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Energy efficiency retrofit and decarbonization of old and historic buildings in California

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Energy efficiency retrofit and decarbonization of old and historic buildings in California

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Abstract

Buildings are responsible for almost 40% of total global greenhouse gas emissions and the retrofitting of existing buildings is an essential part of solving the problem. About 75% of buildings in Californian were constructed before the first energy-efficiency building code was adopted in 1978. Old buildings are inefficient, responsible for large carbon footprints and must be retrofitted to stay on track with the state's climate targets. However, current policies do not require substantial changes and tend to favor historic preservation over energy efficiency, missing improvement opportunities. Recognizing the significance of carbon intensity, the 2019 California Energy Efficiency Action Plan shifted the attention of policies from energy efficiency to the decarbonization of existing buildings. However, there is still a gap between Californian goals and practices. This study investigated strategies for old buildings' decarbonization, and the literature review focused on climates related to California. Secondly, the Californian building code, Action Plans and other initiatives were examined. It was found that to decarbonize existing buildings, first, the shift of the building system is required to electric heat pumps for air heating and cooling and water heating. Next, increasing the building envelope's airtightness should be considered. In contrast, insulation choices require a careful trade-off between increasing indoor comfort and using less carbon-intensive materials. Also, strategic landscape design should be part of a retrofit program. However, to implement those practices in substantial quantities, policies need to find the opportunities – "trigger events" - to initiate the retrofit works by mandate and support.

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1 Introduction

The built environment is integral to our lives, with Americans spending about 90% of their time indoors (Klepeis et al. 2001). In 2015 globally buildings and their construction were responsible for almost 40% of greenhouse gas (GHG) emissions and 36% of energy consumption (Abergel et al. 2017). Buildings use about 39% of total US energy; of that, 21% is from residential and 18% from commercial buildings (EIA 2022). Moreover, this amount grows to an estimated 48% when a more holistic approach includes transportation, infrastructure, and end-of-life stage (Baum 2007). While energy used during buildings operation per square foot is declining, population growth and global urbanization are increasing the floor area by about 2.3% per annum, adding every week to the planet a size equivalent to Paris. As a result, the building sector energy demand keeps growing by around 1% each year (Abergel et al. 2017). The energy intensity of the buildings needs to go down almost five times faster than the current rate to be on track with Paris Agreement goals and to reach carbon neutrality by 2050 (IEA 2021). Thus, decreasing energy demand and related GHG emissions of the building sector play a significant role in the global transition to carbon neutrality.

To address the carbon intensity of the built environment, countries and cities set targets to cut the energy used by buildings and to decarbonize them by making net carbon neutral. For example, the EU's goal is to have a 60% GHG emission reduction by 2030 and 100% decarbonized buildings by 2050 (Vercoulen et al. 2022). California aims by 2030 to reduce building-related emissions by a minimum of 40% from 1990 levels (SB 32 2016), and the goal of San Francisco, California, is to make all its buildings zero GHG emissions by 2040 (SF environment 2021). Globally it was estimated that the energy per square meter in 2030 needs to be no more than 55% compared to consumption in 2020 (IEA 2021), and strategies are drafted to reach the target.

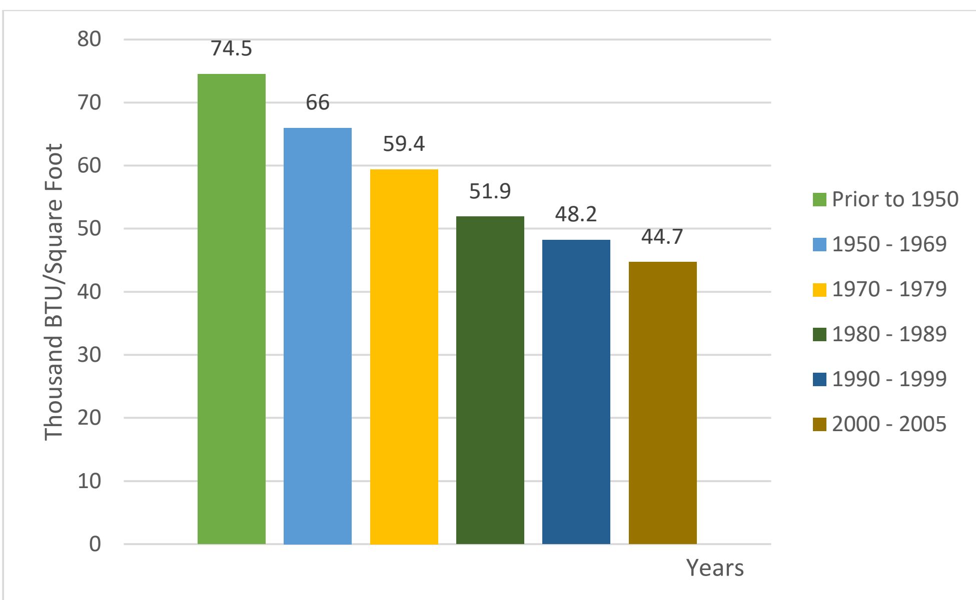

Figure 1-1 Residential energy intensity by housing vintage, the U.S. Note that the older buildings in average consume more energy per square foot. Three left columns represent the buildings constructed before 1978 – the first in the U.S. building energy efficiency code (data source U.S. Department of energy 2012).

Energy efficiency in buildings coupled with building electrification is the main strategy for reaching those goals. This is easier to achieve for new constructions that are more typical for fast-growing countries such as China and India. To be globally carbon neutral by 2050, 100% of new buildings and at least 20% of the existing buildings must be zero-carbon by 2030 (IEA 2021). North America and Europe feature a large stock of old and historic buildings that have been shown less efficient (Figure 1-1). Therefore, retrofitting old existing buildings is a significant contributor to the decarbonization of the building sector. National Park Service Technical Preservation Services (NPS TPS) updated in 2011 *Conserving Energy in Historic Buildings* and issued *Standards for Rehabilitation & Illustrated Guidelines on Sustainability for Rehabilitating Historic Buildings*. Those documents objected to bring more focus on energy-saving technologies and alternative energy sources for historic buildings and provide guidelines for the practices. However, there is a disconnect between common practices and knowledge, as the recommendations fail to provide guidance on how to balance different aspects of old and historic built environments (Boote 2018; Nutkiewicz et al. 2021)

There are several parameters that need to be considered to a particular upgrade project and while some present co-benefits, others introduce tradeoffs between two or more aspects. For example, adjustment of windows' sizes and locations can improve both the indoor lighting and controlled solar heat gain, resulting in decreased energy for air conditioning and lighting. On the other hand, historical preservation strategies may prevent the reconstruction of existing buildings for increasing their energy efficiency. Present policies favor preservation of the cultural heritage over energy and natural resources preservation. At present, each project needs to go through individual case-by-case assessment and modeling to find the best strategies to improve the building performance. However, with lack of support and motivation from policies on the one hand, and without more defined and achievable reconstruction strategies on the other hand, present retrofit projects in California miss the opportunities to improve efficiency of old buildings.

The appearance of historic cities is part of social identity, attraction for tourism and business and hence a crucial socio-economic factor, so energy retrofit of old and historic buildings can be seen as both a necessity and an opportunity for historic cities. First, revitalizing historic neighborhoods with well-monitored cultural preservation is a powerful tool to boost the economy, activate urban life and enhance social experiences. Second, retrofitting old existing constructions adds valuable volume to real estate inventory by using existing buildings and infrastructure, which conservates materials and resources. Third, retrofits are beneficial for local economies by creating local jobs (Vercoulen et al. 2022), in contrast to new construction that often utilizes a smaller workforce but much more intensive on shipping new materials with related environmental externalities. Last but not least, the comfort and health of the occupants can increase significantly with indoor climate improvement – including thermal conditions and air quality. The latter, for example, became even more important for Californians with the increased number of wildfires associated with climate change. With the benefits of retrofit in mind, the question is raised of how to regulate reconstruction projects and their strategies to preserve the historic fabric of our cities while improving the efficiency of the buildings.

The observation of the current gap described above encouraged the goal of this paper - to contribute to the knowledge of finding the balance between the preservation of historical heritage in Californian cities and the improvement of its buildings' performance. With extreme climatic events of the last decade and the new energy crisis of 2022, the philosophical question of where the sustainable line between the preservation of humane culture and natural resources is, has turned into an essential question that needs to be addressed in a relatively short period of time. Therefore, this research aims to answer how to balance the decarbonization of the building sector and energy retrofit with the preservation of the old and historic urban environment in California. To answer the question, two sub-questions will be examined:

1. What are the strategies for decarbonization and retrofitting of old or historic buildings? What is the relationship between the three groups of retrofit strategies – Internal building system upgrade, building shell improvement, and the control of the building external context?
2. How do California policies regulate energy efficiency and decarbonization of old and historic buildings?

2 Background

2.1 Energy performance in old and historic buildings

A large part of building stock in developed countries are historic and old traditional buildings that are more than 50 years old - the typical threshold between new and old or potentially historic buildings. Overall, historic structures - so-called "listed" - with stringent preservation rules are estimated to be between 1% and 5% of all building stock in developed countries, and summed with old traditional buildings between 10 and 40%. The range varies depending on the region's historical heritage and the policies with different age thresholds. In the US, 31.5 million homes (or 41.5%) were constructed over 50 years ago (Statista 2021). The floor area of about 42.653 billion sq. ft or 13% of total building stock was built before 1940 (Kamel and Memari 2022). In Europe, more than 40% of housing was built before 1960, with the largest ratio of old buildings being in the UK, Denmark, Sweden, France, Czech Republic and Bulgaria (Economidou et al. 2011).

In general, this segment of the built environment is responsible for about 20 – 40% of the total energy consumption of developed countries, depending on the vintage of the local urban environment (Webb 2017a) . The energy performance of a building and related GHG emissions are not always consistent across geography, the building use and the age of the construction. Retrofit, reuse, revitalization, and energy upgrade projects are complex and multi-perspective tasks that lay between different fields, namely: building physics, energy sector, cultural, economic, policies, urban and climate studies. This background section of the paper will overarch those fields and look at the basics of energy consumption by buildings.

Despite the common belief that old buildings are inherently energy efficient as they were built before the wide spread of inexpensive air conditioning, deeper research showed that it is often not true (Boote 2018; Webb 2017). For example, data from 2015 shows that residential buildings constructed before 1940 spend 54% of total operation energy on heating and cooling of the indoor air, while similar structures dated between 2000 and 2009 use for that only 43% of their energy (Kamel and Memari 2022). Another study across five climate zones and different building types in the U.S. showed in all building types, the thermal energy load for building constructed pre-1940 was about doubled per square foot of floor area compared to post-1980 construction (Reyna et al. 2022). In other words, the energy required for space conditioning in older buildings is generally higher than in more modern (Figure 1-1). However, besides energy for operation, other factors, such as the energy for construction work and the source of energy, play roles in the overall carbon intensity of a building.

2.2 Operational energy

The operation energy of a building describes the energy used after a construction phase is finished, so people use the space for their needs. Figure 2-1 shows the breakdown of the uses in a residential building in the U.S., and it can be divided into a few functional categories: First and biggest is associated with air conditioning – heating, cooling and ventilating of the space to make it comfortable for occupants, that is often called Heating, Ventilation, and Air Conditioning (HVAC) system. It is followed by water heating and lighting. Wet cleaning - cloth and dish washing - also in large consume energy by heating the water but more depends on the appliances. The next group is practically electricity users, with significant refrigeration/freezing contributions. Importantly, computers and televisions are not influential contributors despite common beliefs. In other words, almost half of the energy used in American buildings depends on the ability of the building to provide the occupants with daylight and shelter from external cold and heat. Thus, the building itself - the shell – vastly determines the built environment's intensity.

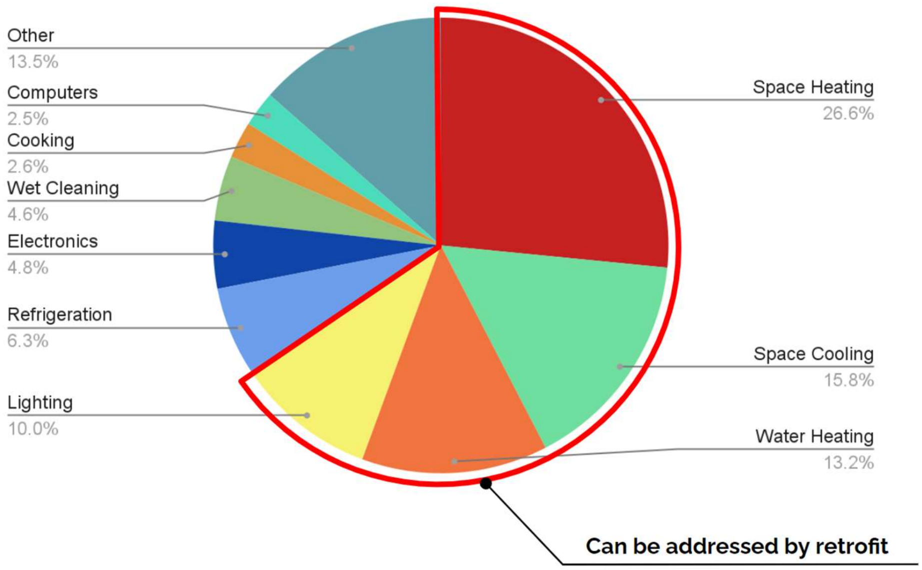

Figure 2-1 Operational energy in the U.S. commercial and residential buildings. Note, space heating, space cooling, water heating and lighting are responsible for more than half of total operational energy and can be addressed by retrofit measures (data source Frey et al. 2012)

2.3 Construction or embodied energy and related carbon

However, before the occupants enter the building, it already has used a significant amount of energy - the construction or embodied energy - and is responsible for so-called embodied carbon. The energy cost comes from materials' extraction, manufacturing, and transportation, summed with the energy for the construction of the building and its infrastructure, though the latter is not always included. More holistic analyses, such as Life Cycle Assessment (LCA), also include energy related to the end of life – demolition, recycling and/or disposal. A nonprofit, solution-oriented research organization, *Architecture 2030,* recognized by the industry and *the American Institute of Architects (AIA)*, summarized the Energy Information Administration Agency (EIA) data. Figure 2-2 illustrates the approximate built environment carbon footprint, including construction energy, materials production and transportation, operational usage, the end of life of the built environment and related infrastructure. The total GHG emissions from the built environment are estimated to be around half of all global GHG emissions (Architecture2030 2022).

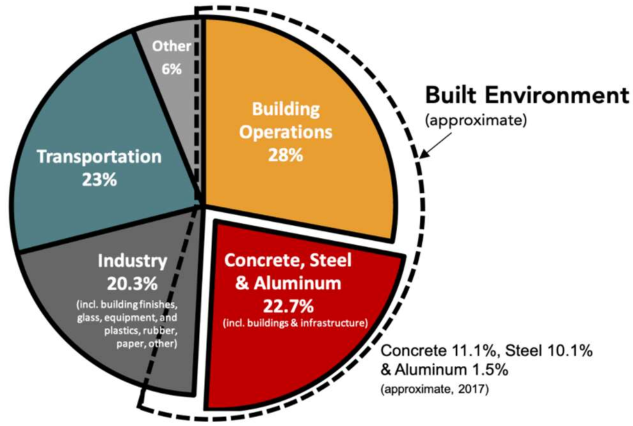

Figure 2-2 Global GHG emissions by sectors. Note, conventional assessment of buildings emissions is about 40% of total global, but can be estimated higher when related industries, transportation, and end-of-life is added (adapted Architecture2030 2022).

The Green building movement initially concentrated its attention on operational energy, representing the more significant energy load in the buildings. Embodied energy is yet a substantial part of the total building's energy portfolio, typically estimated between 10 and 20% (Webb 2017). However, there is a tradeoff between energy efficiency that lowers operational energy often by adding more materials and thus increasing embodied energy share. The apparent advantage of existing buildings is that this upfront energy already has been spent, and therefore this saves a substantial portion of energy compared to building a new similar one (Hao et al. 2020). Additional materials to increase energy performance results in additional embodied energy. It is essential to highlight that aluminum and glass for new windows and insulation are one of the most energy-intensive materials, besides having other environmental impacts such as toxicity of some insulations. The type of building under the retrofit project influences the improved efficiency with the range from 25% to 50% of avoided carbon emissions. Old steel and concrete buildings have been shown on the most effective side as saved steel and concrete are carbon intensive materials and this building type tend to have poor thermal envelopes and inefficient HVAC (King et al. 2017).

Furthermore, the range of insulation carbon intensity varies significantly from foams and XPS are on the worst side of the spectrum and cork, sheep wool, cellulose and wood fiber boards on the less intense side. Moreover, electrification of the transportation and manufacturing of bio-based insulations is the critical factor in their low carbon intensity (Densley Tingley et al. 2015; Graham et al. 2021; Grazieschi et al. 2021; Tártaro et al. 2017). From a slightly different perspective, wood parts of a building are, in essence, carbon sink that stores carbon, preventing it from transferring to the atmosphere and so contributing to the GHG emissions in case of demolition and decay. From that perspective, the conservation of wooden structures is even more meaningful as part of retrofit work. Overall, the embodied energy topic became not only significant in the scientific literature but started entering policies such as, at present, the voluntary third-party certified standard Zero Carbon Certification by International Living Future Institute.

2.4 Embodied vs operational energy as a building age

The timeframe for Life Cycle Assessment (LCA) is an essential part of the conversation about balancing operational and embodied energy. The period that buildings will function varies from 50 to hundreds of years and building materials could be from 30 to 60 years (King et al. 2017). On the one hand, the longer the building stays, the more operational energy accumulates, and the less significant contribution of embodied energy becomes. On the other hand, with the urgency of climate change mitigation and reduction goals as close as 2030, the time frame for evaluating the total carbon footprint can be considered as short as ten years (Figure

2-3). Thus, embodied carbon can be seen as *a carbon investment* - one needs to invest carbon upfront (increase the embodied GHG footprint) to save later on the operational GHG emissions. So, if additional insulation uses a carbon budget of 50 years, it means the building will offset the added GHG emissions during the next 50 years of more efficient operation. While this could lower utility bills, it cannot help decarbonizing the building, as the climate goals need to reach neutrality in a shorter time.

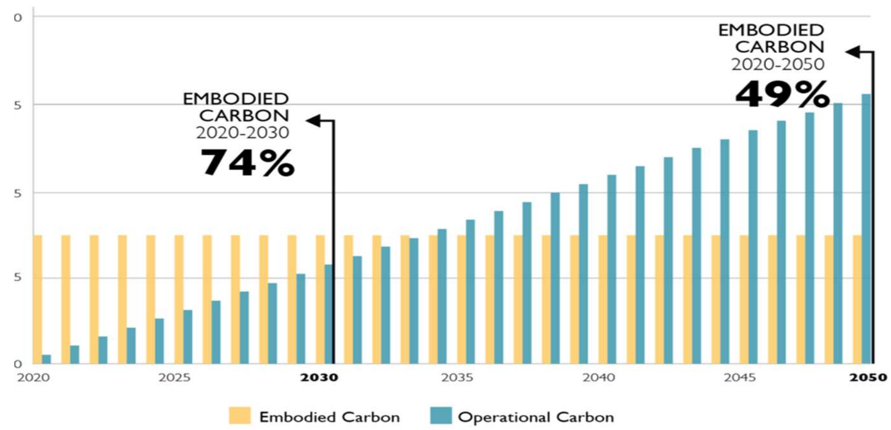

Figure 2-3 Total carbon emission of a new construction built in 2020, change of the ratio embodied and operational carbon from 2020 to 2050. When the timeframe of 50 years is considered, the contribution of operational energy is more significant (about half of the total footprint carbon footprint) as it continues to accumulate. However, a 10 years' timeframe of assessment – to reach carbon neutrality goal – embodied carbon represents 74% of the total footprint (adapted Architecture 2030).

For example, Dahmen et al. assessed the relationship between operational and embodied energy impacts in terms of its *emission payback period* - the time required for the operational energy savings to offset the construction energy cost. They evaluated single-family houses in Vancouver, Canada in the context of the city's plan to reduce buildings' CO_2e emissions by 80% by 2050. Modeling showed the CO_2e payback period for new construction to be, on average, 168 years (range from 73 to 548 years) with construction under current regulations and 29 years (range from 25 to 36 years) under tightened regulations proposed for 2025. Hence, the investigation concluded that replacing the old buildings with new high-efficient ones is not an effective strategy for achieving municipal decarbonization goals and retrofit would be a preferable strategy (Dahmen et al. 2018).

Similarly, Preservation Green Lab compared retrofit scenario and new constructions of similar type, size, and climate zone. LCA showed that a new building, 30% more energy efficient than the average existing, will need from 10 to 80 years to offset embodied carbon and other (Ecosystem Quality and Human Health) negative environmental impact of the construction, where the time depends on the used materials and methods. Shorter payback times have been seen in school and multifamily residential projects, 10-16 years and 16 -20 years, respectively. Furthermore, from a climate change mitigation perspective, all types of retrofit and reuse projects were more sustainable than new construction. The report estimated the savings of GHG emissions by retrofit or reuse projects to be, on average, 9% for base cases and 15% for advanced cases. Also, all cases showed overall environmental benefits such as prevention of resource depletion, ecosystem and human health quality preservation. The only exception was found in the conversion of a warehouse to a multifamily residential building typology, which showed 1-6% worse environmental footprint compared to new construction, mainly due to the negative impact on human health (Preservation Green Lab 2011). To conclude, embodied energy of any building project, including retrofit, is a significant aspect that has its tradeoffs. While generally, retrofit shows savings of embodied energy compared to demolishing and new construction, the retrofit's materials also require mindful consideration of embodied energy, which will be discussed in section 4 of this paper.

2.5 Energy source and impact of transition to renewable

The main driver of energy efficiency improvement is public and governmental awareness of energy-related emissions. Emissions negatively impact human health with air pollution and climate change with increased concentration of cumulative GHGs. While two similar buildings can have similar energy performance, their environmental footprint may vary dramatically depending on their energy source. US buildings are steadily moving from fossil fuels and in 2021 residential buildings' natural gas accounted for 42%, reducing from 44% in 2019 and 58% in 2015 (EIA 2022). About 68% of the used gas was needed for space heating and the rest for water heating, cooking, cloth washing and dryers (Kamel and Memari 2022). Renewable energy in the houses had a 7% share, out of which wood, roof solar, and geothermal were 58%, 37%, and 5%, respectively. Retail electricity purchases increased from 41% to 43% between 2019 and 2021, reflecting the electrification policies as an essential tool for decarbonizing the urban environment (EIA 2022).

It is essential to distinguish two ways to evaluate a building's energy – *site* and *source* energy. The first – *site* – is only the energy consumed by the building during the operation, while the second - *source* - is the total required primary energy including the generation and distribution. The most significant difference between source and site energy is the electricity generated from fossil fuels. The fossil fuel burning to heat the water to rotate the turbine is a highly inefficient process. Production losses account for about 65% due to the wasted heat and mechanical inefficiency. Nowadays, the electricity in the country is mainly produced by fossil fuels (59%) and nuclear (22%), while renewable sources that have significantly smaller adverse environmental impact account for 21% (EIA 2022). To decarbonize the urban environment, the buildings need to switch to electricity that is sustainably generated.

One of the biggest challenges of the transition to renewable energy resources is timing. Balancing the supply and demand of electricity on the grid is the most challenging in the evening pick hours between 4 and 9 pm. During evening hours, solar electricity generation falls while energy demand rises for numerous reasons. Namely, the pick of air conditioning to fight overheating caused by lowering sun and increased domestic electricity use for lights, TVs, computers, cooking and over appliances as people come from work or school. The oversupply of electricity during the day and underproduction during the evening has a common name for *the duck curve* (Figure 2-4*)*. Thus, measures that decrease operational energy in the evening hours are essential for residential buildings and will be discussed later in this paper. However, for office buildings, mornings could be more influential. A case study of Sacramento showed that for office and large-scale residential buildings, the most substantial improvement in energy performance was upgraded windows to reduce heat gain in the morning hours, which influenced the cooling demand for the whole workday (Nutkiewicz et al. 2021).

The electricity is the cleanest (larger ratio of renewables) during daytime at the peak of solar supply and in the middle of the night when the wind generates more energy (Randolph 2022). Hence, maximizing electricity use at those hours introduces additional opportunities for decarbonization. For example, scheduled heat pumps for water and space conditioning can function as thermal energy storage to lessen energy demand at pick hours. Therefore, the design of retrofit strategies must consider the required energy's time in relation to the building's function.

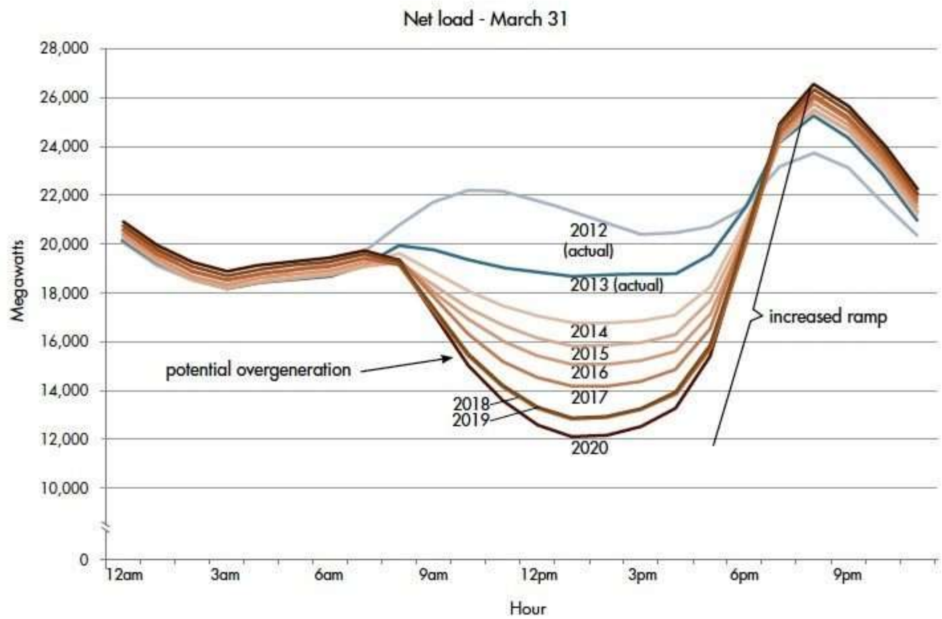

Figure 2-4 Duck curve graph. The "belly" shows reduced midday electricity demand, and the "head" is increased consumption in evening peak hours. Renewable energy generation is at odds with the pattern - higher during the day and low at evening (source energy.gov)

2.6 Synergy of retrofit goals

Besides improving the energy performance of the existing buildings, there are other intentions to complete work on a building that can be used as an opportunity to increase energy efficiency. One of the reasons is a seismic upgrade to adhere to current regulations. For example, San Francisco legislated the *Soft Story Ordinance* in 2013. According to the 2013 Ordinance, all three or more-story wood-framed buildings with large windows (such as a store or a restaurant front) or garage doors on the ground level and five or more residential units above that built before 1978 must be retrofitted (Structural Engineers Association of Northern California 2022). Similar policies exist in other seismic regions triggering retrofit work and creating the potential for improving energy performance. Recent studies of integrated seismic and energy retrofitting for moderately seismic areas of southern Europe showed both potential and necessity for deeper investigation of optimal strategies that benefit both goals (Bianchi et al. 2022; Pohoryles et al. 2022).

Another retrofit type that increases its presence and significance is adaptive reuse – for instance, the conversion of a warehouse to commercial usage or commercial properties into a residential or multi-use building. The main driving forces for that are the challenging necessity for more housing combined with the reduced demand for retail and office spaces due to behavioral changes. For example, converting 10% of office spaces in Los Angeles (~15,500,0000 sq. ft.) can create about 8,000 to 16,000 new homes, which is supported by local policies such as Los Angeles's 1999 *Adaptive Reuse Ordinance*. An additional benefit of adaptive reuse retrofit is the locations of commercial buildings potentially used for conversion. They are generally situated at transportation corridors and have good pedestrian connectivity and access to public transit (Garcia and Kwon 2021). While this factor does not relate to the energy efficiency of the particular building, it contributes to lowering the carbon intensity of the urban region due to transportation - another significant contributor to GHG emissions. Overall, both scenarios described above require substantial work on a building and thus provide an excellent opportunity to maximize the energy performance of the building.

2.7 Background conclusion

Old and historic buildings are a large portion of the current building stock in developed countries. Yet they often show energy inefficiency and so represent a substantial potential to decarbonize the built environment. Retrofit measures improve the satisfaction of occupants of the building with thermal comfort, air quality, lighting, and sound quality (Webb 2017b). Retrofit also can preserve and revitalize the historic built environment. Inherited emphasis on cultural preservation with neglected energy performance in the regulations now shows a slow shift in policies and public perception. However, there is still a need for more detailed study of possible strategies, their challenges, and the influential factors, which will be discussed in the next sections.

3 Method

This study used the research method of analyzing scientific literature, reports and policies to investigate the research question of balancing decarbonization and preservation of old buildings in California.

To answer the first sub-question and investigate the strategies for old buildings' decarbonization and retrofit, a scientific literature review was performed. The selection of the papers was primarily narrowed down to the last ten years (2013-2022 years of publications) with few exceptions for general building science data independent of the technologies' improvements. The geography of the studies was generally limited to North America and Europe, where similar conditions of existing buildings can be observed. Because California has 16 climatic zones, different climates were observed regarding California conditions. Additionally, few studies from Turkey and South Korey were used as their climate and latitude could correspond to California. The numerical data expressed in energy saving percentage was summarized in the summary tables to compare and illustrate the weight and importance of the different retrofit strategies. The longer version of the table with additional data was created as an appendix to the study.

The policy chapter analyzed California guidelines and initiatives to answer the second sub-question. 2015 California's Existing Buildings Energy Efficiency Action Plan and 2019 California's Energy Efficiency Action Plan were investigated. Overview of California building code - Title 24 - was performed from the perspective of the existing buildings' energy upgrade. A brief overlook of European policies opens the chapter to put Californian practices into perspective.

Additionally, the study used data from governmental resources such as The U.S. Energy Information Administration (EIA), the International Energy Agency (IEA), the U.S. Department of energy, Statista, Energy.gov, California Air Resources Board (Ca.gov) and similar sources. Also, in order to have a local perspective, the study used two additional tools. First, a GIS (Geographic information system) mapping was used for the Context Approach section (section 4.3). The map utilized Census data and San Francisco Cultural Resources data. Second, to gain insight into practitioners' perspectives on California building policies, three interviews with local architects were performed.

4 Discussion and Results

Factors influencing a retrofit design project fall into two major categories – physics-related and policy-related. The first includes the climate zone, building typology and materials, equipment and construction condition, level of maintenance, occupancy, and urban context. Therefore, this paper will first investigate retrofit strategies that change the energy performance of an old or historic building by adjusting its equipment, construction, or context (Chapter 4, sections 4.1-4.5). In addition to physical-related factors, policies and regulations determine the allocation of money and effort of the building owner and the retrofit design team. Policies, on the one hand, can support or discourage specific retrofit design, while on the other hand, can influence the accessibility of "green" materials and technologies. Thus, in Chapter 5, the paper will examine the Californian policies that determine current practices. Figure 4-1 shows in blue the retrofit design strategies that this paper will investigate, divided into three categories – internal (the building systems), shell (the building envelope), and external (the building context). Additionally, the figure acknowledges that other strategies such as providing roof Photovoltaic (PV) electricity generation or water conservation are viewed in some studies as retrofit strategies but are not included in the present study. The policies that influence the strategies are displayed in red and importantly influence building envelope changes as can be seen by the connections shown in Figure 4.1.

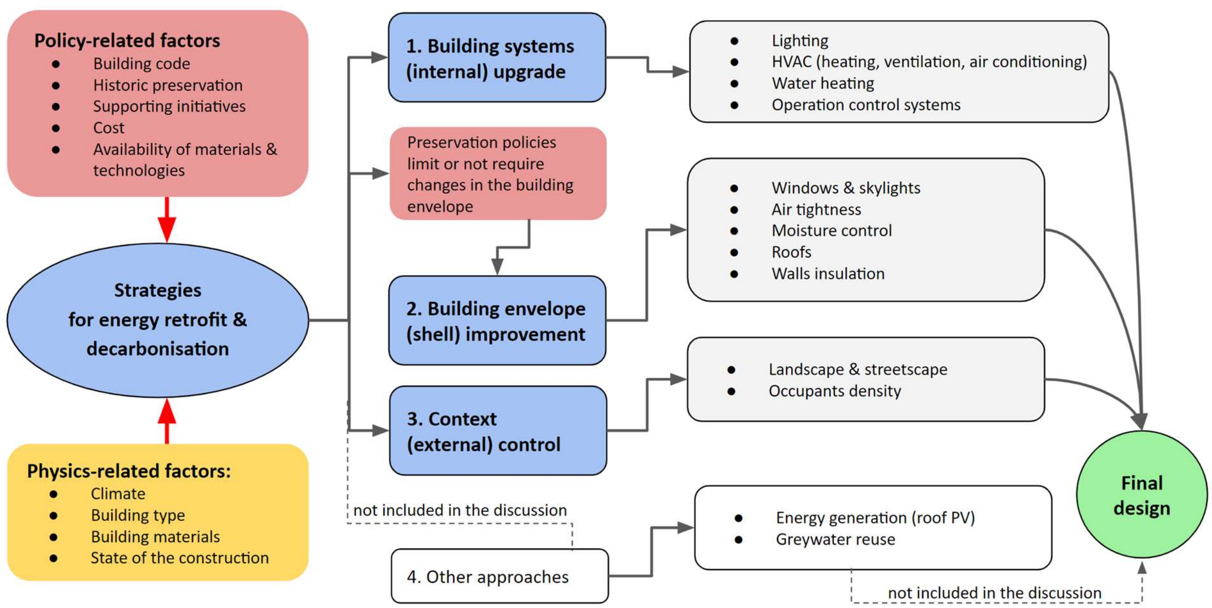

Figure 4-1 Design process diagram, with 4 categories of retrofit strategies that are influenced by physics-related factors and policy related factors

4.1 Strategies of buildings' decarbonization and energy retrofit – overview

Strategies that are considered for a retrofit project typically address two main reasons for the inefficiency of a building: first, grandfathered inefficient building systems such as lighting, cooling, and heating equipment and second, uncontrolled heat transfer through windows, the loss of conditioned air through air leaks, and not sufficiently insulated envelope. Hence, internal systems upgrade, and envelope improvement are two major categories of strategies to improve energy performance. A large number of modeling and case studies presented in scientific literature investigate the combination of system and envelope upgrades to reach the optimal and efficient level of the retrofit project (Fernandes and Regnier 2022; Regnier et al. 2022; Timur et al. 2022). A combination of strategies showed the best results with the range depending on the initial conditions and other factors. For example, a study of 32 old non-residential buildings (45% of them being historically significant) located in 25 states of the country and different climate zones were investigated (Martinez and Choi 2018). The data after the retrofit of the systems with and without the envelope (with the average five years after the retrofit measures) were analyzed. Envelope-inclusive retrofit (without wall insulation) showed an average of 28% energy savings resulting in 11.7% energy cost savings (compared to no-retrofit data), while HVAC and lighting system upgrade alone showed 8.8% energy cost savings or 2.9% lower, proving the cost significance of system upgrade (Martinez and Choi 2018). Similarly, retrofit actions for two-story traditional buildings in the Mediterranean climate of Turkey displayed up to 30% energy savings with envelope improvement (without wall insulation) and around 65% when combined with HVAC improvement (heat pump installation)(Timur et al. 2022).

However, besides changes in the internal systems and the building envelope, two more types of strategies could be considered to shift the building's performance towards carbon neutrality goals, namely: addressing the building's context, for instance, streetscape and occupants' density; and second – the energy generation (e.g., roof photovoltaic (PV) panels or building integrated photovoltaic (BIPV). For the scope of this research PV and BIPV systems were not included as they are less suitable for historic buildings. However, focusing on the building's context could be a suitable solution in an old or historic built environment. Therefore, strategies related to three important elements of a building will be analyzed in this chapter: (1) internal building systems upgrade, (2) shell or envelope improvement, (3) and context control strategies. The investigation results will be summarized in tables 1 to 4 to deliver a simple way to compare the efficiency of investigated strategies and the key influential factors. The outcome of this section is expected to provide the knowledge of practical solutions to formulate recommendations for California building policy adjustments, which will be presented in Chapter 5.

4.2 Building internal systems upgrade

Upgrading a building's systems is an essential measure for old buildings as the old equipment is often inefficient compared to contemporary technologies due to the design and/or loss of efficiency with age. The internal building systems include lighting systems, heating, ventilation, air conditioning (HVAC) systems, and water heating. New systems that control and regulate parts or the whole building also increase efficiency. Smaller appliances such as cooking equipment, washer and dryers, or computers impact the overall performance but are usually not included in the studies, though some of the studies include them in the retrofit design analysis (eg. Fernandes and Regnier 2022). It is crucial to highlight the significance of the internal system's improvement for historic buildings due to the significant limitations of envelope interventions because of historic preservation concerns (Piselli et al. 2020). This is especially true in cases of high historic preservation status (Boote 2018). In other words, the system upgrade could be the only efficient, feasible and allowed energy retrofit strategy for some historical or old buildings.

4.2.1 Lighting

Upgrading indoor and outdoor light sources by switching old lights to a light-emitting diode (LED) is a simple measure to improve energy performance. It is already well-established and keeps growing across the nation, with an increase from 4% in 2015 to 47% in 2020 of homes having all or almost all LED lights (EIA 2022). The upgrade can be achieved by re-lamping existing fixtures or by changing to new LED integrated fixtures. The high efficiency of LED light sources - about 80% more efficient than incandescent bulbs - delivers significant energy reduction. Accordingly, this step should be implemented in the buildings that still grandfather old bulbs, which were found more often in low-income and rented spaces in the US (EIA 2022).

To continue, combining LED lights with control systems such as motion or occupancy sensors, automatic daylight dimming, or zoning controls has the potential for further savings. For instance, a laboratory study compared upgraded office space with and without lighting controls, in addition to the change to LED instead of existing fluorescent lights, which are already more efficient than incandescent bulbs. The result showed 20% annual lighting energy savings for system updates without switching to LED, 38% with only changing the fluorescent light source to LED, and 72% by combining the measures (Shackelford et al. 2020). Furthermore, LED light sources have the co-benefit of reducing air cooling load. While incandescent and fluorescent light sources release about 90% and 80% of their energy as heat, LEDs utilize about 95% for lighting, and only about 5% is emitted as heat (Energy.gov 2022). Lessening additional heat from equipment can be significant for non-residential buildings such as offices and retails with high occupancy and a large number of light fixtures, especially during cooling periods, as this reduces the HVAC energy consumption (Fernandes and Regnier 2022).

4.2.2 HVAC – heat pumps and energy recovery ventilation

Heating ventilation and air conditioning (HVAC) is the most significant contributor to the operational energy consumption in an un-retrofitted historic building, with heating being the primary contributor even in the hot/humid climate of Atlanta (Figure 4 -2). Accordingly, HVAC system upgrades present a significant opportunity to reduce energy consumption. A heat pump (HP) system is often named to be the optimal solution. An HP system combines heating and cooling and is the most advanced modern technology offered on the market and has been shown to be an essential and required component for decarbonizing buildings, including existing and historic (Li, X. et al. 2022). Heat pumps use electricity to transfer heat (not to generate), making the technology significantly more efficient than gas heating or conventional electric heating.

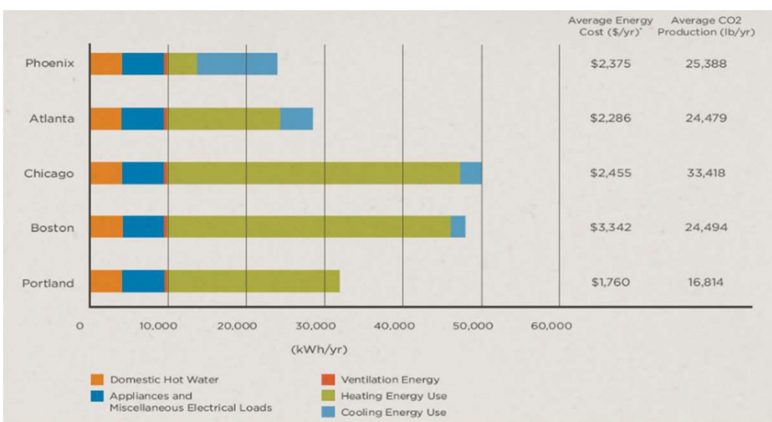

Figure 4-2 Annual energy use for historic residential building with low efficiency HVAC. Note the significance of heating load including cases of Atlanta, GA with hot/humid climate and Portland, OR in temperate climate (adapted from Frey et al. 2012)

A ground-source HP, while more expensive, can also operate in a cold climate with winter temperatures below freezing, showing higher efficiency than air-source HP. Use of ground-source HP in Mediterranean climate with short but cold winter in the southwest of Turkey showed 52% energy savings in two studied single family house, that are more than hundred years old in Turkey (Timur et al. 2022) Similarly, analysis of the retrofit of an existing heating system that used heated water for air conditioning in an Italian historic building showed a reduction of annual energy consumption and CO_2 emission up to 73% and 69%, respectively (Figure 4-3) when the system was switched from a gas boiler to ground source HP (Piselli et al. 2020). Therefore, retrofitting with a HP system contributes to decarbonization by both the substantial increase of efficiency and by electrification of the building.

Besides HP's efficiency, a valuable advantage of technology is the combination of heating and cooling in one, easier controlled system, unlike the conventional and grandfathered HVAC with separate equipment for heating and cooling. HP transfers heat from the outdoor environment to the indoor during the heating season, and for cooling in the summer months, the heat is transferred from inside to outside. The energy saved on the air heating and cooling depends on the initial HVAC conditions. It can be as high as 65-68% for summer and 22-25% for winter in a small office building in the mild climate of Berkeley, California (Fernandes and Regnier 2022). Combining the two systems in one simplifies installation and maintenance and reduces embodied energy of the HVAC. It also increases adaptiveness and flexibility for possible issues related to climate change, such as atypical heat waves or low-temperature events. Finally, HPs vary from small, ductless so-called mini-split systems, suitable for single-family houses, to large whole-building systems. In both cases, the efficiency increases additionally due to their flexibility to schedule and use heating or cooling only when and where it is needed (Lu and Warsinger 2020).

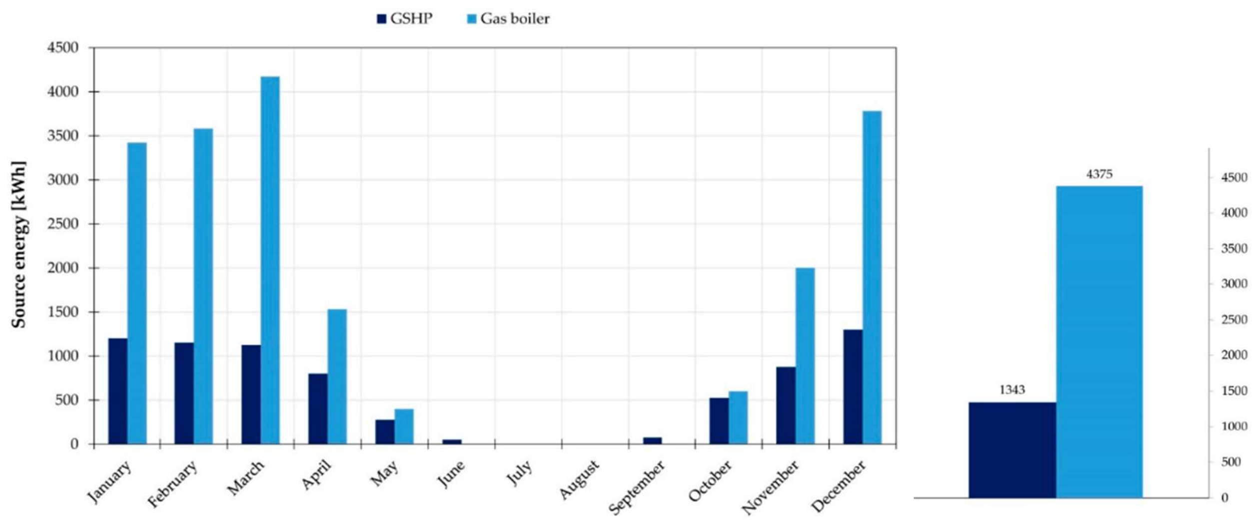

Figure 4-3 (left) Annual energy consumption and (right) annual CO2 emissions by ground source heat pump (GSHP) vs gas boiler heating system. Case study of historic building in Italy with Mediterranean climate, similar to costal California (adapted from Piselli et al. 2020)

Traditional ventilation systems exhaust conditioned indoor air, losing with that all the energy for heating or cooling the air. Heat recovery ventilation (HRV) or energy recovery ventilation (ERV) systems use a heat exchange to transfer heat from warmer air stream to the cooler, while supplying fresh air and exhausting the interior air. This is preserving about 70%-80% of HVAC energy (Energy.gov 2022). The ERV is different from HRV as besides heat it transfers vapor, and so controls the humidity, which makes it more efficient for hot-humid climates. As both HRV and ERV are relatively expensive equipment and require more maintenance compared to conventional (fan) ventilation, the systems showed the highest cost-efficiency in the regions with extreme winter and summer temperatures. Importantly, the technology is necessary for new well insulated buildings and for retrofit projects aiming high performance such as Deep Energy Retrofit, Passive House (more than 60 – 75 – up to 90% energy savings) or Net Zero (similar energy savings with renewable energy generation). Those types of projects significantly reduce air leaks through the building shell and thus rely on the mechanical ventilation to provide healthy indoor air (Less and Walker 2015).

4.2.3 Water heating

Water heating is closely related to the HVAC system, as it can be a part of it, or it can work separately. The source of the heat for water in decarbonized buildings could be either electricity or direct solar radiation. First – electricity – an air-to-water or ground-source heat pump water heater (HPWH) can be used. Technology was developed in Europe several decades ago and showed its efficiency. Nevertheless, only recently the U.S. customers began to consider the technology, which was shown as a missed opportunity (Mills 2022). The efficiency of air-to-water HPWH can save, for example, 63.7% of water heating energy in Houston, TX and 40.2% in Chicago, IL, compared to the conventional electric resistance water heater leaks (Willem et al. 2017). One of the criticisms of HP is the potential leaks of refrigerants that have high global warming potential (GWP). However, relatively new technologies developed in Japan (the leader of HPWH) use CO2 as the refrigerant, which has lower GWP and shows energy savings of up to 75% (compared to gas water heaters) while reducing environmental impact from leaks (Willem et al. 2017).

The second approach is the use of solar thermal radiation for water heating. It is a basic vernacular strategy that was developed with modern technology. Heat collectors could be installed on a horizontal or tilted roof, similar to Photovoltaic panels. The tubes or the container with water are shielded with glass to accumulate more heat and protect the heat from loss, and double glazing is more efficient than a single (42% and 30% efficiency, respectively). Additionally, an evacuated tube design could be used for colder climates. A special dark-shaded coating is used on the glass to increase the heat gain. The heated water accumulated in the insulated water tank for later use. The range of energy savings, and water temperature depends on the geographical location, exposure to solar radiation and season, but the water temperature can be substantially high even at low ambient temperature. For example, in Egypt, the water was heated up to 62°C (Marmoush et al. 2018). The life cycle analysis for the U.K. of the two types of solar water heaters showed the feasibility and sustainability of the technology for the country. Solar water heaters were comparable to heat pumps (at the moment of study, 2014) as a tool for the building sector's decarbonization. The GHG emissions savings were estimated at around 88% compared to gas water heating (Greening and Azapagic 2014).

Even in the cold climate of Helsinki, Finland, solar thermal water heaters have shown to be energy and economically effective. A study of Arabzadeh et al. investigated the installation of collectors on the roof of a traditional four-story apartment building. The size varied from $52m^2$ to $82m^2$ (~560 to 880 sq ft), and the collector-to-tank ratio was from 13 to 17 m^2 per m^3 of the tank's volume. Consumption of district heating energy by the building was assessed to decrease by 22% to 32% with the cost-optimal solar system (Arabzadeh et al. 2019). However, the drawback of the solar thermal system is that it cannot ensure to supply 100% of hot water demand and need to be paired with other water heating equipment (Greening and Azapagic 2014). Combinations with PV systems and heat pumps are the most common in the green building practice. For example, solar assistant heat pumps for water heating showed about 20% GHG reduction for Canadian houses (Asaee et al. 2017a).

The significance of water heating as an integrated building system (used for domestic water use and space heating) is the result of the high heat capacity of water that could be used as thermal mass or storage for heat. The water heated in the middle of the day when the supply of solar-generated electricity or solar thermal energy is high can be accumulated in a thermally insulated water tank and used during evening pick hours. For example, about 73% of annual thermal savings were shown in Italy with a ground source to the water heat pump for domestic water space heating uses (Piselli et al. 2020). A large study in Canada showed that 71% of the Canadian housing stock could be eligible for the air-to-water heat pump. Using the technology for retrofit would result in 36% end-use energy savings and was indicated as part of the decarbonization strategy of the Canadian building sector (Asaee et al. 2017b).

4.2.4 Operation controls, Building energy management systems (BEAMS)

Operational control systems are another type of internal building upgrade that can maximize efficiency of energy use and mitigate energy usage resulting from occupant behaviors such as leaving the heating on in unoccupied rooms. The behavior patterns contribute to the energy performance of the building. A study of behavior influence in a listed residential building in London revealed that behavior change could be more influential than energy retrofit, when historic preservation policies limit the latter. The upgrade of the building envelope (wall and roof insulation, secondary glazing, draughtproofing) and building systems upgrade (insulation of hot water pipework and boiler upgrade) was modeled in three potential retrofit scenarios (minimum, medium, maximum) and the base case (no retrofit). Based on the monitoring surveys, energy consumption was classified into three behavior patterns – reasonably low, average, and reasonably high energy consumption behavior - and compared. The modeling showed that the high energy consumption behavior could result in 2.2 times higher energy use than average, mainly due to the air heating. This behavior may offset the benefits of energy retrofit measures (Figure 4-4). Also, the difference between average and low-energy behavior was less significant than between average and high-energy behavior. Thus, the measures targeting reducing energy-intensive behaviors should prevent overconsumption instead of attempting to reach the lowest consumption level. Overall, the behavior factor is vital for buildings with limitations of physical changes as the best energy behavior showed savings of 62-86%. However, the increase in retrofit improvement reduces the significance of behavior factors (Ben and Steemers 2014).

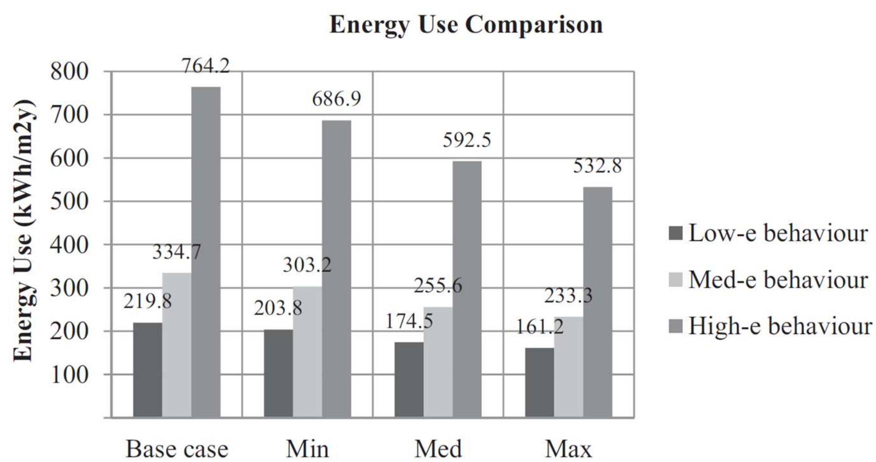

Figure 4-4 Influence of behavior on energy consumption - Base Case and three levels of retrofit with three behavioral scenarios. Low-e is an energy saving and High-e is an energy wasting behavior. Note, that High-e behavior can double energy use and offset retrofit measures (adapted from Ben and Steemers 2014).

To continue, modern operation control systems could minimize the human factor. Technologies from simple motion sensors, timers, and daylight sensors to smart building systems, also known as building management systems (BMS) or building energy management systems (BEMS), maximize the efficiency of electricity usage. As discussed in the previous section, some modern HVAC systems can vary the performance in time and intensity of work depending on the occupancy and type of room. For example, a multizone variable air volume ventilation control system can save up to 18% to 56% for an average house and 12%–55% for a large house. The higher savings were shown for the regions with the hotter climate and the more significant cooling load (Los Angeles, Ca, Houston, Tx, Honolulu, Hi) (Lu and Warsinger 2020).

Time of energy demand is one of the crucial factors of decarbonization as it influences the uneven distribution of supply and demand on the grid, as explained in section 2.6. Smart building systems (BMS or BEMS) save energy by balancing the demand for lighting, HVAC and appliances efficiently. The computer integrated in to the BMS communicates with the electric grid (smart grid), gathers data and makes predictions. Web-based technologies such as Wireless Sensor Network (WSN) or, more specifically, the Internet of Things (IoT) and Web of Things (WoF) level and optimize all the devices and sensors. Sensors provide the system with external context data (e.g., weather or electricity supply) and the real-time status of the appliances. The minute scale measurements and communication provide high system accuracy, which is essential for supply-demand balance of the grid, still maintain relatively low internet use (Ibaseta et al. 2021). The systems utilize maximum electricity at the low demand/high supply hours (middle of the day and night) and minimize during the peak-demand evening hours (Figure 2-4, Duck Curve). Energy savings with BEMS are estimated to be 10-20% higher than individual controls of lighting, HVAC and other equipment (Sayed and Gabbar 2017).

The most holistic BEMS coordinates four components: (1) energy generation, for example, roof PV or solar heating; (2) energy storage in the form of electric batteries or thermal such as water tanks and heat/ice storage units; (3) energy demand; (4) control and communication (Mariano-Hernández et al. 2021). The advantage and cost efficiency of retrofit with smart building systems is seen in large-scale projects as the system can manage dozens of devices simultaneously (Ibaseta et al. 2021). Lastly, behavior changes with the help of control systems have a co-benefit of lower embodied carbon solution as they use fewer material resources and prolong the life of the equipment in the building. To summarize, smart home systems that tend to be used more commonly in new buildings could play a significant role in historic buildings, especially with limited opportunities for envelope improvement.

4.2.5 Non-residential buildings

Residential buildings represent most of the building stock - more than 70% in the U.S. by floor area. However, the commercial and residential sectors consume an approximately equal share of national energy consumption (EIA 2021). National Renewable Energy Laboratory (NREL) studied thermal energy efficiency and retrofit potential across five climate zone in the U.S. The study showed that while for residential buildings climate plays a significant role, for non-residential buildings, the function of the building is more influential. The function determines the occupancy, equipment and its energy demand, outweighing the challenges or positive influences of the climate. The range of operational energy intensity varies from 3–41 kBtu/ft2 for warehouses up to 100–190 kBtu/ft2 for the most demanding segment of food services. Office buildings represent the largest share of commercial building types, with 28% of the floor area and use 22% of commercial thermal energy. The use of small, packaged HVAC units, even in large buildings, is an area of improvement, according to NREL. Ventilation is a large driver of inefficiency, especially for commercial buildings where large occupancy requires a high rate of fresh air supply (Reyna et al. 2022). Therefore, NREL recommended retrofitting all commercial buildings' HVAC systems with heat pump conditioners coupled with ERV or HRV within all the climate zones of the U.S. (Reyna et al. 2022).

Restaurant buildings in the U.S. have the highest energy consumption per square foot, using 30% of thermal energy for space heating, 22% for ventilation due to cooking and 33% for water heating for dishwashing (Reyna et al. 2022). The use of energy recovery ventilation is challenging in restaurants due to smoke and grease in the exhaust air. However, demand-control ventilation and efficient electric water heating can improve the energy efficiency of the sector (Reyna et al. 2022). Also, more efficient cooking and refrigerating appliances are opportunities to improve efficiency. Similarly, a U.K. study highlighted the restaurants-pubs sector as the most profligate energy users and showed that energy use could be even higher than previously estimated (Mudie 2016). However, evaluating energy use per total floor area could be misleading, while the kitchen size, which is correlated with the equipment load, is a better measurement. Also, the number of meals is not always an influential factor for energy intensity, as commercial kitchens tend to keep all the equipment on independently of the number of meals prepared (Mudie 2016). In California, restaurants and food stores with refrigeration were also shown as the most energy-intensive non-residential sector. They consume three times more energy than the average commercial building and together represent 17.7% of energy use in the state commercial sector, while offices use 16.1% (California Energy Commission 2015). Importantly, there is a very limited number of studies about food service buildings' energy efficiency, which may indicate a missing opportunity to improve the commercial building sector.

4.2.6 Internal systems conclusion

Internal system upgrades are key in improving energy performance and decarbonizing an old or historic building. This is mainly because of three reasons:

1. The grandfathered equipment is typically outdated and inefficient.
2. The transition to electricity from gas and other fossil fuel burning is required for building decarbonization.
3. Constraints of historic preservations and the difficulties of work with older structures leave limited opportunities to improve the building shell.

Switching to LED lighting is the "low-hanging fruit" and the only retrofit measure that advanced significantly (about half of lights in the country) and must continue to be part of a retrofit, but not a large enough contributor to be the only solution. On the other hand, heat pumps (HP) for air heating and cooling and for domestic water heating showed the most promising results and were often named as the essential and required element to decarbonize old buildings. Energy savings depend on conditions but showed 25-36% on the lower end of the spectrum up to 52-73%. Energy recovery ventilation was not indicated as a necessary step and showed the most effectiveness in the more extreme temperatures and for non-residential buildings. Operation control systems are valuable tools for decarbonization as they help demand-supply balance of the electric grid. They should be used for both residential and non-residential sectors. Also, among non-residential buildings, food service (restaurants and food stores) is the most energy-intensive sector and represents an opportunity for improvement. Lastly, control systems can increase the efficiency of each system and the whole building while also mitigating the negative influences of unmindful occupant behavior.

4.3 Envelope / building shell improvement

The laws of thermodynamics determine the performance of a building envelope, where conduction, convection and radiation are the main forces defining the heat transfer from higher to lower energy levels. Radiation is the main factor of heat gain through the glazing of windows or skylights. Airtightness or limitation of air leaks prevents heat loss through convection – raising the warmer air. Conduction, as a part of a building system, can be seen in insulation and thermal mass. Insulation is a material with low conductivity lowering heat transfer and evaluated with R-value (heat flow resistance or insulation value per surface area). Thermal mass is the material with high heat capacity that accumulates thermal energy and releases it later. For instance, absorbing heat during the hot day and release during the colder night (Kamel and Memari 2022). Thermal mass commonly plays a larger role in historic buildings constructed from brick or other masonry materials. The thermal mass of old buildings was used as an argument for the inherited energy efficiency of historic buildings, which was disproved by later studies (Boote 2018). This and other differences between the old and modern building techniques influence the retrofit strategies and will be discussed in this section.

Envelope improvement can significantly reduce building energy consumption when substantial work is permitted and financially feasible. Depending on the climate and initial condition of the building, the energy savings can be in the range of 25-50% (Kamel and Memari 2022) and up to 80-94% when Passive House principles for old and historic buildings are used (Bastian et al. 2022). The high values emphasize the large potential of energy savings. However, there are two major obstacles to the deep energy retrofit design. First, shell improvement for old and historic buildings is often challenging and limited due to preservation requirements, access to certain components of the building, and cost efficiency. The second significant consideration in the envelope retrofit is embodied carbon. While, for example, additional insulation reduces operational energy consumption, it simultaneously increases embodied energy. Balancing the tradeoffs is important when the goal is to decarbonize the building sector. Therefore, strategies to address old buildings' inefficiency will be examined with those positions in mind. The discussion will go as follows: (1) windows and skylights, (2) Air tightness (infiltration) improvement, (3) moisture control, (4) roof improvement, and (5) walls insulation.

4.3.1 Windows and skylights (glazing)

Windows represent a large advantage by providing natural light and view but may cause about 30% of total heating and cooling energy losses through glazing's conduction (Berardi 2019; Jiang et al. 2021). First, about 84% of shot wave solar radiation as sunlight enters through the clear float glass to the interior space and is trapped there as long waves (heat) radiation resulting in the heat gain (Sullivan 2013). Heat gain, when controlled, could be a positive factor, often called passive solar heating and can reduce the required energy for heating. However, uncontrolled solar heat gain can cause overheating of the indoor space leading to discomfort and increased energy load for space cooling. This issue is extremely prominent for west-oriented windows as already heated during the day interior gains more direct short-wave radiation with the lowered sun at the time of the electricity pick load. Counterintuitively, south-oriented windows are better for preventing excessive heat gain in many regions as the high summer midday sun is easier to shade, and it penetrates less into the interior space. Thus, the orientation of the windows needs to be studied to find the most suitable retrofit solution.

On the other hand, glass transfers heat (from a warmer environment to a cooler) through conduction, which typically results in interior space heat loss. Heat loss by a building envelope is measured as U-factor, the inverse of R-value (heat flow resistance), where U=1/R. The U-factor of a single glass window is very high, about 1, and R-value is very low - about 0.91. Additionally, glass prevents heat loss mainly with the thin air layers along its surfaces so that the wind can reduce the insulation property of a window even further. For comparison, the Californian building code for new construction requires in most climate zones windows with a U-factor of a maximum of 0.32 (about three times more energy efficient than a single pane), and the typical wall assembly requires a minimum R-20 (about 22 times more heat transfer resistant). Thus, single-pane windows are greatly responsible for heat loss, especially in north-oriented windows where the indoor-outdoor temperature difference is larger, so the heat flow is higher.

From another perspective, natural light is considered to be the healthiest for people and saves energy on indoor lighting. However, when not managed properly, excessive daylight through the glazing can create discomfort to the eyes due to the glare and thus needs to be managed. Also, glass reflects some sunlight, for example, 8% (4% per surface) at a 30° angle. However, when it is at an 80° angle, for instance, during low evening sun, a window can reflect as much as 50% (Sullivan 2013). This factor became important in a high-density urban environment when reflected light from one building may create overheating of others, increasing energy for cooling (Makvandi et al. 2019). Window-to-wall ratio (WWR) - the area of the windows divided by the total wall area - is typically higher in larger commercial buildings, making the glazing quality a more significant factor for this type of structures (Nutkiewicz et al. 2021). As more than half of commercial buildings in the country were constructed before the adoption of the first energy standards (the 1978), windows are one of the key targets of office buildings (Martinez and Choi 2018). To summarize, the WWR, exposure to direct or reflected sunlight and quality of the windows determines if the windows provide beneficial or unfavorable features for the building.

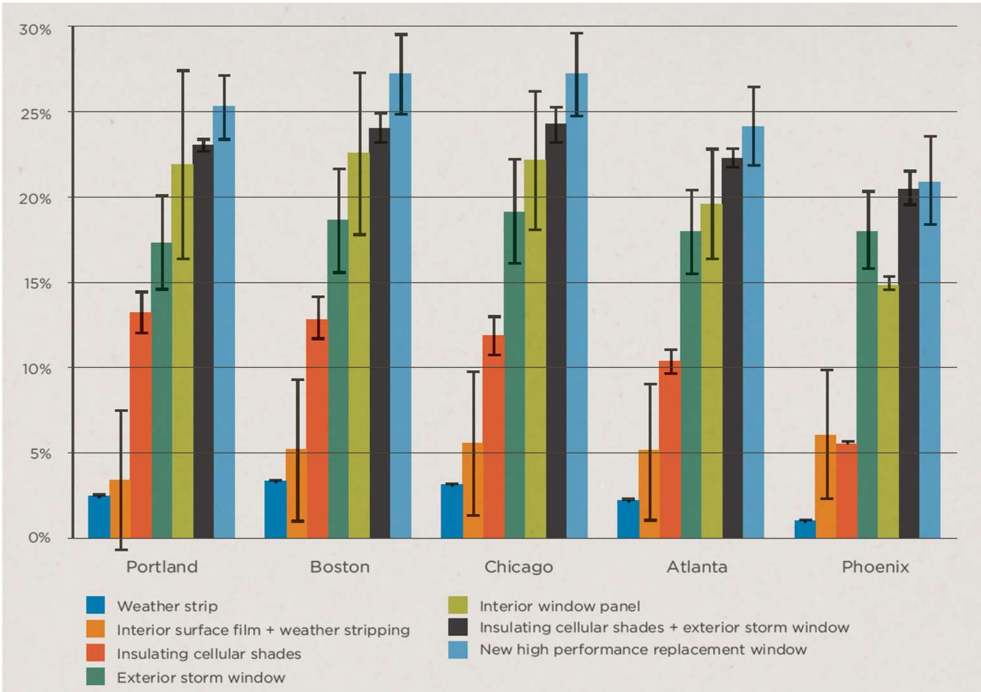

Figure 4-5 Annual energy savings for different window retrofit measures and different climates (Portland - temperate, Boston & Chicago cold, Atlanta - hot/humid, Phoenix - hot/arid climates) (adapted from Frey et al. 2012)

One approach is replacing the windows with double or triple-glazed, well-insulated, low-emissivity (low-E) high-performance. When selected and installed properly, new windows have sufficient protection from heat gain, heat loss, and air tightness of the assembly. Installing new, high-performance low-E windows shows the highest level of energy reduction and higher cost-efficiency in colder climates (e.g., Boston) (Figure 4-5). A cost-efficient alternative to new windows for residential houses in cold climates could be exterior storm windows or interior window panels. In a cooling-dominated climate (e.g., Phoenix), interior surface films, including low-E films, offer the highest return on investment rate (Frey et al. 2012). The film could be applied directly to the existing glass to reduce the heat gain. Low-E films also reduce U-value, lessening radiant heat loss. Importantly, the orientation of the window also plays a significant role. North-oriented windows do not have direct sun and are thus rarely responsible for heat gain, but in case of low quality can be the major cause of heat loss. On the contrary, south, and even more west-oriented windows tend to affect heat gain unless properly shaded (Berardi 2019). Consequently, the north windows will more likely benefit from a replacement, while the south and west windows will benefit from film application.

An emerging smart windows technology that can benefit some energy retrofit projects is a thermoresponsive hydrogel - an adaptive or dynamic material. The technology uses a common medicine thermoresponsive material that changes its property from hydrophilic to hydrophobic at the rising temperature. The heat changes the structure of the polymer chains shifting from transparent to opaque at the temperature of 30 - 31°C (86-88°F) (Jiang et al. 2021; Zhou, Y. et al. 2020). Importantly, there is no visual effect of the hydrogel on the glass when it is colder than the temperature of the change (Figure 4-6). The study of four locations utilizing hydrogel window films for double-pane windows showed annual cooling energy savings of up to 8.1% in Tucson, AZ, with the lowest at 3.1% in Los Angeles, Ca(Jiang et al. 2021). The high thermal capacity (4.35 kJ /kg K) of hydrogel also adds to energy savings by postponing the heat to after peak load hours. When a thicker layer (1 cm) of hydrogel is used for new windows, the annual HVAC energy savings could reach up to 19.1%, 24.3%, and 44.6% in Shanghai, Las Vegas, and Singapore, respectively (Zhou et al. 2020). The material can be used as a film to apply to existing glazing, which is critical as a retrofit solution when windows cannot be changed (Jiang et al. 2021). Sound reduction and solving glare issues are co-benefits of the material, making it desirable for office buildings in busy neighborhoods. However, the visual properties of this material would restrict it from being used on the historically significant (so-called listed) buildings, but it can be suitable for some old commercial buildings in the historic districts.

Figure 4-6 Smart thermoresponsive window treatment change opacity at surface temperature of 31°C (adapted from Zhou et al. 2020)

From the historic preservation perspective new windows could be seen as an invasion into the streetscape and not permitted. In some cases, new glazing is allowed when it visually similar to old, but that could lower energy performance (Nehru 2022). On the other hand, new glazing on an historic facade can be seen as a sustainability statement of the society to highlight the integration of history into contest of modern life. Visual characteristics of the film applied to historic building are also monitored to preserve authentic view of the building and avoid coloring of the glass (Figure 4-7) *(Boote 2018).*

Figure 4-7 window film reducing heat gain applied to listed building in Los Angeles. Left – blue tint was not accepted by historic preservation committee. Right – colorless film was approved (Adapted from Boote 2018)

Skylights and Tubular Daylight Devices (TDD) or light wells are other tools that should be considered during a retrofit design, as they provide large advantages. Skylights and light wells are suitable for many buildings in historic districts as they do not influence the buildings' appearance on the street level and are the most effective for low-rise buildings. Energy saving could come in a few forms: natural ventilation, controlled heat gain, and natural light. The depth of the ceiling-roof assembly and the orientation of the tilted skylight are the influential factors besides the skylight-to-roof ratio (SRR). The first is crucial as the thicker ceiling provides natural shading but reduces the amount of light. A Korean study argued that the typical recommendation of 5-6% of SRR shows optimal results only when modeled without ceiling thickness. For the Seoul and Ulsan (Korea) locations (which are comparable by latitude and weather to Californian climate zone 16 - Lake Tahoe or mount Shasta), energy savings by passive heating and natural lighting were modeled. They showed higher savings at the thinner ceiling, optimal 5% SRR with no thickness resulting in about 10% energy savings. However, with a 1.5 m thickness, optimal SRR was found to be 8% with 4.2% and 9% savings for Seoul and Ulsan, respectively. No HVAC or lighting energy reduction was found with the ceiling thickness above 1.5 m (Irakoze 2021).

Furthermore, northeast orientation skylights can be favorable for buildings lacking south windows and with higher demand for passive heating in the first part of the day. However, south-oriented skylights must be combined with shading devices to prevent overheating with high midday sun radiation. For example, in Berkeley, California, where cloud cover of more than 50% during the heating season provides diffusion of sunlight, clear glass double glazing south-oriented skylights of total 7.2m2 (77.5sq ft) tilted of 40° showed significant energy savings with minimum embodied energy investment. The skylights were combined with movable and scheduled insulation of the glazing, scheduled shading, natural ventilation, and thermal mass wall. The thermal mass was created with a brick wall at the north side of skylight that accumulated the solar heat and released it during the night (Figure 4-8). They showed two-thirds of HVAC load reduction. The cooling was reduced by nearly 80% with the internal rolled-blind shading of the glass and natural ventilation was scheduled depending on the outdoor temperature. The heating load reduced by more than 50% with optimal timing of movable insulation (longer than nighttime) and thermal mass (Rempel and Lim 2019).

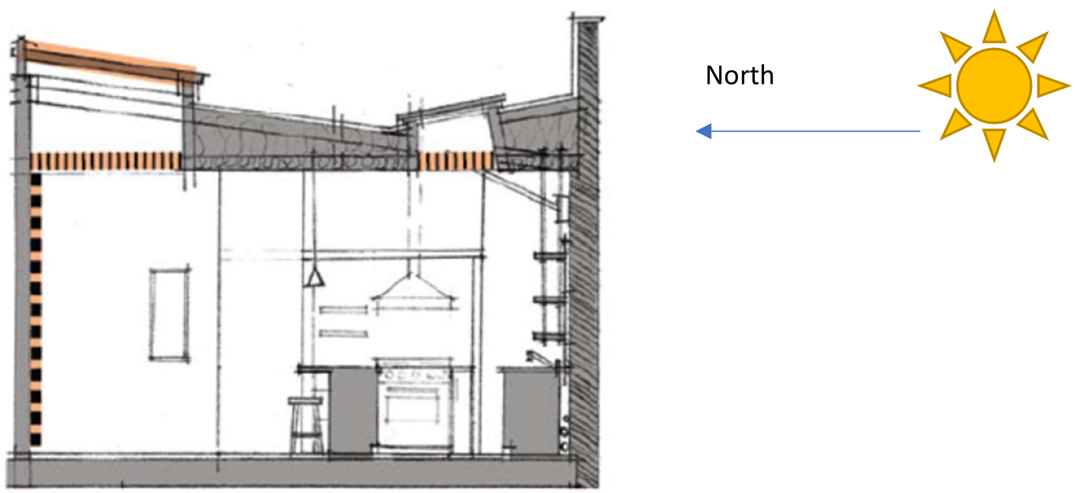

Figure 4-8 Section view of the residential unit (adaptive reuse retrofit). Movable insulation of skylights to reduce heat losses during the night (fine dashes) and additional brick wall as thermal mass to accumulate solar heat during the day and release at night (heavy dashes) (adapted from Rempel and Lim 2018).

A tubular Daylight Device (TDD), also known as a light tube, is a useful tool to deliver natural light at a location where a skylight cannot be installed or there is a risk of overheating and glare. Similar to skylights TDD present an opportunity for historic buildings as preserve facades and streetscape. Savings on the lighting could be dramatic, especially when combined with updated LED systems. For example, the combination of new TDDs and upgraded LED lighting in small commercial buildings in California resulted in 85% of total lighting energy savings. The LED light was combined with infrared occupancy photo sensors for automatic dimming and turn-off and the savings we found regardless of window orientation (Fernandes and Regnier 2022).

4.3.2 Air tightness (infiltration) improvement

The air tightness of a building describes how well the building envelope prevents air leakage, which is essential from three perspectives. First, as the air moves from warmer conditions to colder (typically from inside to outside), it transfers heat, creating significant heat loss. Second, the air pressure difference makes drafts that could cause discomfort for people inside and decrease indoor air quality in case of exterior pollution (proximity to busy roads, industrial zones and/or exposure to wildfire-born pollutants). Third, the vapor transmitted with the air can cause unfavorable moisture in the building shell, resulting in additional energy losses and potential mold or rot. The latter is responsible for faster degradation of the structure and also jeopardizes indoor air quality. However, depending on the climate and particular measures, increased airtightness also can cause moisture accumulation in the body of the building.

Air leaks or infiltration can be estimated when the internal air pressure is changed, controlled, and measured and, in essence, shows how fast the indoor air will be changed due to leaks. Normalized average volume (cubic feet) per time (minute) per area (square foot) under the pressure of 75Pa, or CFM/ft2 at 75Pa, is one of the common units of air infiltration through the envelope. The approximate benchmarks of the test are ~1.00 CFM/ft2, ~0.60 CFM/ft2, 0.40 CFM/ft2 and 0.25 CFM/ft2 for poor, leaky, standard and excellent building condition, respectively. It also can be measured in liters per second per square meter, cubic meters per hour per square meter and under other pressure. The variations of the units make the measurement more difficult to use, especially in international settings such as reports and building standards. Another way to measure airtightness is blower door pressurization tests, where the number of Air Changes per Hour at the pressure of 50 Pa (ACH50) is the unit, with a benchmark of the standard condition of 7ACH50 (equal to 0.35-0.40 CFM/ft2). The 2021 International Green Construction Code (IgCC) requires air leakage not to exceed 0.25 CFM/ft2 at 75Pa or 5 ACH50. Passive House certification, the most rigorous certification from an energy efficiency perspective requires even higher airtightness, no more than 0.6ACH50 for new constructions (equal to 0.08 CFM/FT2 at 75 Pa and in some cases 0.11 CFM/FT2 at 75 Pa). The retrofit version of Passive House certification EnerPHit has a threshold of 1.0ACH50.

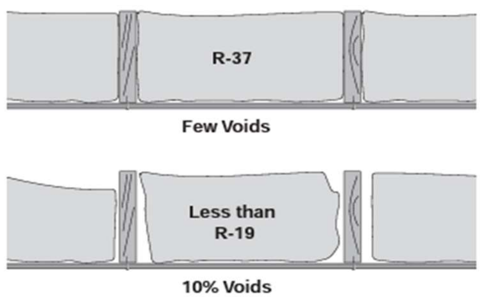

Figure 4-9 schematic representation of the wall with less or more air leaks and related energy losses. R-value is the measure of heat transfer resistance with higher R reflecting better insulation properties (adapted from Musick et al. 2000)

The range of efficiency improvement with increased airtightness depends on the initial conditions of the building, which may vary significantly across the same building type, vintage, and location as the result of various maintenance and the undergone changes (Webb 2017). Study of retrofit potential across five climate zones of the country and different building types reveled in all cases infiltration being the primary contributor of thermal energy inefficiency with the most significant in Cold/Very-Cold climate regions where two-thirds of heat loss in multi-family residential buildings and also being main reason of energy losses in single family houses (Reyna et al. 2022). Another study showed that a structure in average condition (5-7 ACH50) can save about 2-5% of annual energy, depending on the climate. In comparison, a building in a poor state (about 20 ACH50) can see an annual improvement from 5 to 20% (Allana 2020). Kamel and Memari measured energy improvement between 3.5% and 30% for different climates in the U.S. (Kamel and Memari 2022). Deep energy retrofit (DER) can show even higher results – the average air leakage reduction in the U.S. is up to 63% (Less and Walker 2015).

In other perspective, addressing air leaks could be vital for houses in poor states. Besides, less advanced communities that are often exposed to low-quality outdoor air due to close locations to highways or industrial zones would benefit from higher energy savings and indoor air quality improvement. For instance, the uprise of airtightness of doors and windows with gaskets, seals and window replacement in three old school buildings in Korea increased airtightness by about 3.33ACH50. It improved indoor air quality, reducing ultra-fine dust by 23.61%, 48.49%, and 41.40%. Those measures combined with 50mm external insulation also showed more than 9% potential energy savings. The total energy use reduction was found despite a 7% increase in cooling energy, as more than 23% heating savings offset the latter (Jo et al. 2022).

Finally, the energy losses due to air leakage can drastically compromise other energy efficiency investments. For example, the insulation with heat-transfer resistance (R-value) of 38 installed with 10% air voids reduced its efficiency up to half with a final R-Value less than R19, when also accounting for the effect of framing (thermal bridges), drywall and air films (Musick et al. 2000) (Figure 4-9). Air leaks are distributed across the building envelope (doors, windows, walls, ceiling, floors and) and the building's HVAC systems. Smaller but still significant (about 13%) air leaks at the points of plumbing penetration through the walls should also be considered (Figure 4-10). Nevertheless, air leakage diminishing is a feasible, efficient and cost-effective measure. For example, the airtightness improvement of a 13-story multi-unit residential building in Vancouver, Canada, showed an average weighted improvement of 53% in air leakage reduction, ranging from 36% to 72% in different dwelling units (Urquhart et al. 2015). To conclude, in many studies increasing airtightness is named as by far the most effective and energy-efficient measure to improve building performance (Bastian et al. 2022; Ben and Steemers 2014; Kamel and Memari 2022; Musick et al. 2000; Reyna et al. 2022; Rose 2005; Webb 2017). Having in mind the limitations of working with old and historic building's envelope reduction of air leaks in all the existing, old, and historic buildings could be a part of local policies similar to mandated seismic upgrade that was discussed in Section 2.7.

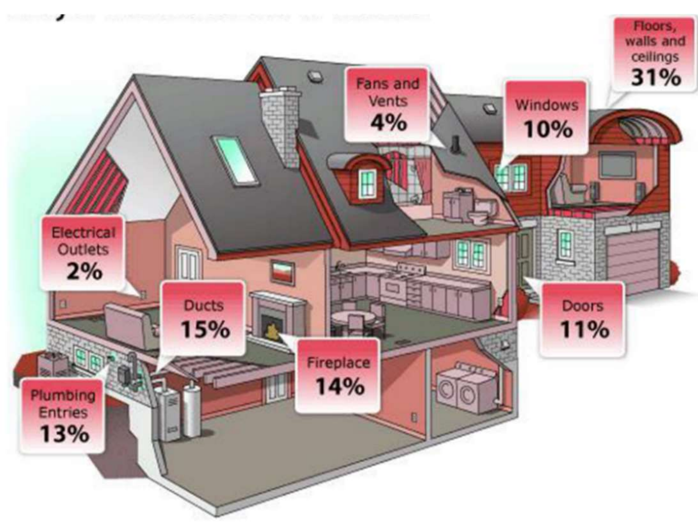

Figure 4-10 Distribution of air leaks across the building - major leaks through the envelope, followed by HVAC systems, and significant contribution of pluming entries. (adapted from Allana 2020)

4.3.3 Moisture control

Moisture dynamics is the prevalent concern of policymakers in the conversation of energy retrofit for historic buildings, as it is common knowledge that retrofit can increase moisture in the envelope by increasing the airtightness of the building intended to conserve energy. It could lead to a loss of energy efficiency (hygrothermal performance) and cause mold growth. In contrast to modern buildings controlling moisture by excluding it with rain screens and membranes, older building techniques allowed moisture to enter the walls and evaporate. This difference creates conflict when current techniques are used on old and historic buildings.

Prior to a retrofit, uncontrolled ventilation through air leaks prevents possible accumulation of moisture with the cost of energy losses. An increase in airtightness of the envelope combined with insufficient natural or forced ventilation may increase moisture damage, harming people with reduced indoor air quality and compromising building preservation (Hao et al. 2020). However, field measures of the indoor insulation application (the most common in the case of historic preservation of facades) demonstrated that while the moisture level in the wall is increasing, there is no significant risk of damage by the moisture. This was shown in the case study of two listed masonry buildings in Copenhagen, Denmark, when normal interior ventilation was maintained (Odgaard et al. 2018). Moreover, old drafty buildings still have moisture-related issues. For example, in Germany, moisture damage was found in 20% of old buildings (Bastian et al. 2022). Therefore, the problem should be solved by finding better practices rather than avoiding building improvement.

There are two sources of moisture – internal (e.g., condensation from indoor air) and external (e.g., rain or fog). The first is often attributed to the increased airtightness of the building envelope. However, it can be avoided by keeping the interior wall surface temperature above 12.6°C (at normal indoor conditions with 50% relative humidity and 20°C ambient temperature), including thermal bridges (Bastian et al. 2022). Thermal bridges are the parts of the building shell with higher thermal conductivity, which result in heat transfer. Thermal bridges are typically found at structural elements; for example, studs are more conductive than the wall itself. Thus, mold growth often happens at the corners or window frames where lower surface temperatures and higher relative humidity can be found. Importantly, with increased indoor humidity, the required wall surface temperature increases. Thus, to prevent moisture movement into the walls, it is important to provide adequate (typically mechanical) ventilation, especially in wet rooms. However, the maximum airtightness for retrofit projects that did not trigger mold growth was shown to be relatively high (similar to Passive House requirements) when ventilation was provided (Bastian et al. 2022). Consequently, reducing air leaks should not be excluded from a retrofit design.

The second source of moisture is the outdoor environment, and one of the most damaging types of precipitation is Wind Driven Rain (WDR) as the moisture is forced into the building's shell with the force of the wind (Zhou, X. et al. 2022). Older buildings control moisture by letting the walls become wet and then dry. Because of that, old and historic buildings are more affected by WDR – a higher amount of moisture was found in a historic wooden wall compared to contemporary. Surface water absorption is a parameter that determines how much atmospheric water from rain or fog may enter the envelope. It is important to notice that the same material in a different part of a historic building can have various moisture absorption (Hao et al. 2020). The moisture dynamic is a complex issue for the retrofit project and especially challenging for areas with more humid climates and/or areas where precipitation level is predicted to increase with climate change.

Lastly, wall insulation, which will be discussed below, is a large contributor that showed both positive and negative impacts on hygrothermal performance (Bastian et al. 2022; Hao et al. 2020; Rose 2005). There is a critique of wall insulation retrofit and the studies that only focus on increasing R-value (Webb 2017b). For instance, a retrofit can advance frost damage in regions with regular temperatures below zero. Frost damage occurs when water on the exterior wall enters the cracks and expands during the freezing, increasing the cracks' size. The increase in damage happens as colder exterior walls (less heat is transferred from inside) cause the water in the wall to freeze earlier (Hao et al. 2020). Similarly, colder (better insulated) walls have lower drying capacity, which is crucial for historic buildings (Webb 2017b).

4.3.4 Roof improvement

Heat gain and loss through a building's roof are typically more significant per surface area than through the walls. The gain is larger as the sun's angle is close to perpendicular, so the solar radiation intensity is higher. The heat losses are also higher when the outdoor temperature is lower than the indoor. The warm interior air rises (convection) and escapes through the roof due to insufficient insulation and air leaks. Hachem et al. (2014) showed increased heating and cooling demands by about 20% and 8%, respectively, on the last floors of residential buildings in Montreal, Canada, compared to the previous floors (2014). That is why in building codes, typically, the insulation requirements for attics or roofs are approximately doubled compared to walls.

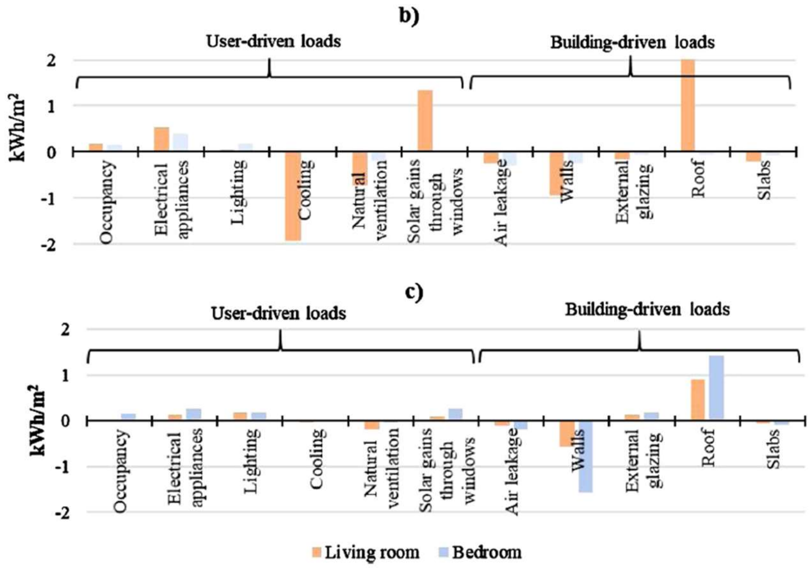

Figure 4-11 Heat gains and losses during the typical week, case studies of historic residents in Seville, Spain. Cases b and c were located on the upper floors and showed major heat gain through uninsulated roofs. Note, in case b the solar gain through windows is allocated to user-driven load as could be mitigated by opening the windows for natural ventilation (Caro and Sendra 2020).

A case study of heritage 2-5 story residential masonry buildings of Seville, Spain, during hot summer showed the middle and lower floors could be retrofitted without additional insulation (with shading, glazing enhancement for south windows and increased natural ventilation during the night). However, the apartments on the last floor showed a major heat gain through the roof, resulting in a large air conditioning energy load (Figure 4-11). The study concluded that insulation for upper floors was a vital retrofit measure (Caro and Sendra 2020). However, Kamel and Memari (2022) in the study for hot and cold climate envelope retrofit, noted that roof improvement with insulation had a smaller impact than other strategies (2022).

Green roofs and cool roofs are other retrofit possibilities. Green roofs with growing plants and trees reduce heat through shading, evaporation from leaves and insulating soil layer. A cool roof is a roof with a high albedo, or the ability to reflect solar short-wave radiation. Surfaces with albedo close to 1.0 (e.g., snow) reflect almost all sunlight. Dark surfaces with low albedo, such as asphalt (0.04-0.19), absorb most radiation and then release or transfer it as heat. Cool roofs use a special white coating material or paint to reflect solar radiation. Both strategies showed a successful reduction of cooling energy use. For instance, modeling of a London office building showed both green and cool roofs being more efficient – fewer hours and lower intensity of HVAC were needed - than applying new insulation to an insulated roof. Cool roofs (albedo 0.7) demonstrated slightly better cooling performance, however, the authors noticed that green roofs would also reduce winter heating energy with the insulation capacity (Virk et al. 2014). Similarly, cool and green roofs demonstrated a 10% and 7.5% reduction of cooling energy in a hot climate (Elnabawi and Saber 2022).

Shittu et al. used LCA to assess cool roofs for hot climates. Retrofit with a cool roof was compared to insulation for two locations with prominent cooling and some heating energy load - Sicily and Jamaica. It was shown that both locations' annual energy savings with cool roofs were similar to energy savings with insulation, but the environmental impact of cool roofs was lower (Shittu et al. 2020). Pisello et al. compared the retrofit of two buildings in Italy with cool tile - roof tile visually similar to historical but with a higher albedo – and a combination of the cool roof with a heat pump for HVAC. The cool roofs lowered the number of uncomfortable hours and showed a 3.8% reduction of cooling energy for the whole building and 14% for the attic (Pisello et al. 2016). A ground source heat pump (HP) for a water tank HVAC system reduced energy use by an average of 64.3% for heating and 67.0% for cooling. The combination of cooling roof and HP reached an average of 64.0% for heating and 69.2% for cooling, with five years of payback time. The avoided GHG emissions were assessed for the combination scenario and showed 82% compared to current conditions with gas heating water tank for space heating and separate window installed AC units. Additionally, the visual improvement of the historic facades was noted as current window AC units are not permitted and significantly compromise the aesthetic of the heritage buildings (Pisello et al. 2016).

4.3.5 Wall insulation

Walls in a building often represent the largest surface, depending on the building configuration, height, and window-to-wall ratio. Adding wall insulation can significantly improve energy performance, however, there are three drawbacks: (1) limitation and difficulties with the application during the retrofit, (2) moisture movement or hygrothermal performance, and (3) embodied carbon. Regarding the first challenge, historic preservation policies often do not allow disturbance of the exterior walls, so the insulation needs to be installed from the interior side of the building. Interior insulation is often seen as less advantageous. It is also more challenging to provide the optimal quality of installation in the existing building (Bastian et al. 2022; Rose 2005). To install the insulation, walls partly need to be disassembled, which results in extra work, cost, and materials while still likely will not achieve the maximum performance (Bastian et al. 2022). This is one of the reasons why blown cellulose - recycled paper blown inside the wall assembly without opening the wall – is one of the most attractive insulations for retrofit. The second appealing nature of blown cellulose – low embodied carbon – will be discussed below.

The Hygrothermal performance of the wall was already discussed above. However, from the insulation perspective, it was argued that more insulated walls (high R-value) tend to accumulate more moisture (Rose 2005). However, wet insulation significantly loses its resistance to heat flow, thus lowering the R-value (Musick et al. 2000). In other words, failure to control moisture may diminish the retrofit effort. While new buildings can prevent water from entering the wall with rain screens and vapor barriers, old facades rely on drying capacity. However, Zhou et al. modeled and measured in the field the moisture dynamic in a retrofitted masonry wall with insulation on the interior side. It was found that wind-driving rain and water absorption of the exterior surface played a larger role in moisture risk. Glass wool insulation, being capillary active, allowed moisture to dry towards the interior and showed a negligible influence on the moisture risk. In contrast, vapor tight insulating system reduced the drying capacity of the wall and thus increased moisture and mold risk in the wall (Zhou et al. 2022).

The third challenge of envelope insulation for retrofit is the carbon intensity of the conventional insulating materials. While additional insulation would save operational energy, the benefits could be offset by the high amount of added embodied energy. The attention of scientists and activists to the embodied energy of building materials pushes the market towards low embodied energy products (e.g., natural wool, prefabricated straw bale, or wood fiber panels). However, those insulations are rarely used for retrofitting projects due to the smaller scope of work and low availability (Birukova 2022) One of the approaches to evaluate energy retrofit is to compare global warming potentials (GWP) of saved operational and additional embodied energies.

Graham et al. explored saved carbon emissions and compared 11 types of conventional insulation in the case of retrofit in Canada. Different materials showed a variety of GWP per the same R-value. Furthermore, the amount of saved operational carbon is not linear to the added insulation. When R-value is increased from R1 to R2 (approximately from one sheet of plywood to an uninsulated wall) – GHG emissions are reduced by 50%. However, after ~R8 the curve is flatter, and between R39 and R40 insulations, only 2.5% of avoided GHG emissions exist. To put it into context, modern building code requirements for walls are around R-20 (California) or R-24 (Ontario, Canada). Figure 4-12 illustrates the R-values curves of different common insulation types and the resulting total GHG emissions. The increase of the R-value first drastically reduces total GHG emissions. However, the amount of avoided emission became smaller per layer of insulation or even increased in some cases (Graham et al. 2021).

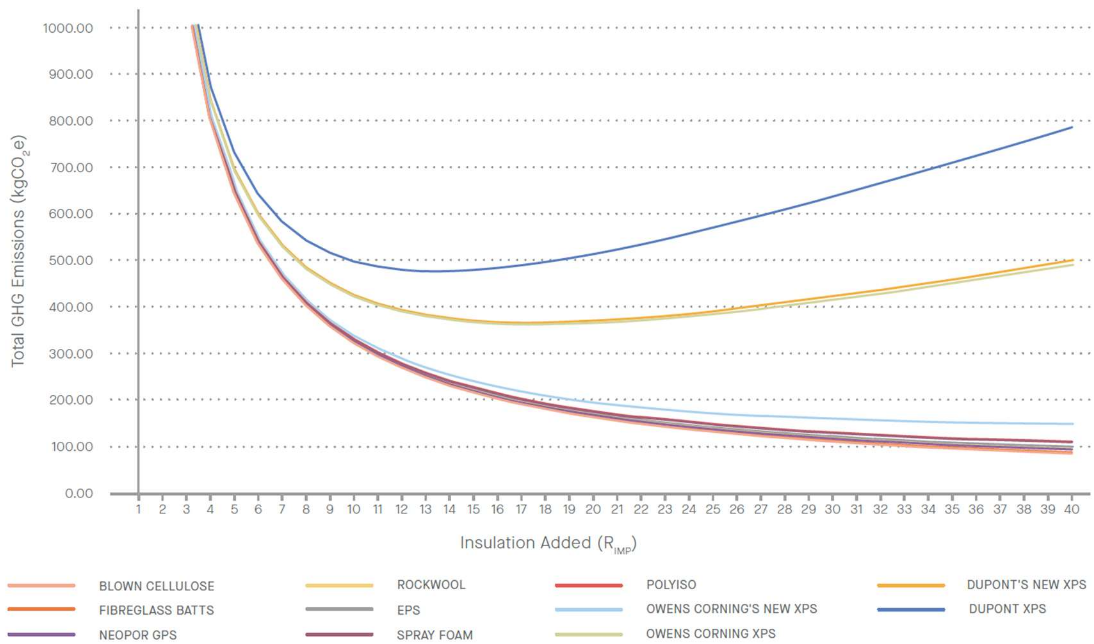

Figure 4-12 Total GHG emission per R-value for 11 types of conventional insulations, over 30 years operation in Toronto, Canada. X-axis represents R-values (heat flow resistance of the wall, higher R-value means better insulation). On the Y axis total GHG emissions (embodied from insulation plus operational for heating) – case of natural gas heating (adapted from Graham et al. 2021)

Blown cellulose showed the lowest GWP among the conventional insulation with 0.7 $kgCO_2eq/m^2$ and was suggested as the preferable choice to decarbonize old buildings. It was followed by fiberglass (aka glass wool), Neopor graphite polystyrene (GPS), and stone wool with 1.04, 1.87, and 2.06 $kgCO_2eq/m^2$ (Graham et al. 2021). Similarly range of GWP was showed by Grazieschi et al. with 0.6-1.2$kgCO_2eq$/FU and 1.4–4.2 kg CO_2eq/FU (FU is functional unit of $1m^2$ wall) for glass wool and stone wool insulation respectively (2021). Authors also noted that glass wool and stone wool were relatively competitive compared to natural insulations. However, this could be due to yet lower efficiency of production and transportation of natural materials. On the other hand, high-performance contemporary insulation materials showed a significantly higher range of GWP, for example, aerogel 11.6–18.7 kg CO_2eq/FU (Grazieschi et al. 2021). On the carbon-intensive side of the spectrum, XPSs (Expanded Polystyrenes) have significantly higher GWP than other insulations. The older generation of XPS is 15-20 times higher than an average conventional material of the same R-value. Therefore, XPS cannot outweigh the embodied carbon with reduced operational energy and cannot be used for buildings decarbonization (Graham et al. 2021).

The trade-off between saved operational energy and embodied energy of the insulation depends on the type of HVAC system used in the building. Natural gas heating is responsible for much higher GHG emissions than heat pump heating, depending on the source of the electricity. Therefore, if insulation is added to a house with gas heating, the carbon "payback time" will be much shorter than if the building uses a heat pump. In other words, the time when carbon investment of insulation is breakeven by saved emissions from heating will be much shorter in the case of gas heating and much longer in the case of heat pump use. Graham et al. used the case of the current electric grid of Toronto, Ontario, where gas heating is about 12 times more carbon-intensive than electric heat pumps (2021). Figure 4-13 depicts the total GHG emissions when the same insulation materials are used in the case of the electric heat pump. Compared to Figure 4-12 (gas heating) total carbon footprint is significantly lower in the case of the heat pump. For example, consider the goal to stay under 100 kg CO_2eq of total (operational plus embodied energy) GHG emissions in 30 years timeframe. In the case of gas heating, the wall assembly needs to be with cellulose or fiberglass insulation and have R-30 value (exciding the local code). In contrast, with heat pump heating R-value of the wall need to be ~2.5, which is typical uninsulated wood frame wall. Therefore, the study concluded that upgrading HVAC systems with heat pumps is a more effective strategy to lessen the carbon footprint of existing buildings. Moreover, only low embodied carbon insulations can positively contribute to decarbonization (Graham et al. 2021). It is important to note that the lower evaluation period will increase the material's embodied carbon ratio, as discussed in section 2.3 (Figure 2-3), making heat pumps an even more attractive solution.

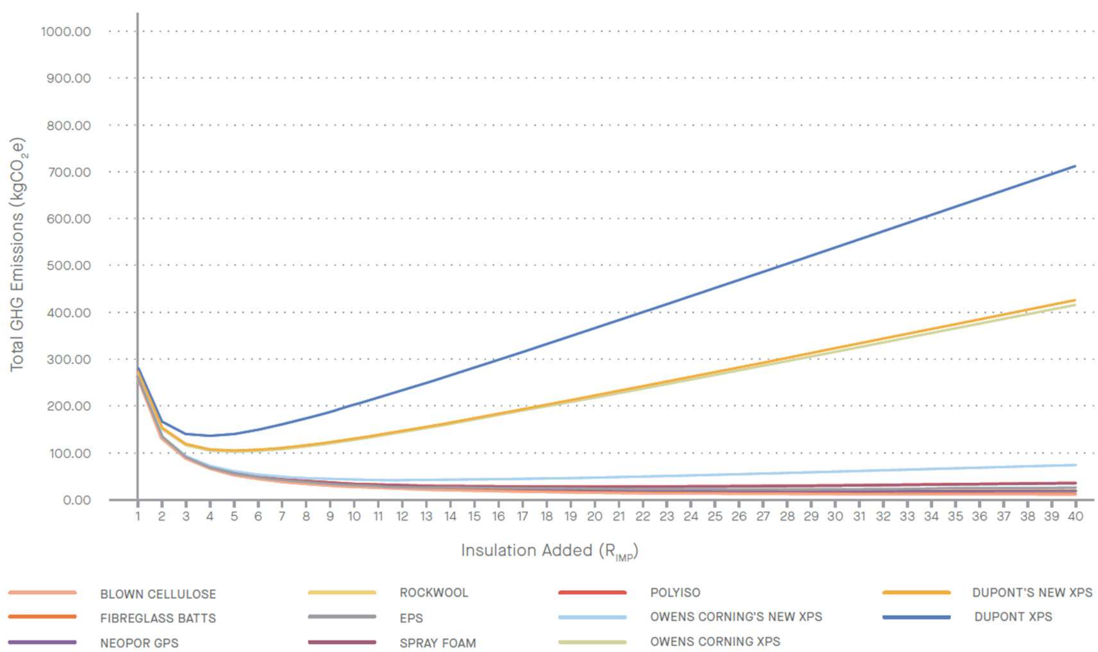

Figure 4-13 Total GHG emission per R-value for 11 types of conventional insulations, over 30 years operation in Toronto, Canada. X-axis represents R-values (heat flow resistance of the wall, higher R-value means better insulation). On the Y axis total GHG emissions (embodied from insulation plus operational for heating) – case of heat pump heating (adapted from Graham et al. 2021)

Likewise, analysis of different retrofit scenarios of English house stock used a carbon budget of 30 years (from 2021 to 2050) to align policies and practices with climate goals. The study showed that insulation with low embodied carbon materials, coupled with a rapid transition to using heat pumps for HVAC and water heating, is the only path to staying within the climate targets (Li et al. 2022). To achieve this, policies need to regulate the building materials market and support the less carbon-intensive insulation choices. The requirement steps will be to offset the manufacturing energy and create an inventory of net-zero GHG emissions materials by 2040 (Röck et al. 2020).

To conclude, envelope insulation is predictably more beneficial in colder climates (Kamel and Memari 2022). With climate change, additional insulation of historic buildings can increase interior overheating if performed without upgrading the HVAC system. This would result in cooling energy overconsumption and materials decay (Webb 2017). The case study of four residential units in Japan showed that combining traditional and modern techniques to improve envelope performance would yield a positive outcome. However, the authors highlighted standardized approach is not the best as the surrounding of each case (e.g. shading, orientation) need to be taken into account (Chang et al. 2020).

4.3.6 Envelope improvement - conclusion

To summarize, increasing airtightness is the preferable strategy among all envelope improvements but needs to be coupled with additional ventilation, especially in a humid environment. Window upgrade is the most significant for buildings with a higher window-to-wall ratio (large windows). South and west-oriented windows would benefit from reflective films when heat gain needs to be reduced. Changing windows from single pane to double glazing is most beneficial in north orientations to reduce heat losses. Skylights are attractive solutions, especially when alteration of facades is not permitted. Equipped with control systems, skylights can provide significant energy improvement. Additional insulation is a controversial retrofit measure required to balance several aspects and should not be a default option, especially for the walls. However, it is important to recognize that in some old buildings, it is necessary to provide occupants with a comfortable indoor environment. When possible, blown cellulose is the preferable choice among conventional insulations. Glass wool also has relatively low GWP and introduces lower moisture risk. Attention to moisture control, the embodied carbon, historic preservation requirements and the ability to access the envelope and perform effective work need to be balanced for each case. Therefore, detailed local (city or county level) retrofit guidelines should be created and become accessible to assist building practices in considering local climate and building types to equilibrium potential benefits and risks.

4.4 Control of the external context

The context or external parameters of the building (e.g., climate, urban landscape) influence its energy performance and carbon footprint. While those factors are more complex, opportunities to influence the context can still be evaluated. First, the influence of future climate change must be considered. The microclimate of the building can create a negative impact (e.g., urban heat island effect and related energy load) or can generate a positive influence and reduce energy consumption. Landscape strategies could be especially valuable in historic districts, where facade preservations limit envelope changes. Furthermore, a green streetscape promotes walkability, additionally decarbonizing the built environment. Another component is the people that inhabited a building. In section 4.2.4, operation control systems were discussed as a tool to mitigate the less energy-responsible behavior of occupants. In the current part of the paper, section 4.4.4 examines how the number of occupants using the building is related to the decarbonization of the building sector.

4.4.1 Climate change

The Intergovernmental Panel on Climate Change predicts that global warming will likely reach 1.5˚C between 2030 and 2050. This brings other aspects that need to be highlighted in the retrofit discussion. First is the tread from extreme events such as heatwaves, wildfires, abnormal winds, rains and flooding. Preventive measures could be applied in each specific region, and the challenge of a retrofit is to predict the possible events and plan accordingly. The second aspect of climate change is the increase in average temperatures and precipitation levels, which need to be reflected by building codes, respectively. The climate zone map created by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is widely used by the building industry and International Code Council to guide specifics of the energy performance of the building in the zone. However, the reclassification of the climate zone will influence only future structures. This would leave old buildings even more behind the efficiency (Figure 4-14).

Several studies emphasize the urge to consider climate change in the retrofit design of historic buildings. Adapting capacity (the ability to adapt to changes and withstand hazardous conditions) is essential for preserving cultural heritage (Hao et al. 2020; Webb 2017; Wilson 2022). Specifically, increased temperatures and wind-driven rains are the two major factors discussed, as they accelerate erosion, decay, and weathering. For instance, mold growth was observed at a higher rate during the last 20 years in old buildings in Sweden (Hao et al. 2020). Another example is an increase in indoor discomfort in historic buildings in Spain and England. The comfort was provided by traditional approaches such as thermal mass and natural ventilation for interior air conditioning. In those examples, when moisture is forced to the wall with increased wind or when natural ventilation that depends on temperature differences works less efficiently, measures, such as external protective features (solar shades, wind protection walls), are necessary. However, usual historic preservation regulations do not allow altering facades which leaves the buildings less protected and retrofit projects even more challenging (Hao et al. 2020).

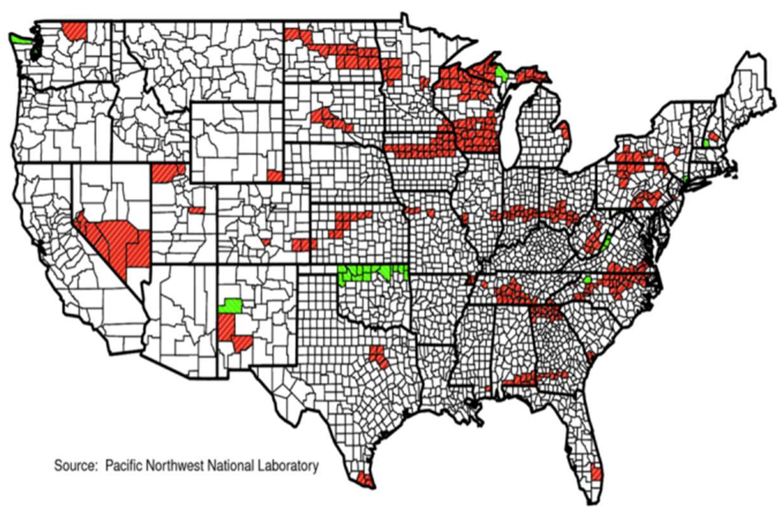

Figure 4-14 Updated climate zone map of the U.S. due to climate change. Issued by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Counties that changed assigned climate zones indicated by red and green colors to use for building standards adjustment. Red counties were changed to hotter climates, green to colder (adapted from Gibson 2021)

A different standpoint on climate-related changes in the building sector is the usage of space cooling, which already grew between 2010 and 2020 from 27% to 35% of households globally (IEA 2021). Atmospheric temperatures rise will drive the necessity for indoor air conditioning, which will be a more significant contributor to the total operational and embodied energy. While generally, the thread of overheating due to climate change is larger, in some cases, heating savings can still offset the increased cooling load. A school building in Korea that was permitted to apply 50mm external insulation showed by modeling 9.89% HVAC energy savings, despite the correlated cooling load growth and projected 5∘C or more summer temperature increase by 2090 (Jo et al. 2022).

To conclude, climate change exhorts mitigation and adaptation actions; in other words, retrofit is needed for both reduction of building-related emissions and to protect buildings from more challenging weather conditions. The most discussed threads are moisture control in increased humidity and wind-driving rains and the ability to withstand heat waves. Therefore, new electric HVAC systems with heat pumps that provide flexibility between heating and cooling and allow different building zones to operate separately should be considered for historic building preservations. Another strategy to mitigate some of climate change's negative impact is to adjust the building's microclimate, which will be discussed next.

4.4.2 Microclimate

A microclimate is an essential part of a building's context that influences the energy performance and potential savings of the retrofit measures yet is not considered by building standards. For instance, analysis for retrofit scenarios of 29 commercial and mixed-use buildings closely located in downtown Sacramento, California, was performed. Simulations were compared with and without accounting for the urban context. The results showed the effect of the surroundings as an influential factor, with an impact rate of up to 7.4% in electricity use (Nutkiewicz et al. 2021). Likewise, two similar houses in a close location in the southwest of Turkey (Mediterranean climate) were examined. One house was in the urban center, and another was in the adjacent rural area. The comparison showed a 4.7% higher energy demand for HVAC for the rural house, with much higher (27.6%) for short heating seasons and slightly higher (3.1%) for longer cooling seasons. The study estimated that the difference originated from the density of the building - in urban settings, nearby structures prevented winter wind-related heat loss and shaded the house during the summer, reducing overheating (Timur et al. 2022). This finding is interesting as an example of advocating for a denser urban setting that had many benefits (transportation, economic, social) but is often associated with the Urban Heat Island (UHI) effect.

Urban Heat Island (UHI) effect is a phenomenon when the surface temperature of an urban area of a city is higher than in the surrounding rural areas. Heat-related mortality raised energy consumption for indoor air conditioning, and increased street pollution are caused by UHI (Taha 2015). Climate change is worsening the effect, raising the issue in areas previously not influenced. For example, the recent Climate Central report rated San Francisco as the fifth Nationwide city with increasing UHI effect, with over 7˚F increased temperatures in some neighborhoods of the city. The majority of city's historic districts and old buildings are located in the neighborhoods with the highest UHI effect (Figure 4-15). Mitigation of UHI is essential for decarbonization as the heat accumulated in the thermal mass of the buildings and street surfaces is released back during the evening energy peak hours (Cao et al. 2015). Therefore, usage of HVAC to mitigate the additional heat puts further stress to the renewable greed as was discussed in section 2.5 and illustrated with Figure 2-4.

One of the tools to decrease the heating of the streets is Cooling pavement. The pavement with a high reflective value (albedo) ricochets short-wave solar radiation and prevents overheating. Touchaei et al. showed that the higher albedo of street surfaces lessened the temperature inside the buildings and decreased energy consumption on cooling (2016). However, in the case of a high window-to-wall ratio of non-residential buildings, the reflected radiation from the pavement can overheat the storefronts. For example, in the case of Phoenix, Arizona, *reflective pavement* increased cooling energy for the building by about 11% (Yaghoobian and Kleissl 2012).

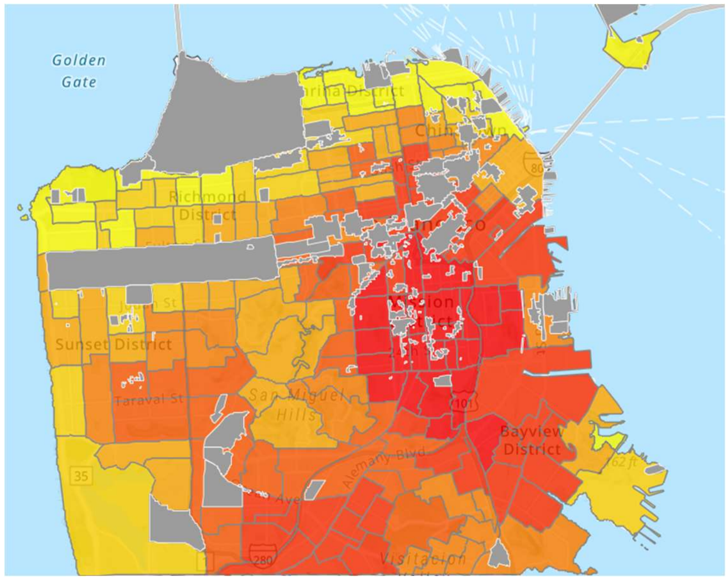

Figure 4-15 The average summer surface temperature in San Francisco, Ca. Gray color represents historic preservation districts, where the large areas on the west side of the city are the parks such as Golden Gate Park, while the area in the center of the city shows the historical districts' buildings and the majority of them are located in the hottest part of the city with a very low ratio of trees. Data source: Census.gov

Trees combine shading and evaporation cooling effects and are the most pleasant for pedestrians. This may reduce the ambient street temperature by 11–25°C (EPA, 2021). The cooling savings were shown in a wide range of 2.3-90% (Ko 2018) or 10-50% (McPherson and Rowntree 1993) Shading the evening sun on the west side of the street (North-South orientation of the street) is two-three times more effective in reducing cooling energy load than other locations. For example, by planting trees on the west and south sides of the building, summer electricity use was reduced by 5.2% in Sacramento, California (Ko 2018). However, for the pedestrian, trees are the most beneficial on the East-West streets, with a ratio of the tree canopy of about 70% (Sanusi et al. 2016). An important role in mitigating UHI represents evaporation. Evaporation from a tree produces three-four times more cooling effect than its shade (Ko 2018). Similarly, blue-green landscape design can reduce UHI with evaporation.

On the other hand, vegetation also can reduce buildings' heating load, protecting them from strong winds. Windbreaks predictably show larger energy savings in colder climates, with the range of 1-20% (Ko 2018) and up to 40% (McPherson and Rowntree 1993). However, McPherson and Rowntree showed that inefficient plants location could increase heating energy, with higher "cost" also in colder climates. For example, east-located trees would shade beneficial morning heat gain in Portland while did not protecting from prevalent wind and evening summer overheating. Prevalent winds that landscapes should consider for energy savings are typically western. Similarly, western protection from evening overheating is most effective. Therefore, the authors noticed that the western location of the trees presented doubled energy savings compared to east-located trees for any climate in the U.S. (1993). Furthermore, green walls with climbing vegetation also contribute to energy reduction with shading and lessen of infiltration through walls (reduction of air leaks ~ 10% per wall) (Susorova et al. 2014).

Lastly, wind-driving rain (WDR) was shown as a negative factor that increases moisture in walls, threatening historic buildings. Wetter walls lose their thermal performance, deteriorate the building structure and compromise indoor air quality. However, the influence of WDR depends on the wind force and exposure to the water. Figure 4-16 depicts the influence of the WDR distributed unevenly across the façade. As the wind is typically higher at the building's or building block's corners, the buildings' corners are more subject to moisture damage (Hansen et al. 2019). Thus, protection with denser and taller trees from the dominant wind might be even more beneficial at the corners. To conclude, the strategic location of the trees and other landscape forms can significantly improve energy performance and preserve old buildings. Therefore, building codes should include those strategies in the requirements to maximize efforts and increase the efficiency of the buildings.

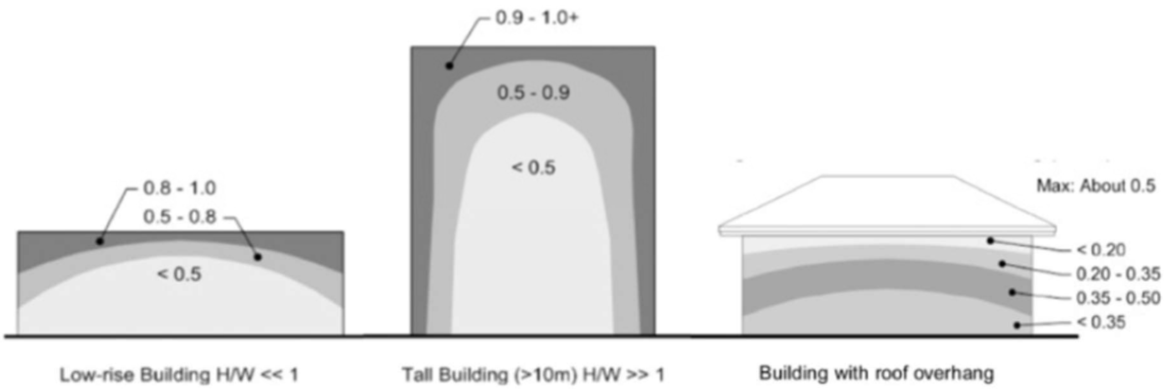

Figure 4-16 Rain admittance function distribution on the building facades for low-rise and buildings with roof overhang (adapted from Hansen et al. 2019)

4.4.3 Occupant density and measuring per person

The energy of a building is typically measured per floor area and, in some cases, per volume. However, the overall energy performance of a city or country offers a better understanding when expressed per capita. As the primary purpose of buildings is to provide space and shelter for human needs, it would be correct to use this approach for buildings while evaluating retrofit measures. Between 1973 and 2015, the average household in the U.S. declined from 3.01 to 2.54 persons per household, and the average floor per person increased from 551 to 1058 square feet (U.S. Census bureau 2016). To put it in perspective, the average residential floor area per person in the UK, France, Germany, and Denmark in 2008 was 337, 417, 424 and 585 square feet, respectively (Enerdata 2008). Figure 4-17 illustrates that despite a steady decrease in energy consumption per floor area (graph on the left), the energy use per household increased in the last decades in the U.S., offsetting the improvement in the energy performance (Frey et al. 2012). Consequently, a retrofit project altering the layout to increase occupants' capacity can be considered an energy upgrade. In addition to the operational energy savings, embodied energy and related GHG emissions will also be reduced. European studies are already discussing the sufficiency and optimization of occupational density (Röck et al. 2020).

Measuring building efficiency per person is rare, yet some papers use this principle to estimate retrofit. For instance, a comparison of upgrades in the University of Genoa (UNIGE), Italy, and the Florida International University (FIU) in Miami, USA. The results were measured in energy units and GHG emissions per area and per person. UNIGE had higher student density, and while it showed better results per square meter, it was even better when measured per person (Del Borghi et al. 2021). As discussed, about half of the energy in the building is used for heating and cooling the indoor air. Unoccupied conditioning rooms are estimated to waste about 14–20% of HVAC energy (Meyers et al. 2010). Therefore, low occupancy of a house offsets the energy efficiency improvement, while an increase in density can increase energy efficiency.

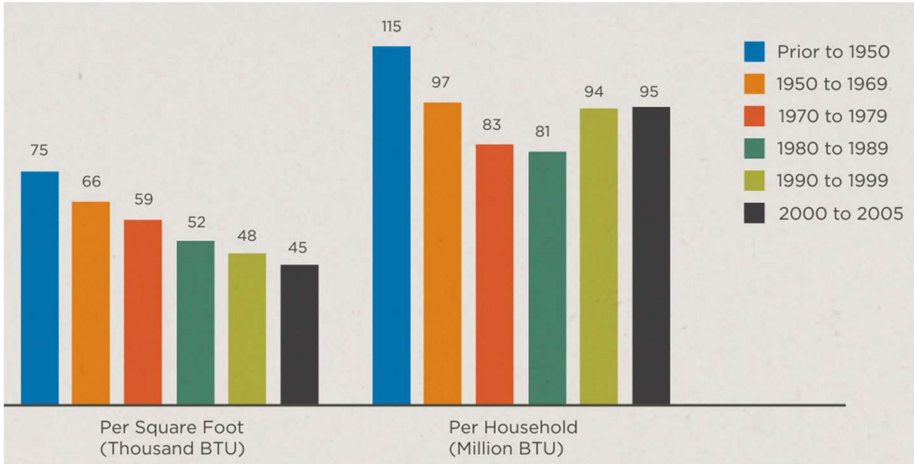

Figure 4-17 Residential annual energy intensity in the U.S. by house vintage. Left, per square foot. Right, per household. Increase of the houses in last decades offset the energy efficiency improvement (adapted from Frey et al. 2012)

Alteration of facades can be required to increase occupancy density. For example, additional entrances, egress or windows change, which can be limited by historic preservation policies. While the local historic preservation committee should evaluate each project to ensure consistency with the urban appearance, the perspective of energy efficiency per occupant number could be a part of the conversation. In 2015 a new energy metric on the base of occupancy was proposed to the Green Building Advisory Committee of U.S. General Service Administration. It was described as "energy consumed by the building in one year per person served by the building," and the advantages of that metric were highlighted (Energy Use Intensity Task Group 2015). This approach needs to be further studied but could be approached similarly to increasing urban density in low-density areas with infill development. Infill development promotes new constructions in areas with large housing demand and the capacity to increase density. It was shown as a strong strategy to improve a city's energy efficiency (Paull 2008; Silva et al. 2018).

4.4.4 Context control - conclusion

This section highlighted the significance of the context on a building's energy efficiency and carbon footprint. The challenges of climate change and the opportunities of microclimate control should be considered by retrofit projects and incorporated into policies. Similarly, measuring the efficiency of a building per person can add another perspective on the retrofit evaluation.

4.5 Strategies of buildings' decarbonization and energy retrofit – conclusion

Investigations of retrofit strategies showed a promising potential for old buildings' decarbonization. First, it was found that a shift in the internal building system is required to decarbonize existing buildings. Most importantly, electrification with heat pumps for air heating & cooling and water heating was shown as the essential component. The strategy showed high performance across different climates and building types and should become a requirement. An upgrade of lighting systems was found to be well-managed in the U.S. and should continue the transition to LED lighting. Additionally, building operation systems can increase electricity usage efficiency and help balance the supply and demand of the renewable electric grid.

Next, increasing the building envelope's airtightness should be considered a low-cost, highly efficient envelope improvement. In contrast, additional wall insulation does not always positively impact building energy improvement and decarbonization. The high carbon intensity and potential moisture accumulation in the building shell are the two main concerns that need to be evaluated for each case. Window films and cool roofs are relatively low-cost and effective strategies for areas with high cooling energy demand. Skylights present a potential for historical buildings as they do not alter facades and can be valuable for light, heating and ventilation. However, skylights require detailed design and modeling for each case to balance heat gain and loss in favor of the building.

Third, planning for future climate change is important, especially since heritage buildings are more susceptible to the negative impacts of the changes. Strategic landscape design, influencing the microclimate, is an effective method. It reduces a building's energy demand while being compatible with urban historic preservation principles and should be part of a retrofit program. It also can be part of the adaptation to the climate change program of a historic building. Lastly, the assessment of decarbonization and an energy retrofit project with occupancy base metrics shows its potential. It is entering the scientific literature and policy conversations, proposing more accurate appraisals of efficiency.

Tables 4.1 - 4.4 summarize the numerical data for different strategies in the percentage of energy efficiency improvements (total, thermal or specific areas). The comments highlight approximate climate conditions relative to California and details about the studied buildings. Note that some studies examined combinations of different strategies (Table 4.1), while others studied only one specific method (Tables 4.2 - 4.4). Lastly, as insulation represents a controversial factor, some building shell retrofit included it and some excluded from the scope of work – the description of the study notify the presence of insulation. Lastly, the green color code of results / energy savings columns indicate a positive influence of the retrofit on the performance of the studied buildings, while red color represents the negative impact.

Table 4.1 The summary of retrofit strategies - combination of internal systems, envelope and / or the context improvements.

reference	strategy	description	results / energy savings	*comments*	type of building	window wall ratio	climate zone / location	Historic/ age
COMBINATION INTERNAL SYSTEMS, ENVELOPE and /or CONTEXT								
Martinez and Choi 2018	overall system w/o envelope	HVAC, Lighting	8.8% energy cost savings	*compare to no-retrofit data, cost savings*	non-residential, 1 -7 stories offices, average size of 424,000 sq. ft.	low (mean 0.38)	US, 25 states	average 1965 45 % historic preservation
	overall system w envelope	HVAC, Lighting + increase airtightness (NO additional WALL INSULATION)	11.7% energy cost savings & 28% energy savings					
Timur et al. 2022	envelope	floor insulation, airtightness, secondary glazing, window shutter schedule, scheduled night-time window opening for summer, roof insulation, NO WALL INSULATION	26.5% energy savings	*urban case before retrofit used 4.7% less energy due to shading and wind protection by adjacent buildings*	urban traditional house - two stores with exterior gallery on both floors, (masonry with wood on the second floor)	5.6% ground floor, 20.0% second floor	Mediterranean - Mugla, south-west Turkey	the second half of 1800s
	envelope + HVAC Heat pump	above + ground heat pump	64.7% energy savings					
	envelope	floor insulation, airtightness, secondary glazing, window shutter schedule, scheduled night-time window opening for summer, roof insulation, NO WALL INSULATION	30.4% energy savings		rural traditional house - two stores with exterior gallery on both floors, (masonry with wood on the second floor)	11.8% ground floor, 18.6% second floor		early 1900s
	envelope + HVAC Heat pump	above + ground heat pump	66.7% energy savings					
	HVAC Heat pump	ground heat pump	52% energy savings (both cases)		Both urban & rural cases	Both cases		Both cases
Fernandes and Regnier 2022	HVAC + roof upgrade	HVAC heat pump with energy recovery, dedicated outdoor air system, roof replacement	65% - 68% of total HVAC energy	*more in case of west oriented building as initial load was higher*	small commercial buildings south oriented building and west oriented building	medium	Berkeley, California cooling-prevalent periods	not historic
			22% - 25% of total HVAC energy	*more in case of west oriented building as initial load was higher*			Berkeley, California heat-prevalent periods	
	Lighting including daylighting (TDD)	LED luminaires (26W each with infrared occupancy & photosensor sensor - automatic dim & turn off) & 24"x24" TDD	85% all lighting energy	*regardless orientation*			Mediterranean climate Berkeley, California	
	plug load	"smart" plug strips, laptops instead of desktop computers, EnergyStar appliances	31% of all plug load					
Bastian et al. 2022	Passive House principles for old and historic buildings (EnerPHit)	continues thermal insulation, better windows, better airtightness, elimination of thermal bridges and installing a ventilation system with heat recovery.	80 - 85 % GHG avoided		90 m2 detached 2 story house		Hereford, UK (cool temperate)	historic 1896
			94% total energy improvement		three story multi-family residential masonry		Frankfurt/Main, Germany (cool temperate)	1950s
Pisello et al. 2016	cool roof	cool roof tile	3.8% for the whole building 14% for the attic - reduction of cooling energy	*compared to gas heating (water) and window installed AC units.*	two masonry tree story building	medium	Italy, Mediterranean climate	historic preservation
	heat pump	ground source heat pump (HP) for a water tank HVAC system	64.3% for heating 67.0% for cooling 5 years of payback time					
	combination- cool roof & heat pump	cool roof with ground source heat pump (HP) for a water tank HVAC system	64.0% for heating and 69.2% for cooling 82% avoided GHG					
Graham et al. 2021	insulation with gas heating	XPS insulation (high embodied carbon) with any heating	saved operational GHG emmisions cannot offset the embodied carbon of insulation	*30 years timeframe (gas space heating requires large amount low carbon insulation compared to heat pump)*	residential		Toronto (Ontario) Canada	
	insulation with gas heating	cellulose or fiberglass insulation and have R-30 value (exciding the local code) with gas heating	to to stay under 100 kg CO_2eq of total (operational plus embodied energy) GHG emissions					
	heat pump HVAC	no insulation needed						

Table 4.2 The summary of retrofit strategies – the internal systems improvements.

reference	strategy	description	results / energy savings	*comments*	type of building	window wall ratio	climate zone / location	Historic/ age
INTERNAL SYSYTEMS IMPROVEMENT								
Shackelford et al. 2020	lighting + operation control	old fluorescent lamps combined w/ controlled system (zonal controls, task tuning, daylight dimming, automated solar tracking roller shades)	20 % annual lighting energy savings		office		Berkeley, California	
		LED lights changed from fluorescent	38% annual lighting energy savings	*compared to fluorescent lights that are more efficient than incandescent*				
		LEDs w/ advanced controls and shading system changes (venetian blinds to mechanical roller shades with daylight redirecting blinds) or lighting layout improvements (workstation-specific lighting design)	72 % annual lighting energy savings					
Piselli et al. 2020	HVAC & water	Ground source heat pump - Space heating w/ heated water	up to 73% heating energy & 69% avoided GHG emissions	*compared to gas boiler*	masonry	low	Mediterranean climate Italy	historic
Mahone et al. 2019	HVAC + water heating	air source heat pump + heat pump for water heating	30-60% total GHG emission reduction	*80-90% by 2050 (with transition of the grid to renewables)*	single-family houses, 6 different types across California	vary	California, 6 most populated climate zones (87% of households)	pre-1978 & newer retrofit
Willem et al. 2017	Heat pump water heater	air-to-water heat pump water heater	63.7% water heating energy	*compared to conventional electric resistance water heater*	residential	n/a	hot climate Houston, TX	
			40.2% water heating energy		residential	n/a	cold climate Chicago, IL	
Greening and Azapagic 2014	Water heating	Flat plate and evacuated tube solar thermal water heating for domestic water use	88% of water heating GHG emission avoided, but have human and eco-toxicity not provide enough hot water, not recommended for the UK	*compared to gas boiler*	residential multifamily		England	
Arabzadeh et al. 2019	Solar thermal water heating	52m2 (560 sq ft) rooftop solar thermal collector, water heating	22% of heating energy reduction	*reduction of demand from district hot water supply*	traditional four-story apartment building		cold climate Helsinki, Finland	
		82m2 (880 sq ft), rooftop solar thermal collector, water heating	32% of heating energy reduction					
Asaee et al. 2017a	water heating	solar assistant heat pumps for water heating (combination of heat pump and solar thermal water heating)	about 20% GHG reduction	*compared to present water heating portfolio of the country*	Canadian house stock	n/a	Canada	vary
Asaee et al. 2017b	water heating for domestic use and space heating	air-to-water heat pump for domestic use and space heating	36% end-use energy savings	*compared to present houses' operational energy in the country*	Canadian house stock	n/a	Canada	vary
Lu and Warsinger 2020	operation control system - multizone ventilation	multizone variable air volume (VAV) system (control HVAC system to prevent ventilation and air-conditioning unoccupied rooms)	18% - 56% HVAC savings 36 - 51% cooling energy savings	*higher savings in the hotter climate cooling dominant climate zone models (Climate Zones 1–3: Honolulu, Hi,*	average size (house)	vary	The U.S. Climate Zones 1–7	
			12% - 55% HVAC savings 29 - 44% cooling energy savings		large house (models)			
Sayed and Gabbar 2017	Operation control systems	Building energy management systems (BEMS)	Energy savings with BEMS 10-20% higher	*compared to individual controls for lighting, HVAC and others*		n/a	n/a	n/a

Table 4.3 The summary of retrofit strategies - combination of envelope improvements.

reference	strategy	description	results / energy savings	*comments*	type of building	window wall ratio	climate zone / location	Historic/ age
ENEVLOPE / SHELL IMPROVEMENT								
Kamel and Memari 2022	envelope	overall envelope improvement with continues insulation	25 - 50%	*Compared to gas furnace* **average estimation, higher savings in colder climates*	Two-story slab on grade detached single-family	15% (low)	the U.S. climate zone 1A (hot) & 6B (cold)	n/a
	airtightness	air sealing improvement from 7 to 10 ACH50	3.5 - 30%					
	Improving windows	replacing them with high-performance products (e.g., double- or triple-pane argon-filled), or with an add-on product installed on top of the existing window.	up to 15% improvement					
	improvement of roof	roof insulation	neglectable improvement, especially for warmer climate					
Allana 2020	Air tightness	average energy improvement with increased airtightness	2-5% energy savings	*average estimation*	residential	n/a	the U.S.	n/a
Less and Walker 2015	Air tightness	increase of airtightness with deep energy retrofit	63% reduction of airleackage		residential	n/a		
Urquhart et al. 2015	Air tightness	increase of airtightness with deep energy retrofit (liquid flashing at all cold joints and cracks, window repairs and changes, replace and seal of slab exhaust vents and roof plumbing vents)	average 53% air leakage reduction (range 36% - 72%) *Pre- and post-retrofit testing*	** first floor was already 38% tighter than average, as protection from adjacent garage)*	apartments in 13-story multi-unit residential building		Vancouver, Canada	1986
Jo et al. 2022	Air tightness and insulation	Air tightness at window and entrance doors combined with external wall insulation 50mm	7.03% increased cooling load	*2.19% increased cooling load in 2090*	elementary school		Uijeongbu, South Korea, warm, muggy, wet, and partly cloudy summer, very cold, dry, mostly clear summer.	not historic(2000)
			23.99% savings heating load	*23.98% savings on heating in 2090*				
			9.67% Total HVAC energy savings	*9.89% savings on HVAC in 2091*				
Jiang et al. 2021	window film / smart window	dynamic/smart windows - thermoresponsive hydrogel window film, windows became opaque after 31'C	8.1% (Tucson, AZ) 3.1% (LosAngeles, Ca) annual cooling energy savings		commercial		US hot climate	
Jiang et al. 2021	smart windows	chromogenic windows (dynamic/smart)	74% lighting energy	*through avoiding shades and blinds*	commercial	large	US	
Irakoze 2021	skylight	skylight for passive heating and natural lighting - optimal skylight to roof ratio (SRR) found 8% when ceiling thickness is 1.5m. No energy savings (by passive heating and lighting) when ceiling thickness above 2m	4.2% total energy savings (Seoul)	*Optimal SRR with no thickness 5%, energy savings ~10%*		8% skylight to roof ratio	Seoul and Ulsan (Korea), comparable to California climate zone 16 (Lake Tahoe)	
			9% total energy savings (Ulsan)					
Rempel and Lim 2019	skylight	south oriented tilted (40') skylight with scheduled shading, movable scheduled (extended night time) insulation, natural ventilation & thermal mass	~80% cooling energy load	*climate with cloudy winter (~50% cloud cover)*	office converting to dwelling, unit on the top floor of 2-story, brick and timber row building	large skylights	Mediterranean climate Berkeley, California	1904
			>50% heating energy load					
Jiang et al. 2021	smart windows	chromogenic windows (dynamic/smart)	74% lighting energy	*through avoiding shades and blinds*	commercial	large	US	

Table 4.4 The summary of retrofit strategies - the context improvements.

reference	strategy	description	results / energy savings	*comments*	type of building	window wall ratio	climate zone / location	Historic/ age
CONTEXT IMPACT								
Meyers et al. 2010	context	Unoccupied conditioning rooms are estimated to waste	14–20% waste of HVAC energy in unoccupied rooms					
Ben & Steemers 2014	behavior changes	energy conscious behavior compared to unconscious behavior	62–86% of the total potential savings	*air heating behavior the most influential variable*	residential complex with shopping center and car parking	small to medium	London, UK	listed (English Heritage) 1967
Nutkiewicz et al. 2021	urban context		7.4% impact of urban context	*compared to modeled without context*	29 commercial and mixed-use buildings closely located in downtown	high	Sacramento, California	
Yaghoobian and Kleissl 2012	urban context	reflective pavement	11% increased cooling load	*compared to typical pavement*	non-residential buildings	high	Phoenix, Arizona	n/a
Ko 2018	Landscape	shading and evaporation from trees	2.3-90% reduction of cooling energy					
	Landscape	planting trees on the west and south sides of the building	5.2 % reduction of summer electricity use		residential		Sacramento, California	
	Landscape	Trees as windbreaks	1-20% heating energy savings	*larger energy savings in colder climates*				
McPherson and Rowntree 1993	Landscape	shading and evaporation from trees	10 -50 % reduction of cooling energy				The U.S. locations	
	Landscape	Trees as windbreaks	up to 40 % heating energy savings	*larger energy savings in colder climates*				
Susorova et al. 2014	context	green walls with climbing vegetation	reduction of air leaks ~ 10% per wall					

5 Regulation of energy efficiency and decarbonization of old buildings in California.

Retrofit implementation is heavily influenced by existing policies and regulations, as well as incentives and support mechanisms. The legislations may influence by mandatory prescription of certain measures, by encouraging with tax credits or other supporting programs, by establishing infrastructure to facilitate efficient solution, or negatively by shifting attention from important but non-required measures to obligatory. As it was discussed old buildings are generally show lower energy performance but considering potential risks of retrofit for historic fabric are often exempt from energy regulations by policies in the Europe and U.S. (Webb 2017). However, with the urgency of climate change the perspective on old and historic buildings has started shifting. In this chapter the current state of California's policies for energy retrofit will be reviewed. To put it in perspective a short overlook on the European retrofit will open the section, followed by Californian energy retrofit initiatives, policies and Californian building energy code (Title 24) overview.

5.1 Europe - overview

In Europe around 30% of buildings are historic (Zhou et al. 2022). About 85% of the E.U.'s buildings or 220 million building units were built before 2001 and up to 95% of them expecting to remain in operation in 2050, largely contributing to the energy demand and related GHG emissions. European Union target to achieve 60% reduction of buildings' GHG emissions by 2030 and cut energy for space heating and cooling by 18% (European commission 2020), yet energy performance of existing buildings is not regulated at present (Wilson 2022). The current rate of retrofit in EU is far from substantial and in 2020 it was estimated at about 1% per year with only 0.2% of deep renovations reducing energy consumption by at least 60% (European commission 2020) and even less for nearly-zero-energy building standard (Hao et al. 2020). However, to ensure achieving the *Net Zero Emissions* E.U. goal by 2050 International Energy Agency (IEA) highlights the necessity to reach the milestone of about 2.5% per year deep energy retrofit by 2030 to (IEA 2021). If the E.U. at least doubles the rate of energy upgrade, then around 35 million buildings could be renovated by 2030. This is not only feasible but has been shown economically beneficial as it will create about 160,000 additional green jobs (European commission 2020), so the regulation of the cross-disciplinary field and study of strategies became the latest approach to old buildings retrofit in Europe.

A range of initiatives is seen in Europe to bridge the gap between preservation of cultural heritage and reaching goals of decarbonization (Webb 2017). In 2017 EN *Guidelines for improving the energy performance of historic buildings* was issued to facilitate the design process (Buda et al. 2021) Then in 2018 *Energy performance of buildings directive* (EPBD) - document that regulates the approach to buildings energy efficiency in the E.U. - was revised so all countries needed to create strategies for building renovation to have 80-95% GHG emissions reduction by 2050. Those policies start to regulate heating and cooling systems and their performance along with *smart* systems to optimize energy demand and supply on the electric grid. The major revision (recast) of ERBD issued on December 15, 2021, aims to increase the rate of energy retrofit and electrification so all existing buildings are *zero emission* from 2030. 2021 EPBD central focus was on the worst performing 15% of EU buildings and setting energy performance standards for old buildings. The U.K. targets the goal of net zero buildings including retrofit by 2050, and the country has strong initiatives such as EnerPHit. EnerPHit is the Passive House for existing building program that framework deep and complex energy retrofit. Multi-layer of a retrofit project need to be considered. Aspects such as cost, complex design, access to data and information, socio-cultural values still need to be solved to achieve decarbonization objectives (Alabid et al. 2022). Also, it was highlighted in the scientific literature the importance to take embodied energy into the account, which, at present, is a secondary consideration at the discussion by the U.K. policies (Alabid et al. 2022; Li, Xiangyu et al. 2020).

The current state of existing buildings and the rate of improvement largely depends on the date when energy conservation regulations were introduced. For example, in Sweden conservation policies started as early as 1948, in other countries of Norther Western Europe in 1970s after the oil crisis, however in Portugal insulation requirements appeared only in the 2000s (Economidou et al. 2011). California, that will be discussed below, adopted its first energy efficiency building code in 1978 which since then was constantly improved and in the current version (adopted December 2019) consider to be one of the most advanced.

5.2 Californian policies

California is the most populated state with unique diversity of climate (16 climate zones from hot desert on the southeast to subarctic at the high altitudes, from mild marine along the ocean to continental hot-summer arid in the central valley). The distinct history of the state is cherished and preserved – California is known for its profound preservation policies. Any structure constructed over 50 years ago that possesses architectural or historic significance potentially can be considered as a historic resource according to California Environmental Quality Act (CEQA). For example, in San Francisco most properties are category B and would be examined with Historic Resource Assessment prior to any permitting. Californian "qualified historic resources" includes any local, state, and federally designated buildings, districts, objects, collection of structures and sites "deemed of importance to the history, architecture or culture" (California State Historic Building Code). Importantly, complicated process of historic preservation regulations (e.g. CEQA review) and opportunity to obtain a tax credit for additional historic preservation efforts, creates the client and design team effort emphasis on cultural preservation. This results in having less or no resources such as time and money for optional energy efficiency improvement (Boote 2018).

Principles of historic building conservations, generally, are based on the International Council on Monuments and Sites (ICOMOS) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) guidelines (Webb 2017). The four main directives are: reversibility (ability to undo the changes), minimum intervention, authenticity (materials and detail selections to be true), and compatibility (how the new parts will influence the historic building both physically and visually). Furthermore, the degree or level of transformation may vary. For this, guideline document *The Secretary of the Interior's Standards for the Treatment of Historic Properties* issued by National Park Service U.S. Department of the Interior is often used by industry to navigate the work with old and historic structures. It divides the approach into four levels: (1) Preservation, (2) Rehabilitation, (3) Restoration, (4) Reconstruction (Grimmer 2017).

On the other hand, California is proudly keeping the leadership in the sustainability movement and have one of the most advanced building codes – Title 24. Title 24 is California Building Standards Code created by California Building Standard Commission and is mandatory for all buildings in California. Parts 6, 8, 10 and 11 are Energy Code, Historical Building Code, Existing Building Code, and California Green Building Code respectively. Part 6 Energy Code is unique for California, first issued in 1978 and since then has been constantly updated. Title 24 has very high standards compared to other states and countries, and takes into consideration projected climate change. The high requirements are close to Passive House standards, resulting in minimum operation energy. However, only new constructions must follow the Title 24 requirements. The Energy Code excludes in many cases the existing buildings, the majority of which were built before the energy conservation requirements. Therefore, old buildings stay inefficient and contribute to GHG emissions due.

> *The Standards contain energy and water efficiency requirements (and indoor air quality requirements) for newly constructed buildings, additions to existing buildings, and alterations to existing buildings* (Title24 2019).

Any alterations to existing buildings when a remodeling or reconstruction project takes place potentially could be used for energy performance improvement, but the code does not enforce it, as a substantial part of building needs to be under construction to trigger Title 24. For example, any roof work under 50% of the total area is qualified with the current code as a *Repair*, and thus exempt from Energy Code. Taking the high cost of any construction, owners of any remodeling/reconstruction project tend to navigate scope of work to stay under the thresholds. As a result, many small residential and commercial projects put their resources in beautification without even consideration of energy improvement (Birukova 2022)

Even more Title 24, Part 8 California Historical Building Code regulates preservation, without any thorough consideration of energy efficiency improvement. All historic buildings are excused from California Energy Code buildings compliance and only cumulative energy load for lighting need to meet requirements if new light fixtures are added, which generally means usage of LED bulbs in all fixtures.

> *EXCEPTION 1 to Section 100.0(a): Qualified historic buildings, as regulated by the California Historic Building Code (Title 24, Part 8). Lighting in qualified historic buildings shall comply with the applicable requirements in Section 140.6(a)3Q* (Title24 2019)

To continue, Title 24, Part 10 California Existing Building Code controls safety of existing buildings such as seismic retrofit, but do not have regulations of energy efficiency of the existing buildings. And finally, Title 24, Part 11 California Green Building Code in terms of energy efficiency refers to Part 6, Energy Code, which as shown above misses opportunities to improve performance of old and historic buildings in California.

As it was shown, infiltration rate or airtightness is one of the most crucial parameters for envelope efficiency. Title 24, Part 6 requirement for new commercial building of maximum air leakage for the building envelope is 0.40 CFM/ft2 at pressure of 75Pa (approximately equivalent to 8ACH which is similar to 2021 International Energy Conservation Code (IECC), but less airtight than 2021 International Green Construction Code (IgCC) requirements. However new residential buildings and all old and historic buildings do not require testing, leaving them in many cases at significantly lower quality than possible. Airtightness test of existing buildings, as a state policy could provide important database, public awareness with low-cost improvement recommendations and potential energy and GHG emission savings.

CalGreen (Title 24, Part 11) section 5.106.10 controls grading and paving around the building but only from the perspective of surface water management. Section 5.106.12 regulates shading of the areas adjacent to the building so the trees of certain size need to be planted to secure minimum 50% of car parking and 20% of landscape to be shaded in 15 years, with some exceptions when the shade is provided by structures with PV. However, as it was shown in section 4.4 the landscape and strategic location of trees influence the energy efficiency of the building. Therefore, more precise regulation could suggest using landscape surfaces and vegetation depending on building type and the time of higher energy load (e.g. evenings for residential, days office), the local microclimate, and windows size and their orientation. Those measures could be even more valuable for historic districts where more distinguished measures to improve the building performance are highly limited.

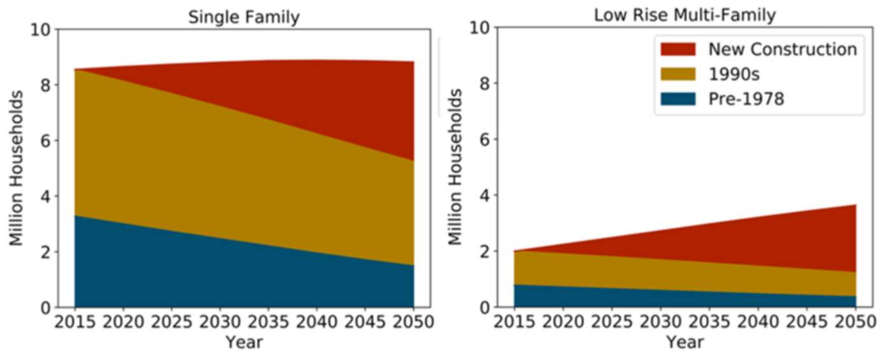

Figure 5-1 California household by vintage and its share projection in 2015-2050. Blue: Pre-1978 – constructed before adoption of any energy codes. Yellow: more efficient yet will require retrofit. Red: new construction aligned with Title 24, 2019 that shown (for new buildings) to be effective to reach climate neutrality (adapted from Mahone et al. 2019).

As the observation of Title 24 showed all the profound energy regulations are only addressing the new constructions. However, more than 75% of building of California were constructed before 1978 when the first, significantly lower than present, energy efficiency standards for buildings were developed (Randolph 2022). Figure 5-1 depicts the share of old, less efficient single family and multi-family houses in California, that will continue significantly contribute to the state energy performance for several decades (Mahone et al. 2019). To address the disparity California supports studies and creates Action Plans.

In 2015 California adopted the Existing Buildings Energy Efficiency Action Plan (EBEE Action Plan) (California Energy Commission 2015). The report highlighted the widening gap between the energy code for new buildings and the existing structures. EBEE provided deep insight into the current state, opportunities, and challenges. Some of the key findings showed (1) potential savings in lighting, shell (envelope), HVAC and appliances upgrade, (2) the significance of small buildings and small businesses, (3) influence of high rent ratio in both residential and commercial buildings, (4) importance of government leadership, (5) necessity of finding "trigger events" – the moment when the energy retrofit can be performed. EBEE emphasized that while Californian households' energy intensity was 31% lower than the US average (California Energy Commission 2015) there are further improvement opportunities that should be used. A ten-year plan of reduction Californian building energy demand by energy retrofit was created. The plan hoped for significant improvement, for example the doubled energy savings in buildings with steady and significant lowering of energy consumption per capita (Figure 5-2). However, the actual data from EIA (2021) for the first five years since EBEE was adopted (2015-2020) reveal the energy use per capita stayed approximately stable for commercial and even increased for residential sectors with the only exception of 2020 due to Covid-19 lockdown (Figure 5-3).

In 2019 EBEE Action Plan became a part of 2019 California Energy Efficiency Action Plan (EE Action Plan) (California Energy Commission 2019) that also included new buildings, industry, and agriculture. The new plan shifted attention from energy efficiency to building decarbonization - the attempt to lessen or eliminate building's GHG emissions. The report indicated progress in efficiency that was achieved since, however more than half of saved energy was as result of buildings lighting change from less efficient incandescent and fluorescent lights to LED. While this was an important step there was not enough progress in other areas of potential improvement. The main tools were described as (1) a clean supply of energy, (2) high levels of energy efficiency, (3) demand flexibility. For retrofitting an old building this could be seen, for example, as an addition to the grid with roof PV, improvement of the building's envelope and its systems and use control systems to regulate supply/demand load. Both energy efficiency and demand flexibility were shown in Chapter 4 of my study as important. This means that EBEE guidelines are up to date with current scientific literature. Among challenges the report named the lack of awareness about the benefits, significant losses due to large volume of small unpermitted work, the split of incentive for renter-heavy residential market and for large ratio of small business in commercial market. The report highlighted opportunities of improvement in the building shell and behavioral changes for smaller residential buildings, HVAC and water-heating for commercial and larger residential buildings. Similar to other research EBEE brought attention to food service and necessity of reduction of natural gas consumption. Importantly, "trigger events" such as during refinance, leasing or sale are the opportunities for major retrofit. Therefore, policies need to focus the attention of the trigger events to prompt the upgrades.

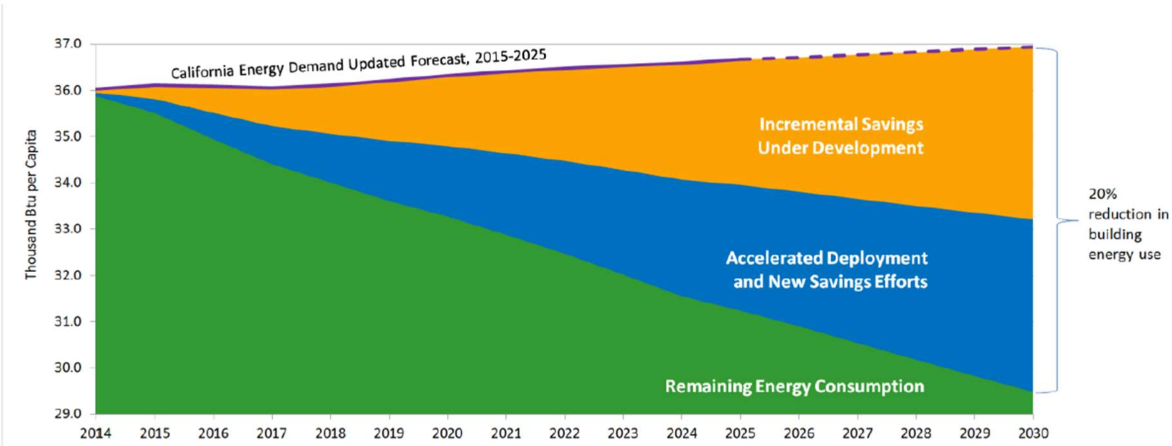

Figure 5-2 California Existing Buildings Energy Efficiency Action Plan, Projection of reduced building energy consumption per capita in California. The steeply declining border between green and blue area is the trajectory of dynamic reduction of building operational energy. (adapted from California Energy Commission 2015).

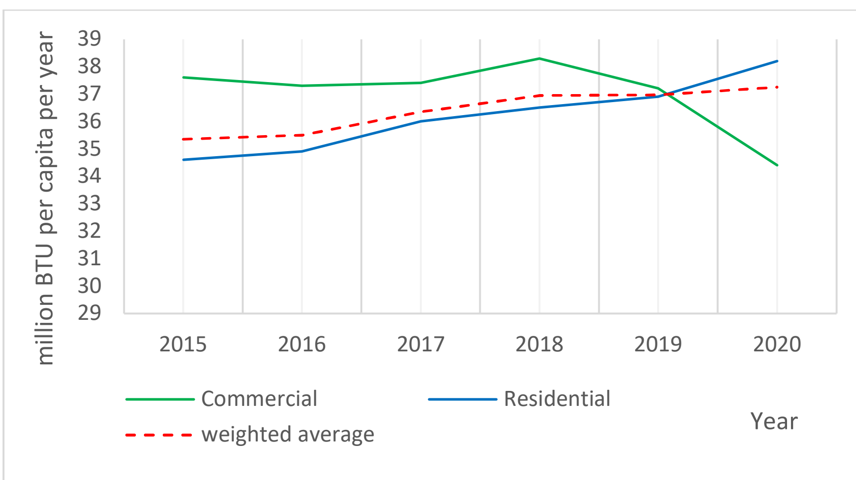

Figure 5-3 California energy consumption per capita in commercial (blue) and residential (orange) buildings, trend between 2015 and 2020. Note atypical consumption in 2020 due to Covid-19 (Data source EIA 2021).

Buildings electrification includes all parts of the buildings, starting with HVAC and water heating to cooking and washing appliances. About 25% of GHG emissions in California now are attributable to operational buildings energy, while to be on track with the states goals it needs to be reduced at least 40% by 2030. About 10% of GHG of the states is coming from natural gas burning inside the buildings (Mahone et al. 2019). California overall is the second largest consumer of natural gas after Texas, the largest in the residential and the second largest after New York in commercial sector. Residential space heating consumes 27% of total energy and about 70% of it is produced with natural gas burning. Water heating – 25% of total residential energy – has 85% share of burning gas (California Energy Commission 2019).

A study of retrofit of space and water heating in Californian showed the necessity of electrification for older buildings in all climate zones for state to reach its carbon neutrality goal by 2045 (Mahone et al. 2019). The six major types of buildings were studied in six Californian climate zone that host 87% of households in the states - namely climate zones 3, 4, 12, 6, 9, 10, with the most populated cities San Francisco, San Jose, Sacramento, Coastal Los Angeles, Downtown Los Angeles, and Riverside respectively. It was demonstrated that homes can reduce GHG footprint by 30-60% even with current electric grid portfolio if switch to air source heat pumps for space and water heating with further improvement up to ~80-90% by 2050 as the grid transition to renewables (Mahone et al. 2019). The study indicated the missed opportunity of electrification due to the low penetration of heat pumps despite economic and environmental benefits. Hence, to reach electrification of old buildings governmental programs need to promote the upgrade, while encouraging “retrofit ready” heat pump market and infrastructure, and providing to the households educational, financial and technical support (e.g. electric panel upgrade, 200-amp electrical service is needed in general) (Mahone et al. 2019).

As it was shown in this paper heat pumps are one of the most effective solutions for decreasing energy consumption and decarbonization of the building sector. However, technology still sees resistance and moves into the practice slowly. At present heat pumps are not required but the updated Title 24 that will be effective on January 1st, 2023 will require heat pump air heating for new single family and nonresidential buildings in certain climate zones. Also, in certain climate zones heat pump water heaters will be required in school buildings and for single family residences, with possible substitution with solar-water heating systems. While this indicates positive progress, those measures would be not substantial as long as there is no tool to include existing buildings. Alabid et al. in the detailed analysis for economics of retrofit with heat pumps combined with energy recovery ventilation showed the advantages of the measures for U.K. At the same time, the study highlighted the necessity of governmental support to booster the market, lowering the prices and shorten payback time for homeowners that in the beginning of 2022 was estimated up to 23 years (Alabid et al. 2022). On the separate note, building’s electrification including home appliances was shown to improve indoor air quality with significant health co-benefits, which is specifically vital for older buildings as many of them are located in older urban locations with lower air quality. California estimated prevention of hundreds of deaths and illnesses related to high NO_x and $PM_{2.5}$ concentrations from house gas usage with approximate $3.5 billion savings per year (Randolph 2022).

Single family homes, besides presenting the largest sector of the whole building stock, have the greatest thermal end-use intensity coupled with the highest floor area per unit, according to National Renewable Energy Laboratory (NREL) and EIA data (Figure 5-4). Therefore, NREL suggested targeting with retrofit policies this type of buildings, overcoming complexity of ownership and the structure’s conditions (Reyna et al. 2022).

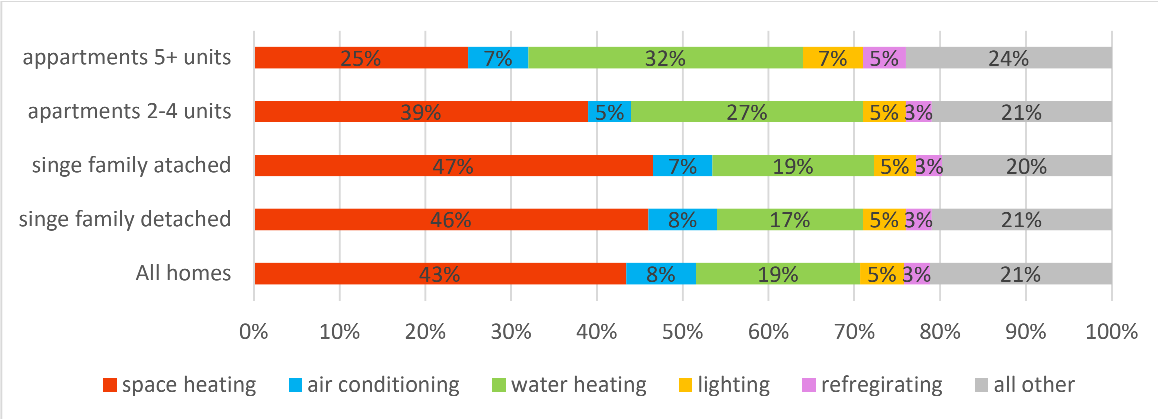

Figure 5-4 California energy consumption per capita in commercial (blue) and residential (orange) buildings, trend between 2015 and 2020. Note atypical consumption in 2020 due to Covid-19 (Data source EIA 2021).

5.3 Policies - conclusion

This section showed that California has deep energy efficiency ambitions, but the large ratio of old houses in the state determines the urgency to shift more attention on the efficiency of the existing buildings. The building code at present misses the opportunity to address inefficiency of old buildings and emphasis on historic preservation withdraw some resources from voluntary energy upgrade. Single family houses and small commercial buildings with specific attention to food services are the building types with major opportunities of savings.

Currently, energy efficiency retrofit and decarbonization are not required, and it seems challenging to adapt them to the building code. However, the approach to retrofit can be compared and use the methods of implementing the Americans with Disabilities Act (ADA), which prevents discrimination against people with disabilities in several areas. Building standards for ADA compliance are rigid and often difficult to achieve, however the code does not exclude old and historic buildings when the building undergoes any tenant improvement project, with minor and limited exemptions where design team need to prove the inability to comply the ADA code (Birukova 2022). While this regulation is challenging for designers and also influences the appearance of historic streets (for example, by construction ramps and elevators) society has an internal agreement of necessity of the measures. The similar attitude to the difficulties related to energy performance improvement in old and historic buildings can be adopted in the light of the energy crisis and the urgency of climate change.

6 Conclusion and Recommendations

Buildings are responsible for almost 40% of total global greenhouse gas emissions and the improvement of existing buildings is an essential part of solving the problem. About 75% of buildings in Californian were constructed before the first energy-efficiency building code was adopted in 1978. The old buildings are inefficient, responsible for large carbon footprints and need to be improved to stay on track with the state's climate targets. However, current policies do not require substantial changes and tend to favor historic preservation over energy efficiency, missing improvement opportunities. Recognizing the significance of carbon intensity, the 2019 California Energy Efficiency Action Plan shifted the attention of policies from energy efficiency to the decarbonization of existing buildings. However, a gap exists between Californian goals and practices.

Chapter 4 of this study performed a literature review of strategies for retrofit and decarbonization of old and historic buildings. The strategies were divided into three groups - internal system upgrade, building shell improvement, and control of the external context. It is important to notice the increase of the first and the third type of strategy (internal and external) as envelope improvement is often limited by historic preservation.

Heat pumps for space heating, cooling, and water heating showed the most potential for decarbonization and energy efficiency gain. They use electricity and are highly efficient. Heat pumps combine heating and cooling, increasing resilience to climate change. Heat pumps for water heating can be used separately or as a part of a space heating system.
Operation control systems for parts and the whole building maximize the efficiency of energy usage. They mitigate the negative human behavior impact by avoiding energy usage for unoccupied space. The more complex (smart buildings) systems, such as building management systems (BMS) or building energy management systems (BEMS), help to balance the supply-demand of the renewable electric grid, additionally increasing decarbonization of the building sector. Food services buildings (restaurants and food stores) showed three times more energy consumption per floor area than an average non-residential building due to the equipment used in this type of building. This indicates the need for additional research and more specified regulations.

Among envelope changes, the increase of airtightness was shown as the most prominent for all climates, with some exceptions in hot and humid climates. Additional insulation is a controversial retrofit measure; it can increase moisture accumulation in the walls resulting in structure decay and reducing the efficiency of the insulation itself. Even more importantly, conventional insulations have high embodied energy. This results in the inability of some insulations (e.g. XPSs) to offset their embodied energy with saved operational energy. It was shown that heat pumps for space heating are more effective than additional insulation in decarbonizing buildings. Furthermore, only low embodied carbon (e.g. blown cellulose) can positively impact the decarbonization of existing buildings.

The window films effectively reduce cooling energy, while changing windows is more efficient for colder climates and north-orientation windows. Skylights require a more detailed design but could be very efficient for controlled heat gain, ventilation, and lighting. Cool roofs with a high albedo and green roofs (with vegetation) reduce cooling energy better than insulation. Skylights and roof alteration provide additional benefits for historic districts and buildings as they are not seen from the street and thus do not change the streetscape.

Landscape design can positively influence the microclimate while also being compatible with historic preservation principles. Strategic trees' location can reduce HVAC energy for cooling and heating, especially in the evenings, reducing electricity demand during evening pick hours. This is crucial for the decarbonization of electric grid. Protection from the wind with vegetation can also lessen the impact of wind-driven rain, which was shown to be the largest factor of moisture risk and a threat to historic buildings. Lastly, an increase in floor area per capita can offset increased energy efficiency per floor area, increasing energy per capita.

Chapter 5 reviewed the current policies and regulations related to old and historic buildings in California. California has viable room for improvement of the old buildings in the state that could be reached by adjustment of the local policies and practices. Currently California does not have the instruments to substantially influence performance of existing buildings. As it was started in 2015 EBEE Action Plan to bridge the gap between the knowledge of efficient practices and changing old buildings it is important to find trigger event (California Energy Commission 2015). The trigger events such as building sale, tenant change, lease renewal, mortgage refinance, redesign project, or maintenance agreement renewal, should be the moments for policies to trigger actions. The actions should combine gathering the data, actively mandated some changes and promoting and supporting positive changes.

Based on the performed analysis it is recommended to improve in the policies:

1. Use occupancy base metric of energy efficiency and decarbonization assessment (per year, per person)
2. Determine and place in the policies “trigger events” to enforce substantial changes in old buildings.
3. Increase awareness of high embodied energy of some common insulation and support the manufacturing of low embodied carbon insulating materials, promote their use. Local guidelines based on research and building science should be provided and be accessible for architects and builders.
4. Allow more flexibility for changes for buildings in historic districts when it improves energy efficiency.
5. Conduct studies and create initiatives to reduce energy and carbon intensity of food services.

It is recommended to initiate at all trigger events the strategies of retrofit and decarbonization that showed the most efficiency and cost-effective:

6. Require at all trigger events rapid transition to heat pumps and have substantial financial programs to support the transitions. The programs should address the Californian specificity of rent-heavy housing market and small business.
7. Mandate at all trigger events measurements of airtightness and include the data to the metrics of the property and provide guidelines for mitigation.
8. Strategic landscape design to improve performance of the building should be part of the building code.

This paper did not discuss several related aspects that indirectly influence energy consumption and could be considered for the further investigations:

- Jevons paradox – behavior paradox when increase of efficiency is offset by more wasteful behavior as the resource became chipper. It was partly discussed in occupancy density section, when lager floor areas offset increased efficiency of the buildings, but this can be found with other aspects of energy efficiency improvement.
- Generation of energy with roof solar photovoltaic and wind generators, are the complimentary or even only strategy for decarbonization of the building.
- Access to efficient and low embodied carbon materials is important. The long-distance shipping of a product not only reduce the likelihood of using it, but also increase the embodied energy due to transportation emissions (Li, Xinyi and Densley Tingley 2021).
- Water conservation, reuse of gray water and related energy consumption.
- Self-regulation and behavior change due to prices on energy and/or carbon taxes.
- The occupants' discomfort before retrofit can be connected to lower health state, while health infrastructure is one of the most energy intensive.
- Socio-economic inequality, when less advantages communities live in low energy performance buildings, but do not have means for retrofit - families and businesses have to bear the burden of higher energy bills and lower air quality.
- Gentrification, when "too good" retrofit may result in displacement.

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