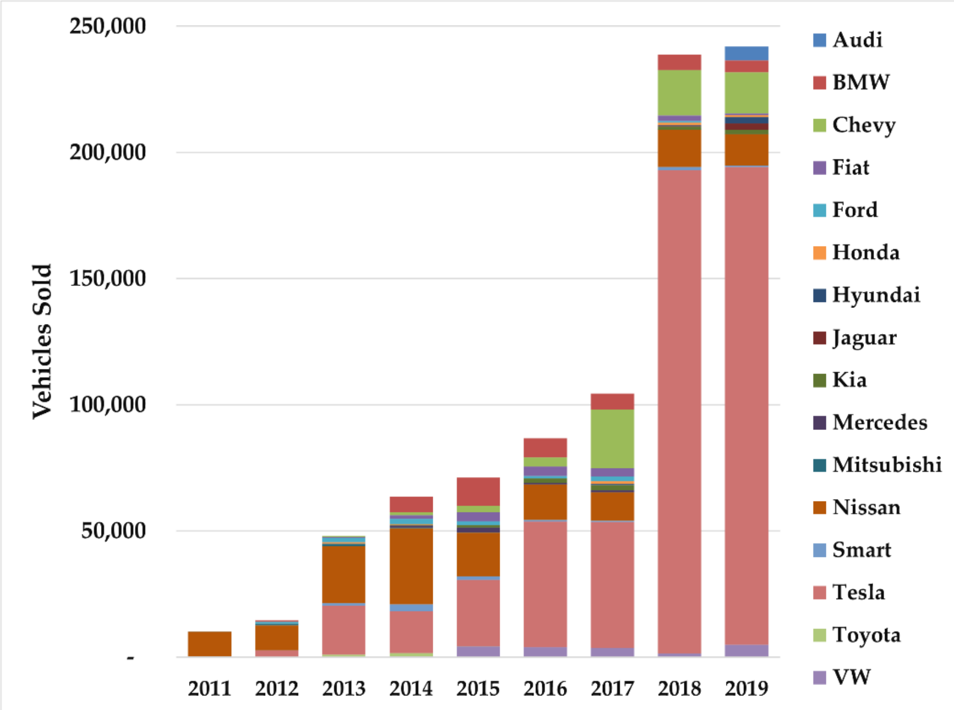

Figure 5. Electric vehicles sold by manufacturer and year. Number of EVs sold is broken down by manufacturer name. This chart does not include plug-in hybrid electric vehicles (data source: [17]).

More steps need to be taken in order for EVs to reach the status of "higher adopted" technologies, as Li et al. [88] and Jang and Choi [89] outline. Li claims that EVs needs more funding in order to reach standards comparable to their fuel-powered equivalent. This funding is required both to enhance EV research and development, and to subsidize the cost of electricity required to power the EVs. The next hurdle is the social influence to convince consumers to buy EVs. An increase in education through popular science propaganda and social discussion would lead to a growth in social norm and, thus, sales [88]. Jang and Choi study the potential demographic characteristics that could influence the purchase of EVs. In the end, the consumers' demographics of gender, age, region, and income weighed the car's characteristics of fuel type, price, body type, driving range and time, and autonomous driving differently. In order to incorporate a larger audience, they made three conclusions: First, the cost of EVs must be lowered to be competitive with fuel-powered vehicles. Second, there needs to be investment in research and development to improve EV performance and charging stations. Finally, EVs need to be marketed better to the demographics that are not currently being reached, such as lower income households or those that believe they prefer specific fuel-type characteristics over EVs [89].

EV has the capacity to grow and serve as a vital step towards complete electrification, lowering personal carbon footprints, and alleviating the discrepancy of grid energy production and demand.

5.3. Storage Solutions

Load balancing is challenging because of the inter-connectivity between technology and human factors. A perfectly accurate load balancing model is impossible to make due to the uncertain human factors, so instead the solution is to invest in electrical, chemical, or thermal storage. Storage helps flatten the curve and disparity between energy supply and demand. Energy storage, if economically feasible, would allow for flexibility, proper optimization, and less energy waste [15]. As of 2019, the US has 402 MW of small-scale and 1022 MW of large-scale total battery energy storage capacities [18,19]. Compared to the US' 97.2 GW of solar power capacity, the total energy storage capacity represents 1.5%.

However, energy storage remains currently an expensive technology and only considered when the residence has onsite renewable power generation sources.

Surveys completed during 2020 indicate that most consumers (69%) want energy storage for added resiliency as a backup solution. The most popular vendors for energy storage batteries suitable for backup power in buildings are LG Energy Solutions and Tesla, with Tesla being the cheapest option by 3% compared to Generac, 19% compared to Eguana Technologies, and 32% compared to LG Energy Solutions [82]. However, the prices for these batteries remain rather high, typically above USD 10,500 for 13.5 kWh capacity, including installation and not including tax incentives or rebates [90]. Luckily, more energy storage solutions are entering the market each year and driving the price down steadily.

5.4. Heat Pumps

Heat pumps are not a new technology, but they are slow to be adopted as common options for heating residential buildings. The EIA reports that only 12.1 million households use heat pumps out of the 139 million households (8.7%) in the US [20]. Currently there are no building code requirements for adopting heat pumps, so unless builders seek to achieve certificate requirements (i.e., LEED, electrification, or other labeling standards), there is no motivation to specify these systems. Heat pumps have higher initial costs compared to gas or oil heating systems and require more specialized knowledge to install. In addition, heat pumps are not suitable for all climates.

However, they offer large potential for energy savings. According to the US DOE, heat pumps can reduce electricity by approximately 50%, in comparison to their electric heating systems [91]. Geothermal heat pumps could reduce heating energy usage by 30% to 60% in US homes, if they have access to geothermal sources [91]. Wu and Skye of the National Institute of Standards and Technology (NIST) state that Ground Source Heat Pumps (GSHPs) can save between 24.3% and 39.2% of energy in heating-dominated regions, depending on the specific climate zone [26]. A case study in California showed a 50% reduction in household carbon emissions when switching from natural gas to heat pumps for both domestic hot water and space heating [92]. Another case study in United Kingdom residences showed a savings of 37% in both cost and emissions when switching from a natural gas boiler to a heat pump [93]. When heat pumps are used for domestic hot water heating, they are two to three times more efficient than standard electric water heaters [91].

Heat pumps driven by renewable power can achieve even higher energy savings compared to conventional heating and cooling systems. Liang et al. [94] investigated solar-powered heat pumps that can provide both electricity from the solar panels and heat from the solar rays. They estimated that these systems can provide up to 24% additional savings [94].

Karytas et al. [95] surveyed subjects in Greece, Spain, and Portugal specifically about domestic hot water (DHW) systems that utilize GSHPs, solar solutions, and thermal energy storage. Through a questionnaire, they gauged interest, willingness to adopt, willingness to pay, and acceptable payback periods, as well as the subjects' demographic characteristics. They concluded that while there is sufficient interest and willingness to accept, the technology needs to be cheaper and have a shorter payback period compared to the non-renewable competitors. They estimated that the technology needs to be as low as EUR 6000 with a 5-year payback period for users to readily adopt it [95].

5.5. Geothermal Systems

Geothermal plants only produce 0.4% of the US' utility-scale electricity generation [21] suitable for space heating, cooling, DHW systems, and electricity generation. Geothermal energy could provide as much as 75% savings when compared to traditional heating and cooling systems [96]. However, geothermal systems may not be economically feasible for all US climates, as Neves et al. assessed [97]. Figure 4 outlines the US climate zones overlayed with terrain with geothermal potential. Specifically, they determined that geothermal systems are not cost-beneficial in climates 1A (e.g., Miami, FL, USA) and 2B (e.g., Phoenix, AZ, USA), but in 6B (e.g., Helena, MT, USA), 7A (e.g., Duluth, MN, USA), and 7B (e.g., Gunnison, CO, USA), there is high potential for geothermal systems.

Reber et al. proposed an alternate geothermal heating solution using centralized enhanced geothermal systems (EGS) [98]. These EGS use terra heat from bedrock, as opposed to relying on geothermal ground water, which is only available in certain locations. The EGS provide a more efficient approach to heating air and water and are available in more locations than traditional geothermal systems. The main concern is economic feasibility, depending on the bedrock conditions. Currently, this system could cost as high as 22.30 USD/MMBtu, but with more research, this cost could be reduced to 12.00 USD/MMBtu [98]. Generally, geothermal systems require large capital investments, but with a large-scale deployment and reduced transportation distances, geothermal energy could become accessible to more homeowners [98].

6. Conclusions

Design and innovation of sustainable buildings have improved substantially since the inception of the "green" movements in the 1950s. With each step, whether it be better design, electrification, or new technologies, the building industry is getting closer to achieving NZEB status. However, there is a need to convince technology distributors, builders, and homeowners to continue adopting and using energy-efficient and renewable technologies. The incentives for adopting these technologies can be promoted through policies and certificates, psychological influences, or education programs.

Many technologies have already been adopted and are commonly utilized today. Energy-efficient envelopes can save energy by reducing heating and cooling thermal loads, mostly due to the requirements set by building energy codes. Efficient appliances use less energy and are adopted due to their brand recognition, affordability, savings incentives, and code requirements. For onsite renewable energy generation, solar panels provide an alternative option to the grid and can significantly reduce utility costs. Onsite PV systems are becoming a social norm due to their energy cost savings and code requirements in some states. Overall, the common characteristics for the "highly adopted" technologies include:

- Brand or technology recognition;
- High energy and cost savings;
- Affordability through low capital costs or high fiscal incentives;
- Code or legal requirements.

The above noted factors driven by policy makers, engineers, technology distributors, and the general public have produced higher adoption rates for sustainable energy technologies for US residential buildings.

On the other hand, several sustainable energy technologies have yet to be commonly adopted. For instance, innovations such as smart windows have not become standard for builders, despite their energy efficiency benefits, because of lack of knowledge, high installation costs, and policy requirements. EVs and battery energy storage systems have not become mainstream because of their high capital costs and limited confidence in their performance compared to their fuel-based counterparts. Heat pumps also have significant energy, carbon, and cost-saving capabilities, yet are far less common than fuel-based heating systems, due mostly to the lack of knowledge, large initial cost, and code requirements. Other renewable energy technologies such as geothermal are not as popular as PV solar panels due to their limited site availability and high capital cost requirements. The main factors for the low adoption of sustainable energy technologies in US residential buildings include:

- Lack of knowledge or brand recognition;
- Climate-dependent savings;
- Higher capital cost, longer payback periods;
- Lack of code or legal requirements.

To increase the adoption rates, each of these factors need to be addressed for all the targeted technologies.

However, there is great promise in the future for the technologies described in this review as well as others to be widely adopted with additional research and developed to lower their implementation costs, standardize their installation, and educate the public about their energy and cost benefits. With these actions, more sustainable energy technologies can be widely adopted and help reduce energy demands and carbon emissions in the building industry.

It is important to pinpoint that the review in this study considers primarily economic and engineering factors; other sociological and psychological actions could be utilized to change human behaviors to increase the adoption of sustainable energy technologies by households. Moreover, the literature review does not include cost–benefit assessments including life cycle cost analyses for these technologies. Further research is needed to evaluate and assess the cost–benefits of a wide range of sustainable energy technologies for both households and societies.

Author Contributions: Conceptualization, M.K.; methodology, E.K.S.; investigation, E.K.S.; resources, E.K.S.; data curation, E.K.S.; writing—original draft preparation, E.K.S.; writing—review and editing, M.K.; visualization, E.K.S.; supervision, M.K.; project administration, M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge Matthew Schroeder for his assistance in developing figures and Gillian Gundersen for her collection of geothermal mapping.

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

Nomenclature

ABC	Achieving events, beliefs, consequences
ACH	Air change per hour
BIM	Building information modeling
CO_2	Carbon dioxide
DHW	Domestic hot water
DOE	Department of Energy
EED	Energy efficiency directive
EEM	Energy efficiency measure
EGS	Enhanced geothermal systems
EIA	Energy information agency
HRV	Heat recovery ventilators
HVAC	Heating, ventilation, air conditioning
IECC	International energy conservation code
IRC	International residential code
kW	Kilowatt
LED	Light emitting diode
MW	Megawatt

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