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Advances Toward a Net-Zero Global Building Sector

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Keywords

building, net-zero, nearly-zero energy building, Passive House, retrofit, embodied energy, embodied carbon, energy efficiency, climate neutrality, cost, policies, cobenefits, renewable energy sources

Abstract

The building sector is responsible for 39% of process-related greenhouse gas emissions globally, making net- or nearly-zero energy buildings pivotal for reaching climate neutrality. This article reviews recent advances in key options and strategies for converting the building sector to be climate neutral. The evidence from the literature shows it is possible to achieve net- or nearly-zero energy building outcomes across the world in most building types and climates with systems, technologies, and skills that already exist, and at costs that are in the range of conventional buildings. Maximizing energy efficiency for all building energy uses is found as central to net-zero targets. Jurisdictions all over the world, including Brussels, New York, Vancouver, and Tyrol, have innovated visionary policies to catalyze the

market success of such buildings, with more than 7 million square meters of nearly-zero energy buildings erected in China alone in the past few years. Since embodied carbon in building materials can consume up to a half of the remaining 1.5°C carbon budget, this article reviews recent advances to minimize embodied energy and store carbon in building materials.

Contents

1. INTRODUCTION: THE URGENCY OF REDUCING BUILDING ENERGY DEMAND	228
1.1. The Context	228
1.2. This Article's Approach	229
1.3. Definition of Terms	230
2. BUILDING ENERGY DEMAND AND EMISSIONS: THE GLOBAL STATUS	231
3. VERY LOW-ENERGY BUILDINGS: ADVANCES IN PERFORMANCE AND COSTS	235
3.1. Illustrative Best Practices	237
3.2. Costing Studies	239
4. TOWARD A NET-ZERO GLOBAL BUILDING SECTOR: FROM VERY LOW-ENERGY TO ENERGY PLUS BUILDINGS	242
5. MOVING BEYOND OPERATIONAL ENERGY OPTIMIZATION: MINIMIZING EMBODIED ENERGY/CARBON AND CARBON STORAGE IN BUILDINGS	244
6. BENEFITS OF AND RISKS AND BARRIERS TO ADVANCED BUILDINGS	247
6.1. Benefits of Advanced High-Efficiency Buildings	247
6.2. Barriers to Advanced High-Efficiency Buildings	250
7. POLICIES AND PROGRAMS TO ACCELERATE THE UPTAKE OF NET- AND NEARLY-ZERO ENERGY BUILDINGS	252
8. CONCLUSIONS	254

1. INTRODUCTION: THE URGENCY OF REDUCING BUILDING ENERGY DEMAND

1.1. The Context

By January 2020, 19 countries, 11 regions, 21 cities, and 34 companies (1) had committed to climate neutrality in order to be in line with the emission scenarios outlined by the Intergovernmental Panel on Climate Change (IPCC) to be compatible with a global warming of up to 1.5°C as compared to preindustrial levels (2). However, reaching this ambitious climate goal, according to these IPCC scenarios, requires either an unprecedented amount of bioenergy combined carbon capture and storage (BECCS) or a drastic decrease in energy demand. Scenarios with a high reliance on BECCS have been heavily criticized by the scientific community as entailing substantial risks (3, 4), therefore a safer approach is to focus on energy demand reduction as a key strategy to achieve ambitious climate goals (5). Buildings, especially their heating and cooling, are among the few areas of energy use where a several-fold decrease in emissions and energy consumption is possible

while maintaining or improving the level of energy services provided. As this end use comprises an important share of global energy demand, low-energy buildings are key to a climate-neutral future.

Recent advances in building materials and design, construction, operation, and retrofitting offer the opportunity to transform buildings in the direction of climate neutrality in a wide variety of climates, geographies, and cultures (6). These buildings are also typically healthier and more comfortable than their conventional counterparts and can often be cost competitive with traditionally built buildings, as outlined in Section 3.2 and Section 4, below. These recent developments raise the following question: Could the building sector become climate neutral in itself (i.e., without offsets or imported zero-carbon energy)?

In an earlier *Annual Review of Environment and Resources* article, Harvey (7) provides an extensive review of recent advances in the performance and costs of state-of-the-art buildings worldwide, focusing on operational energy demand. We build on that review by discussing the latest advances. In particular, we cover advances in best practice buildings approaching or achieving net-zero energy levels, policies that have successfully increased their deployment in several jurisdictions, as well as methods to reduce embodied energy and embodied carbon above operational ones—which Harvey does not discuss.

In light of the Paris Agreement (8), it becomes even more relevant to improve buildings. There are four important issues related to the global building stock in the context of climate neutrality. First, the long turnover rates in the building sector, especially in developed countries where the majority of the buildings determining mid-century emissions already stand, needs accelerated deep energy retrofit programs (9, 10). Second, the Paris Agreement also places a renewed urgency on transforming the building and construction industry in a way that minimizes lock-in risks, as carbon lock-in will seriously jeopardize or delay meeting such targets by decades (11–13). Third, although the frontiers of building operational energy use have achieved major advances in the past decade, the figures that Bai et al. (14) document imply that, alarmingly, constructing just the necessary new urban infrastructure with today's average technologies will consume one-quarter to one-half of our remaining carbon budget to 1.5°C [more than 220 GtCO₂eq of the total remaining budget that the IPCC (2) estimates to be between 420 and 770 GtCO₂eq], without turning even one light on in buildings. This points us to the major responsibility of the building sector in focusing on minimizing embodied emissions in addition to operational emissions (15). Embodied emissions or energy have received less focus than operating emissions or energy in most building policies. An important question emerges: Could the significant amount of material used in buildings be potentially turned into a carbon store rather than a major source of emissions?

1.2. This Article's Approach

This article reviews the recent advances in the knowledge related to building materials, design, construction, retrofitting, and operation from the perspective of the demands posed by the dual challenges of development and mitigating climate change. We break down the mitigation challenge in the context of buildings into its three sub-challenges: (a) lowering operational energy demand; (b) decarbonizing the remaining operational energy demand; and (c) the nonoperation-related emissions of buildings, most prominently the challenge of energy/carbon embodied in construction materials. A systematic literature search has been conducted related to architectural and technological advances and their costs and the market penetration of highly efficient buildings, whereas the coverage of policies, as well as cobenefits, is limited to the more constrained body of new knowledge that is relevant for achieving a wide-scale penetration of the discussed building solutions.

Climate neutrality:

“concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface albedo or local climate. Net zero CO₂ emissions are also referred to as carbon neutrality” [as defined by the Intergovernmental Panel on Climate Change (2)]; climate neutrality for a system typically refers to emission levels where the emissions are equal to or smaller than the sinks of emissions within the system

Embodied energy: in this article, we refer to embodied energy as the energy that is required to produce, manufacture, and transport the materials and components of a building, as well as for the construction and assembly of the building; embodied energy also occurs during a retrofit/renovation of a building through the same processes

Embodied carbon: in this article, we refer to building embodied carbon as the carbon dioxide that was emitted as a result of the production, manufacturing, and transport of building materials and components, as well as during the construction and assembly of the building; carbon can also be “embodied” during the retrofit/renovation of a building through the same processes

Embodied emissions: (see also embodied carbon) embodied emissions are broader than embodied carbon because the manufacturing, use, and dismantling of several building components, such as some forms of insulation, are associated with non-CO₂ greenhouse gas emissions; embodied emissions account for this broader set of gases during the same processes that are responsible for embodied carbon

During our search of the literature for this article as well as our work for the IPCC Sixth Assessment Report, it became clear that the academic literature follows professional practice in this area with some delay. Although there are many net-zero energy, energy plus, and other very high-performance buildings worldwide, the scientific literature documenting these advances is slim. This could potentially be because the relevant areas of scientific innovation—architecture and engineering—are traditionally less rewarded for scientific papers and more for advances in on-the-ground practice, compounded by the pace of recent development and the evolution of the climate rationale (16).

As a result, this article follows a dual approach to reviewing the recent science and innovation in the field: knowledge co-production. The academic authors of this article have teamed up with leading practitioners in order to be able to review the frontier knowledge in the relevant recent science and practice. Where available, the academic literature was used to provide the objective documentation of the advances in science and technology, but the gaps, especially with regard to most recent developments, have been filled in by the professional literature. Knowledge co-production by the academic and professional communities has become an important trend in the advancement of science, particularly in fields where on-the-ground experience is crucial for testing and calibrating new findings, such as in urban science and architecture (17, 18).

1.3. Definition of Terms

There is a broad variety of terms in the scientific and policy literature related to zero-energy buildings or close relatives. As such definitions are often related to political goals and policy decisions, in this article we summarize the key issues that are included in such definitions in the scientific literature rather than in the policy/political discourses. We also provide a figure that conceptually introduces the main categories of terms used for very low-energy/-emission buildings.

In the definition of low-energy buildings and zero-energy buildings, the period and the types of energy included in the energy balance together with the renewable energy supply options, and the connection to energy infrastructure and energy efficiency, the indoor climate and the building-grid interaction requirements are typically considered (19). In the literature, there is no clear definition of the different terms and no agreement between authors, so different definitions can be found. Low-energy buildings are defined as buildings built according to a special design criteria aimed at minimizing the building operating energy (20, 21), buildings with energy saving measures and renewable energy generation (22), or buildings that demand less operating and life cycle energy than conventional ones (21, 23). Zero-energy buildings are one step further in decreasing the energy use for operation of the building to become self-sufficient (23, 24), or buildings that generate energy to counterbalance their consumption (25, 26).

Net-zero energy buildings were first defined around 2010 as those exchanging energy with the surrounding grids with an annual zero balance between exported and delivered energy (21, 27), but also as buildings with reduced energy consumption due to the application of energy demand of HVAC (heating, ventilation, and air conditioning) and due to the adoption of renewable energies and heat recovery technologies (27–32); moreover, net-zero energy buildings are recognized as typically being grid-connected (32–34). According to the literature, an energy plus building outperforms net-zero energy buildings by generating more energy than their residents require (21). In contrast, nearly-zero energy buildings have become an important term in the literature due to the European Union (EU) Energy Performance of Buildings Directive (35) that mandates such levels to be met by December 31, 2020. In the directive, the EU defines nearly-zero energy buildings as the ones that have very high energy performance, following a methodology that considers nine different aspects (e.g., insulation, passive solar, thermal loads). However, each member state

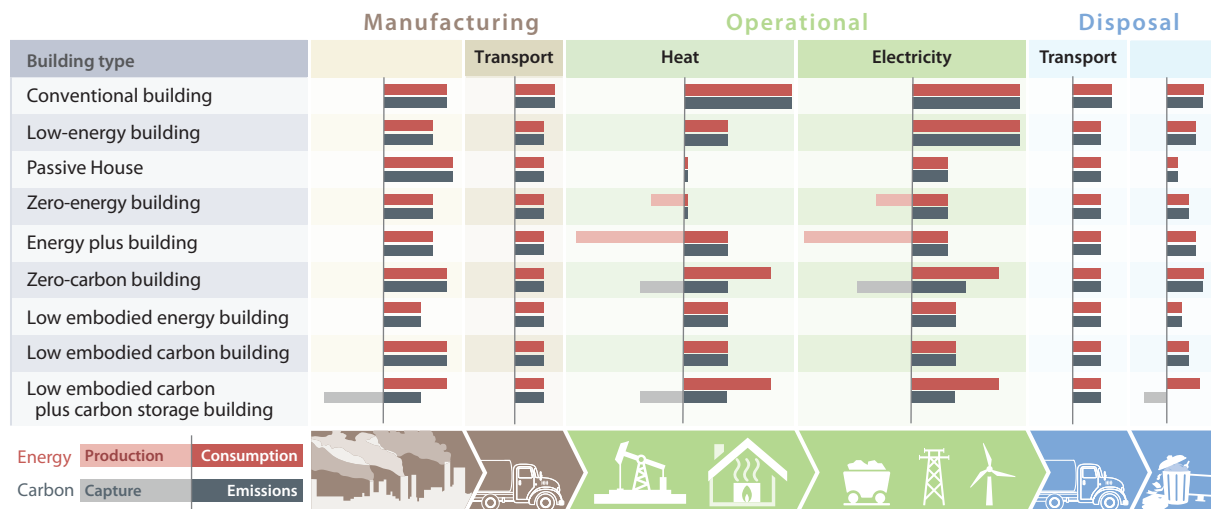


Figure 1

Conceptual illustration of energy demand/carbon emissions from the different life cycle phases of different zero energy relevant building categories. The sizes of the bars are illustrative, although their relative size is based on the authors' best understanding of the literature. Negative bars mean produced energy rather than consumed, and stored carbon rather than emitted. The difference in size between the carbon bar and the energy bar signals non-energy related emissions or capture/storage of carbon. Manufacturing: It is assumed that some low-energy building types need more materials such as insulation to achieve their low-energy demand. Transport: It is assumed that any low-energy building type would use as much as possible local materials and would dispose or recycle the materials at its end of life as close as possible to the building itself; no other assumptions were made. Operational heat and electricity: The production of energy is assumed to be due to renewable heat and the production of carbon to carbon capture and storage. Disposal: This includes recycling and disposal; it is assumed that recycling will be optimized in low-energy building typologies.

is to provide their own elaboration of what this standard means, and there is some controversy in the literature as to whether these standards are truly nearly zero or not.

In the general literature since the 1970s, a Passive House was defined as a low-energy building with a design that makes maximum exploitation of passive solar technologies (20), while having comfortable indoor temperature during winter or summer, and a low-energy request for heating or cooling of the space (36–38). However, with the Passivhaus certification standard gaining traction worldwide, recently most literature uses Passive House to mean a building that meets the criteria of the Passivhaus standard (39), including space heating demand, space cooling demand, primary energy demand, airtightness, and thermal comfort requirements. Therefore, a Passive House also minimizes, to some extent, non-heating related energy demands in order to meet primary energy requirements in the standard (**Figure 1**).

The authors have not found a definition of zero-carbon buildings in the scientific literature. We do provide definitions for net-zero emissions, net-zero emission buildings, and net-zero carbon buildings. In order to understand better all these definitions, **Figure 1** presents a conceptual comparison. In this article, we use the terms net- or nearly-zero energy building as a collection of the most ambitious building standards meeting at least Passive House energy performance levels or better.

2. BUILDING ENERGY DEMAND AND EMISSIONS: THE GLOBAL STATUS

The buildings and construction sectors are crucial for decarbonization: They accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO₂) emissions in

Net-zero energy building: there are many definitions in the scientific and professional literature; this article uses the concept of net-zero energy buildings as those exchanging energy with the surrounding grids (energy supply systems) with an annual zero balance between exported and delivered energy; low operational energy demand is typically key to meeting net-zero energy standards

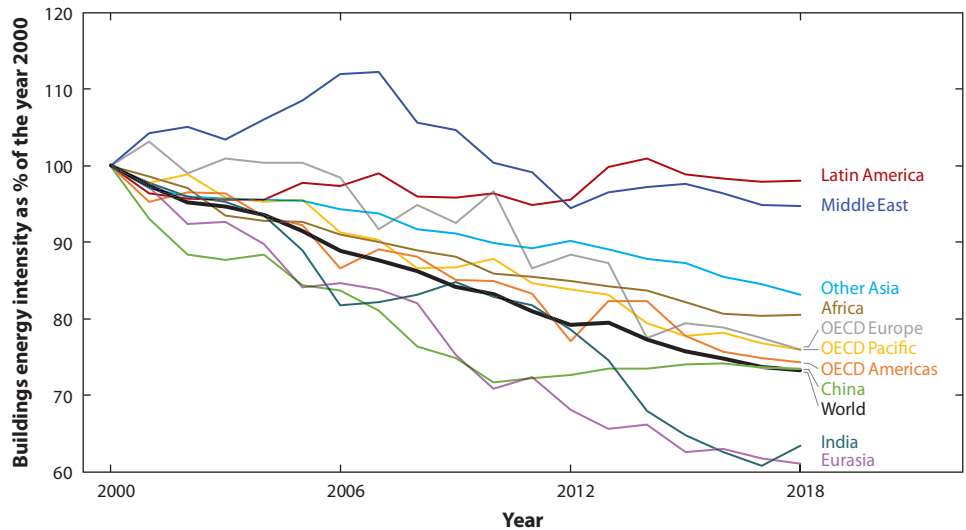


Figure 2

Trends in buildings energy intensity per IEA region in percentage of 2000 values (47). Energy intensity, used as a measure of the energy inefficiency of an economy, is calculated as units of energy per unit of GDP. High-energy intensities indicate a high price or cost of converting energy into GDP; low-energy intensity indicates a lower price or cost of converting energy into GDP. Abbreviations: GDP, Gross Domestic Product; IEA, International Energy Agency; OECD, Organisation for Economic Co-operation and Development.

2018, 11% of which resulted from manufacturing building materials and products such as steel, cement, and glass (40). Energy use in buildings accounted for 29% of global demand in 2018 (41) and for similar percentages of global and regional energy demand (42–44). Increasing prosperity driving demand for increased floor area has outpaced efficiency gains in most regions, thus still raising building energy consumption in the majority of the world (45). Some regions, however, including many countries in Europe, have managed to decouple building energy demand from income and population growth, and managed to achieve absolute reductions in building energy demand despite these growing trends in its drivers (42).

Energy use in buildings accounted for similar percentages of global and regional energy demand in the trends in the past decades (42–44) (**Figure 2**). Global energy consumption is increasing, whereas energy-related carbon emissions present a limited growth (40). Worldwide, thermal energy uses are an important and variable part of this demand (60% in residential buildings and almost 50% in commercial ones). The share of heating or cooling in the total building energy use varies from 18% to 73%, depending on the type of buildings (residential or commercial), the climate, and the region of the world (developing countries versus developed ones). The lowest share (18%) is for commercial buildings in North Africa and the Middle East, whereas the highest one (73%) is for commercial buildings in Centrally Planned Asia (40). The total energy consumption in BRIC (Brazil, Russia, India, and China) countries has already surpassed that of developed countries, and the continuous increase of the building stock predicts the potential continuation in the increase of energy consumption in the countries (46). Strong growth in floor area and population raises the building sector's energy use (40). Economic factors are also a driver of the increase in energy consumption per capita. For example, GDP growth influences the growth of commercial buildings (44).

The main drivers of energy consumption in buildings are the number of households, the number of persons living in each household, the floor area per person, the specific energy consumption (42) (see Equations 1 and 2), access to modern energy services, changes in energy services, building energy performance, and energy technologies and equipment used (40):

$$E_{resid}[kWh] = b \cdot \frac{p}{b} \cdot \frac{A}{p} \cdot \frac{E}{A} \quad 1.$$

$$E_{com}[kWh] = GDP \cdot \frac{A}{GDP} \cdot \frac{E}{A}, \quad 2.$$

where E_{resid} is the energy use for heating and cooling in residential buildings, b is the number of households (activity driver), (p/b) is the number of persons living in each household, also called household size (activity driver), (A/p) is the floor area (m^2) per person (use intensity driver), and (E/A) is the energy (kWh) used for heating or cooling each unit of floor area (m^2), also called specific energy consumption (energy intensity driver); E_{com} is the energy use for heating and cooling in commercial buildings, GDP is the Gross Domestic Product (activity driver), (A/GDP) is the floor area (m^2) per GDP (use intensity driver), and (E/A) is the energy (kWh) used for heating or cooling each unit of floor area (m^2), also called specific energy consumption (energy intensity driver).

There is much variation in the conventional energy consumption of buildings across and within countries, often reported by an Energy Performance Index (EPI) (48). This is a function of different climate zones, building types, usage patterns, and materials, among others. For instance, the average annual specific consumption per square meters for all types of buildings in the EU was approximately 180 kWh/ m^2 in 2013 (49). Specific country numbers differ from 55 kWh/ m^2 in Malta and 70 kWh/ m^2 for Portugal or Cyprus to 300 kWh/ m^2 in Romania (or 285 kWh/ m^2 in Latvia and Estonia), which is significantly higher than the EU average. However, even for countries with a similar climate, significant discrepancies exist (e.g., 200 kWh/ m^2 in Sweden, which is 18% lower than Finland). In Germany, the average residential energy consumption was calculated as 136 kWh/ m^2 (in 2015) (50). Whereas in Greece, an analysis of Hellenic residential and nonresidential buildings revealed ranges in annual average total energy consumption from 108 to 189 kWh/ m^2 in residential buildings and from 167 to 371 kWh/ m^2 in nonresidential buildings (in 2010) (51).

Such variations exist in developing country statistics as well. In India, energy consumption in residential buildings, comprising appliances, heating, cooling, water heating, etc., is in the range of 27–54 kWh/ m^2 , across a range of climate zones (in 2014). For households with more than two air conditioners (ACs) or more than four occupants, EPIs of more than 80 kWh/($m^2 \cdot year$) were noted (52). EPIs reported for Indian commercial buildings are much higher, determined by climate zones and AC use, and range from 86–179 kWh/ m^2 (in 2016) (53). In Mexico, however, commercial buildings have EPIs of 155–250 kWh/($m^2 \cdot year$) (54). For countries such as China, the typical load from residential heating in severe cold zones is approximately 100–130 kWh/ m^2 , and in cold zones it is 80–100 kWh/ m^2 (55).

Figure 3 provides a summary of worldwide EPIs summarized from official data sources. Such differences are partly explained by climate conditions and statistical definitions (56, 57). Importantly, the variation in and complexity of getting reliable data on country-level EPIs points toward the larger issue of the reliability of using EPIs as the metrics of progress. Instead, a standardized measurement methodology is required before accurate comparisons can be made.

Often the reported energy loads reflect modeled or projected energy use, not monitored or verified energy use. Unfortunately, modeling protocols can result in what is commonly referred

Passive House:

A Passive House is a building meeting the international Passive House (originally Passivhaus) standard and is able to provide high levels of comfort while minimizing final and primary energy inputs. It is the most rigorous energy efficiency building standard in the world and achieves that outcome through detailed energy modeling requirements and clear limits on the energy use per meter of useful floor area. For example, heating and cooling are not to exceed an annual demand of 15 kW/($m^2 \cdot year$) or a maximum energy load at any time of 10 W/ m^2 . The Passive House standard also minimizes non-thermal energy demands by setting limits on total energy consumption. The standard requires high levels of insulation, highly efficient windows and mechanical systems, and optimization of building design including passive design features such as external shading. The standard includes separate metrics for retrofits

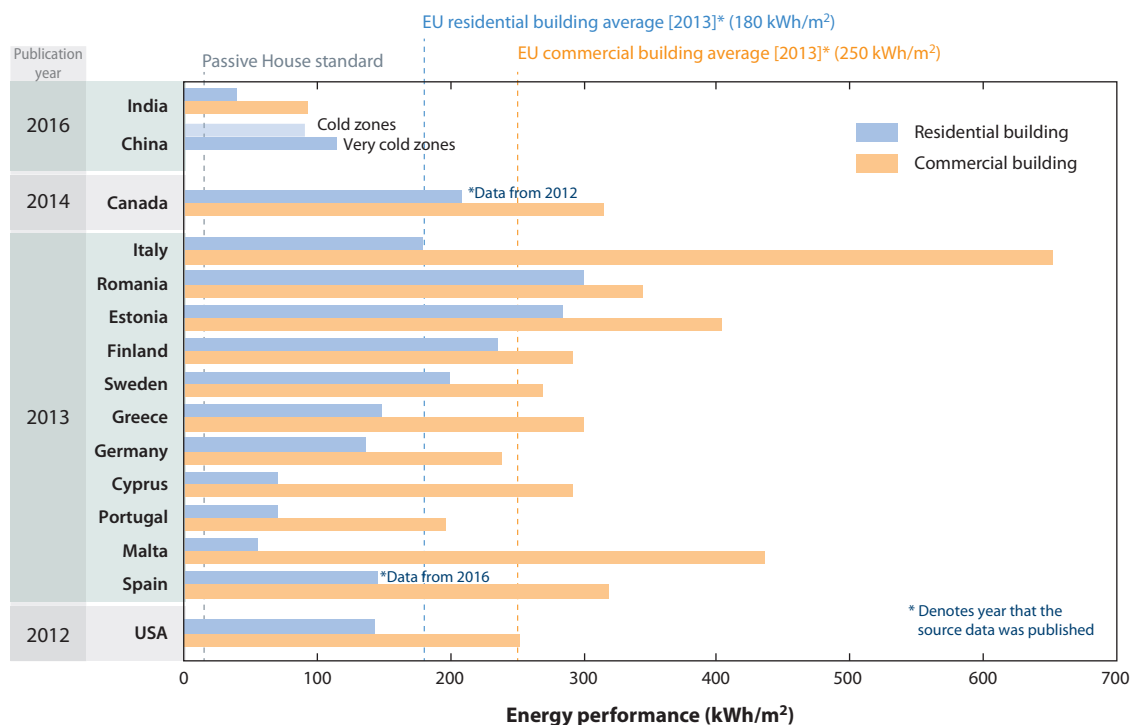


Figure 3

Energy performance indexes for residential and commercial buildings from official data sources (39, 49, 53, 54, 58, 59).

Net-zero emissions:

net-zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period; net-zero emissions for a system refers to the balance of emissions and removals over a specified time period

to as the performance gap, that is, the difference between modeled building energy performance and actual performance (60, 61). The performance gap is both substantial and endemic in the design and construction sector, with large datasets showing gaps of 10–30% (62, 63). Smaller-scale studies have shown performance gaps of 50–250%, and even up to 500% (62). Generally, the gap is more significant for nonresidential buildings than for residential buildings. There are many reasons for the existence of such substantial gaps, including construction and operational deficiencies. However, the most significant factor at the design stage, when the energy model is developed, is that energy models often model the building relative to a hypothetical reference building to demonstrate code compliance. Having regulatory compliance relative to a hypothetical reference building as the primary purpose of the model can lead to differing assumptions, inputs, and definitions of energy loads if the model is not intended to simulate actual occupancies and operational conditions (64).

At the same time, very low-energy buildings can and are being provided without a performance gap (64–68). Monitoring and verification of certified Passive House¹ buildings has been undertaken for decades, with thousands of units being the subject of studies. Such studies have confirmed the building's actual performance is consistent with its modeled performance prior to

¹ In this article, a building referred to as a Passive House adheres to the definition, standards, and performance metrics specified by the Passive House Institute based in Darmstadt, Germany, for both new buildings and retrofits. Such buildings should not be confused with earlier “passive” houses that relied on solar heat gain or other “passive” measures but sometimes overlooked important elements of building science and design.

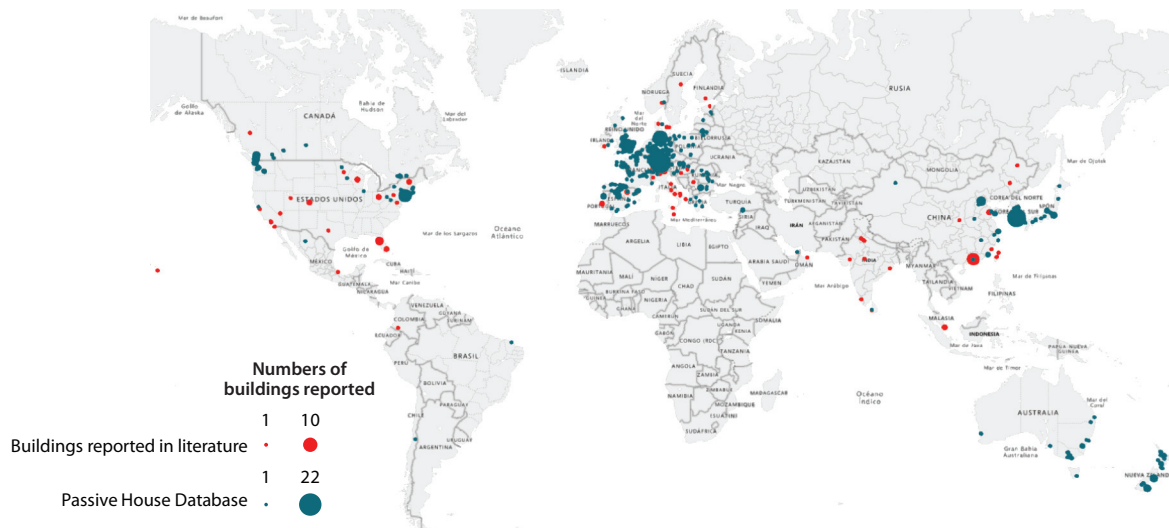


Figure 4

Regional distribution of located documented state-of-the-art low-energy or nearly-zero energy buildings. Red dots represent case studies from the peer-reviewed literature, and blue ones are from the Passive House Database (70). References 15, 30, 48, 71–104 provide the sources for the data points in the peer-reviewed literature. The size of dots represents the number of buildings reported in the literature.

construction and that user behavior is less of a factor in buildings that deliver high thermal comfort with minimal energy use. Furthermore, while one user may consume somewhat more energy than predicted, another consumes less (69). Similar results have been observed for large-scale retrofit programs, such as Energiesprong in the Netherlands (64). Such retrofit programs are being offered to homeowners with a 30-year energy performance guarantee, demonstrating the teams delivering the projects are confident in their ability to predict actual long-term building performance. In addition, the requirement of a performance guarantee rapidly increased the quality of retrofits.

3. VERY LOW-ENERGY BUILDINGS: ADVANCES IN PERFORMANCE AND COSTS

A systematic literature review aiming at identifying exemplary buildings or districts worldwide compiled in this article (see **Supplemental Table 1**; follow the **Supplemental Material** link from the Annual Reviews home page at <http://www.annualreviews.org>) shows that today there are many net-zero, nearly-zero energy, and certified Passive House buildings all over the world, without regard to climate or geographic region (**Figure 4**). The figure illustrates the cases identified from the literature on a global map. It builds on two types of data: Cases documented in the academic literature are marked in red, and buildings that are reported by the International Passive House Association in their database (certified Passive House buildings, but the data are entered by their owners and not peer-reviewed) are documented in blue. The figure suggests that the majority of net-zero or nearly-zero energy buildings are in Europe, with other such buildings in North America, New Zealand, Korea, Japan, China, and India, some with a handful of individual cases. It is only in Africa that no net or nearly-zero energy buildings were identified during our research.

The map reinforces what Schnieders et al. (105) showed via simulation: It is possible to achieve at least the Passive House energy standard of performance, or better, in all relevant climate zones

Net-zero emission buildings: (see also net-zero emissions for systems as described in the definition for net-zero emissions) there are many different net-zero emission building definitions, depending on where the system boundaries are chosen for the building (i.e., including the energy supplied to the building or not) and the time period (a year or including the entire life cycle of the building); this article does not pick one specific system boundary or period, but discusses all options that bring buildings toward net-zero emission goals

Net-zero carbon buildings: (see also net-zero emission buildings) for net-zero carbon buildings, we refer to buildings where the emissions of carbon dioxide, rather than all greenhouse gases, related to the building with the defined system boundaries are fully balanced by removals over a specified period

of the world. Results show the annual heating and cooling energy demand using this approach are 75% to 95% lower than in average buildings (105).

The data presented in the **Supplemental Material** and in the Passive House Database (70) show an important trend. Although specific thermal energy consumption in heating-dominated climates can go down to as low as 15 kWh/(m²•year) in virtually any climate, even in Antarctica, such low specific energy use values are much harder, or impossible, to achieve in cooling-dominated climates, especially in those also requiring dehumidification. In some climates, the lowest values even by Passive House methods (excluding building-integrated generation) are as high as 80–90 kWh/(m²•year), and our literature search did not find any approaches that may achieve better energy performance in a commercial building in a hot and humid climate.

This has several important consequences. First, net-zero energy buildings are easier to achieve in the North, with lower humidity rates and lower cooling degree days, than in the South. This means that the building sector is expected to pose a larger climate burden on these warmer climate countries than in the Global North, assuming these countries continue to take advantage of the major cost-effective opportunities for energy and emission reduction through improved building energy efficiency.

Second, in a warming climate, building thermal energy demand will go up in the long term, even with maximum efficiencies utilized. With high-performance buildings, heating energy demand will significantly decrease, but with affluence, building space, and comfort, energy demand for cooling is very likely to increase due to increasing degree days, unless new technologies for cooling are identified.

Indeed, the energy needed for cooling from ACs is projected to triple by 2050, with an equivalent of 10 new ACs to be sold every second for the next 30 years—requiring new electricity capacity equivalent to that of the United States, EU, and Japan today (106). Overall, 1.8–4.1 billion people may require ACs to avoid heat-related stresses under current climate and socioeconomic conditions in developing countries alone (107). The complexity and urgency of delivering sustainable cooling is only beginning to be recognized in the literature, with large gaps in its implications for climate mitigation and delivering quality of life (108). Yet, zero-energy buildings provide a critical opportunity to influence path-dependent climate emissions outcomes and move toward climate neutrality (see the sidebar titled *The Opportunity Buildings Offer*). Passive building design, which uses layout, materials, and form to accentuate ventilation to reduce temperature, will be key to managing temperature in hot climates, often akin to their vernacular architectural traditions (109–111). Moreover, cooling energy demand coincides with solar availability, giving good chances for solar cooling technologies [photovoltaic (PV) with electrical chillers or thermal solar collectors with absorption chillers] and energy on-site production (112).

The Passive House standard places clear limits on cooling energy just as it does for heating energy; in general, the limit for both is 15 kWh/m² cooling demand plus a dehumidification

Supplemental Material >

THE OPPORTUNITY BUILDINGS OFFER

With global emissions reduction targets being missed, it becomes more important for each nation to pursue all opportunities to minimize emissions. Both the literature and experience reveal that maximizing operating efficiency and minimizing embodied carbon in buildings is one of the lowest cost pathways to significant emissions reductions, and one that generates multiple social benefits. The rate at which buildings are consuming the global carbon budget necessitates urgent action to transform the sector's performance, a transformation several jurisdictions and programs have been demonstrating is possible.

contribution (113). Recent publications (114–116) raise hope that perhaps radically new methods through passive radiative cooling could potentially be developed to cool buildings through advanced materials, but so far this is so much in the research phase that no long-term projections can be made.

The fundamental building science in relation to low-energy buildings was developed in the 1970s (117), identifying the need to focus first on the building envelope to create a thermal bridge-free airtight building with high thermal resistance to heat transfer and highly efficient mechanical ventilation. Heating and cooling loads, typically the largest use of energy, as shown above, are further reduced by shading windows from excessive solar heat gain in hot periods and enabling the capture of solar heat gain during the colder periods. The research identified those key factors during the energy crises of the 1970s, noting such buildings also offer great improvements in comfort, air quality, protection from molds and mildew, and providing resilience, durability, and affordable operating costs (118, 119). Today, we can build and retrofit existing buildings that produce more energy than their occupants demand.

Examples of technical measures used for reducing thermal loads are increased insulation (120), sometimes with natural insulation materials such as grass board with rice husk composites (101); improved windows, with the inclusion of low-emissivity glass (76, 80, 83), triple glass (76, 81, 82, 86, 90, 92, 121), etc.; external solar shadings (48, 74, 78, 96); use of recycled materials to improve the life cycle of the building (76); natural ventilation (48, 74, 96); evaporative cooling (74, 122); heat recovery ventilation (76, 81, 123); thermally active building systems (72); advanced lighting (124); and improved thermal mass (82, 90, 93, 96).

The following section documents a selection of exemplary cases from a diversity of world regions, climates, building types, and vintages identifying the key technological advances that enable these buildings to significantly outperform their local peers and to achieve nearly-zero energy levels.

3.1. Illustrative Best Practices

Some of the buildings constructed as part of early efforts to reduce energy use are still occupied and functioning as well as they did when built 60–70 years ago. The Saskatchewan Conservation House in Canada (**Figure 5**) built in 1977 is largely unchanged other than the removal of solar-thermal collectors for hot water (118, 125, 126). The building envelope continues to perform as designed more than 40 years later.

In the following, some exemplary buildings (also listed in **Supplemental Table 1**) are described. As discussed above, net-zero buildings are much more challenging in cooling-dominated countries. A university research building in Taiwan, however, achieved an energy use intensity of the whole building of 29.53 kWh/m², which is 82% lower than similar types of buildings (87).

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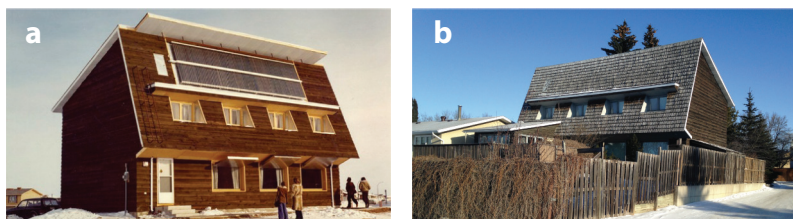


Figure 5

The Saskatchewan Conservation House (126), an early example of an energy efficiency building shown (a) when built in 1977 and (b) today. Photos reproduced with permission from Mr. Harald Orr.

At the same time, its average cost per square meter is almost equal to the construction cost of a traditional office building (85). In the case of the low-energy campus (Namasia Ming Chuan Elementary School), the library attained net-zero energy by 2015, and the energy use intensity of the whole campus was 6.8 kWh/m² (88), 74% lower than the other elementary schools of Taiwan. The key factors that contribute to the low cost and high efficiency are passive design strategies (127), large roofs and protruded eaves that are typical shading designs in hot and humid climates, porous and wind-channeling designs (128, 129), and stack effect natural ventilation. Lin (130) showed that these sun-shading devices could block approximately 68% of incoming solar radiation annually in tropical climates and reduce building total energy use by 20% (48, 127, 131, 132). Stack effect natural ventilation design helped reduce the annual air-conditioning load by 30% (127, 131).

In another example, Singapore launched a green building master plan in 2006 to facilitate a sustainable built environment. As a flagship project, the Singapore BCA Academy Building was renovated to become the first net-zero energy retrofitted building in Southeast Asia (133). Sun et al. (85) found that in this case passive design features such as green roofs, green walls, daylighting, and stack effect ventilation collectively contributed only 5% to the energy savings. However, under the same cost, active designs (energy-efficient lighting, air-conditioning systems, building management systems with sensors and solar panels) helped save 40–45% energy consumption when installed in a well-insulated, thermal bridge-free building envelope.

For quite some time, retrofitting historical buildings into low-energy buildings was seen as not possible due to the constraints in insulation of the façade and roof, or protection of windows and other building elements. The significance of this is that in some world regions a sizeable share of the building stock has protected status or is of heritage where conventional methods for achieving very low-energy consumption would compromise the aesthetical or protected features. Since the Harvey (7) paper, however, significant advances have taken place in technology and know-how, and by now many different examples can be found around the world that have managed to reduce operational energy demand by 80% or more while preserving the heritage or monument features of the buildings. As an example, **Figure 6** shows two historical buildings retrofitted in Vienna (103, 104). Technology progress has made this possible; for example, the Mariahilfer Strasse building used only 5 cm of aerogel insulation in its walls. Moreover, the incorporation of renewable energy sources (RES) in historical buildings has also been shown to be possible in many case studies despite the strict aesthetical constraints (134).



Figure 6

Historical buildings retrofitted to Passive House standard: (a) Before and after retrofit images of a historic building retrofitted to the EnerPHit standard at A-1150 Wien in Vienna, completed in 2018 (103); (b) a building restored to the EnergyPHit standard at Mariahilfer Strasse 182, Vienna (104). Photos reproduced with permission from Mr. Hannes Warmuth.

3.2. Costing Studies

Costs of buildings are difficult to obtain as these are not reported, and no relevant databases for reporting costs exist. Although costing guides reporting the historical average costs of different types of buildings in different locations exist, the market for highly efficient low-carbon buildings remains too new and too small, therefore such averages are not yet available for these cutting edge buildings. However, there have been a variety of studies done to support policy development in several jurisdictions. Examples of those studies are set out below.

The City of Boston in the USA recently released their *Guidebook for Zero Emission Buildings* (135), which, among other things, assessed the incremental cost of zero emissions buildings. The results of their research indicated little to no incremental cost in most cases, and always less than 2.5%. The UK Passive House Trust undertook a costing study in 2019 to determine the incremental cost of Passive House construction over base building code in the United Kingdom. It determined that best practices in the United Kingdom represent approximately a 9% premium, and projected a 4% premium if Passive House construction was adopted at scale (136). The Passive House Trust was part of a 2014 study on the life cycle costs of Passive House projects in Britain that found that, even at that time, Passive House buildings offered lower lifetime costs than conventional buildings.

The Pennsylvania Housing Finance Authority in the United States awards funding to social housing project developers in a competitive bid process in which competing proposals are ranked using a point system, and those projects with the highest number of points are funded. In 2015, that agency started awarding additional points to certified Passive House projects. In the first year of offering this incentive, with virtually no Passive House projects in the state, the incremental cost of Passive House over conventional construction per square meter of floor area was 5.8% but dropped to 1.6% in the second year. By the third year of the incentive, the average cost of successful Passive House projects was 3.3% less than the cost of conventional projects (**Figure 7**). Over the first three years of the program, the 74 Passive House projects funded were an average of 1.7% less expensive than the 194 proposals for conventional construction (137). These results illustrate that

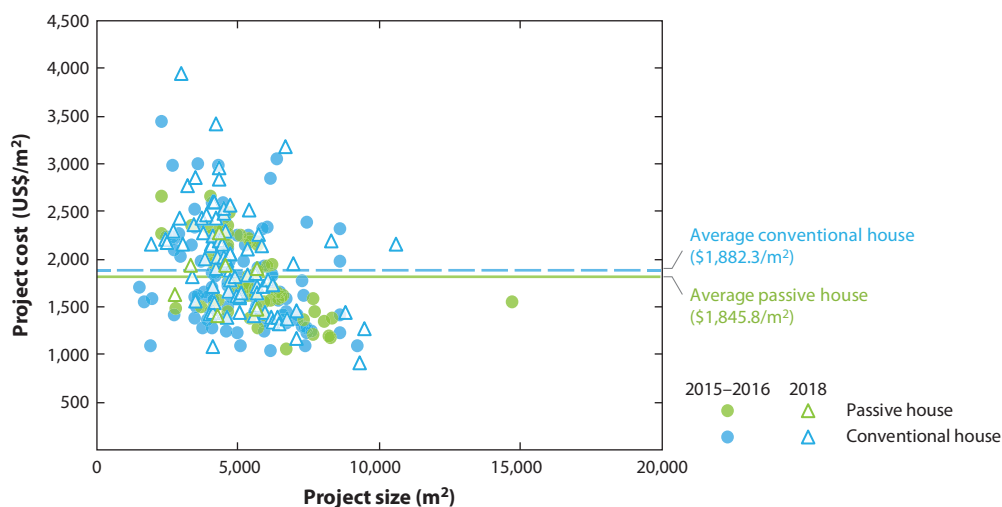


Figure 7

Comparison of the construction costs of comparable Passive House and conventional buildings using selected data from Pennsylvania Housing Finance Authority projects (137).

the cost of energy efficiency is not the main determinant of construction cost, and if important, net-zero or nearly-net-zero energy buildings can be built from budgets for conventional buildings.

The British Columbia Energy Step Code was adopted by that Canadian province in 2017 to improve energy efficiency in buildings through a series of increasing levels of performance. The code was developed after the province reviewed an alternative basis of regulation and concluded that a system of defined targets, including energy use intensity, was the best means of achieving provincial climate goals. As part of that program, a study was performed of the cost implications of improved efficiency in the six climate zones of the province and found the cost premia of improved energy performance varied from nil to less than 3% in the climates in which 95% of the provincial population for building falling under Part 3 of the BC Building Code (generally the larger more complex buildings). For buildings falling under Part 9 of the BC Building Code (generally small simple buildings such as residences), the incremental cost varied from nil to 7.4% depending on climate, building type, and other assumptions (138).

The City of Toronto Zero Emissions Buildings Framework in Canada (139) charts that city's course to low-energy, affordable and resilient buildings. Their research demonstrated that the incremental construction costs associated with the highest levels of performance were less than those for somewhat less ambitious levels and in all cases were only a few percentage points (139). Such costing studies tend to overestimate the actual cost of efficiency, as the studies are undertaken prior to market transformation when the high-performance components are not yet mass produced and new cost optimizing design and construction strategies are not developed.

The City of Vancouver anticipated a small increase in construction costs to result from the increased performance requirements in their building code but experienced a cost decrease of 1% (138). In March 2020, City of Vancouver staff recommended to their City Council limiting the emissions of residential buildings of under 3 storeys to 2 tonnes/year of carbon pollution, and a thermal energy demand intensity of 20 kW/(m²•year). The cost implication of improved performance, representing an 86% reduction in the carbon emissions compared to the City of Vancouver 2007 Building Bylaw, was found to be an increase in the cost of a new home, relative to the cost of one built according to the 2007 Bylaw, of less than 0.5% (140).

The experience in reducing costs gained through the Energiesprong program (64) is a testament to the potential innovation that can also be unleashed in the retrofit market. In 2010, the Dutch government launched a program to develop viable net-zero energy retrofit solutions attractive for the mass market by 2020 through market-driven partnerships to deliver fully integrated whole-building energy-savings solutions. By 2017, the program had delivered more than 2,000 highly efficient homes (some of which were new) and had been contracted to retrofit 111,000 homes by 2020 (64). The program targets energy savings of 45–80%, with energy-neutral buildings by 2020. The team delivering the retrofits must provide a 30-year energy performance guarantee, install the retrofit package within one week while tenants continue to occupy their units, ensure the investment be paid from the energy savings, and ensure the finished product be attractive to tenants. By developing innovative building prefabrication systems and project delivery models, all of this has been possible. The early projects resulted in a 70% reduction in total household energy consumption and cost €130,000/terraced housing unit. The goal is to bring that cost down to €40,000/unit, an almost 70% cost reduction. As of March 2017, the program had reduced costs to €65,000/unit (64).

The New York State Energy Research and Development Authority (NYSERDA) studied the Energiesprong program and is implementing a similar concept in New York state, largely for social housing retrofits. That program is incentivizing the development of new technology and planning to achieve net-zero retrofits of low-rise social housing multi-unit apartment buildings (141). NYSERDA is targeting Passive House performance levels for new buildings to enable roof

OPPORTUNITIES FOR COST SAVINGS

Concerns about the incremental cost of energy efficiency are frequently raised, but data from many jurisdictions illustrate that highly efficient low-carbon buildings can be the most affordable option when competently designed and built. There may be a small increase in design and construction costs, but operational savings more than compensate. Innovation in design, construction, project delivery, and components drive costs down to a greater extent than theoretical costing studies predict. Programs such as Energiesprong and the NYSERDA net-zero affordable housing program demonstrate the scale of cost savings available through innovation, including policy innovation, offering society vastly improved building stock at a lower cost.

mounted PV panels to generate the energy demands of the buildings (142), as well as per housing unit cost reductions of 40% through this program. This will enable social housing agencies in the state of New York to receive the multiple benefits of highly efficient buildings without increasing their pre-existing maintenance and refurbishment budgets while also improving their cash flow through energy savings (143; see also the sidebar titled Opportunities for Cost Savings).

The Rocky Mountain Institute reports in “The Economics of Zero-Energy Homes” (144) that the incremental costs of single-family net-zero or net-zero-ready houses in the United States are within the thresholds homeowners are willing to pay even without incentives. The study was conducted during 2018 and 2019 when the market for such homes represented less than 1% of the market and costs were dropping as the market for such homes matured. Although costs varied somewhat by location, in all cases the incremental cost of net-zero energy ready homes was 0.9% to 2.5% in most climates and only slightly more in cold climates. The cost of net-zero energy homes was higher at 6.7–8.1% with a slight increase in cold climates due to the cost of installing renewables.

Despite Brussels transforming their buildings from among the lowest performing to the highest in Europe with their ambitious building efficiency improvement drive described in Section 7, the region did not experience a significant increase in construction costs. One source found an incremental cost for 50 of the earlier low-energy and Passive House projects comprising 3,236 homes to be 1.25 €/m² (145). Another study found Passive House projects in Brussels cost less to build than non-Passive House projects applying for the same incentive funding under a financial incentive program the region offered called BatEx. All buildings exceeded code minimum performance, but the fact that Passive House projects cost less than others offering a lower level of performance illustrates how small the portion of project costs are attributable to energy efficiency (146). Similar results were obtained in a study of the cost of building terrace houses in the United Kingdom following the Passive House standard together with an optimization tool, finding that affordable Passive House dwelling construction is possible (147).

The costs of deep retrofits, however, are significant. Nevertheless, if the costs of deep retrofits are compared to shallow or medium ones on a specific costs per unit energy saved basis, evidence demonstrates that all depths of retrofits can be delivered at the same low specific cost levels (**Figure 8**). However, as the total amounts are still substantial, especially for a typical household budget, deep retrofits require innovative or subsidized financing solutions.

Although publicly available comparable cost data on exemplary buildings are in short supply, the examples presented above demonstrate that net-zero or almost net-zero energy buildings have been implemented at cost parity, or at a single digit percentage point cost premia over conventional buildings. Even with currently available technology and design experience, such solutions have been implemented at scale, especially if incentives were in place. With higher market penetrations and thus market experience, the cost gap may also be narrowed further.

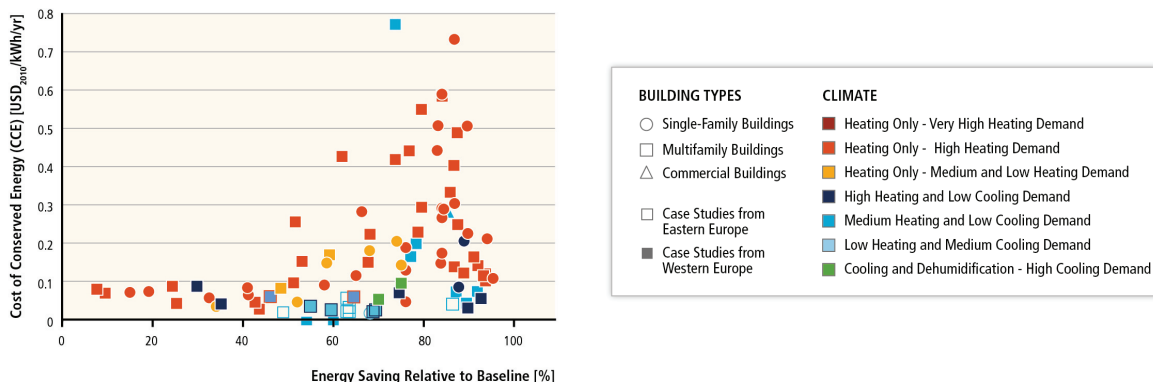


Figure 8

Cost of conserved energy as a function of energy percentage savings for European retrofitted buildings by building type and climate zones. A discount rate of 3% and a lifetime of 30 years for retrofitted and 40 years for new buildings have been assumed. Figure reproduced from Reference 148.

4. TOWARD A NET-ZERO GLOBAL BUILDING SECTOR: FROM VERY LOW-ENERGY TO ENERGY PLUS BUILDINGS

Low-energy buildings can further help with deep decarbonization if in addition to being low-energy consuming they also actually provide building-integrated energy generation. Here, we highlight the main developments that have made it increasingly possible to integrate power generation with buildings as well as the importance of significantly improved energy efficiency.

Net-zero energy buildings have increasingly become a market reality in the past few years, partially due to the breakthrough in the prices of PV panels (149). By 2030 installed PV capacity may exceed 2.4 TW, and by 2050 7.5 TW—surpassing today’s total global installed power production capacity from all sources (150). Due to the scarcity of land and the competition for land by many alternative uses (food production, settlements, bioenergy generation, carbon capture by biomass, etc.), integrating this capacity into existing infrastructure, mostly buildings, both spares these land resources for these other needs as well as locates the generation closer to the consumer, reducing the needs for transmission and distribution.

The reviewed literature (**Supplemental Table 1**) shows that zero-energy buildings need to maximize the energy efficiency by addressing carefully the construction building features to achieve maximum energy performance (minimum kWh/m²) and only as a second step include renewable energy building features, if possible, to achieve maximum renewable energy production (PV, solar thermal, geothermal, and biomass). However, that is not always the case in practice—often so-called net-zero projects shortcut the first step and increase the PV capacity to achieve net-zero levels. By doing so, such projects not only greatly increase the amount of PV and seasonal energy storage required unnecessarily, but also compromise the multiple benefits of highly efficient buildings described in Section 4 below.

In nonequatorial climates, most net-zero buildings rely on the local grid to provide “free” seasonal storage of PV generated energy produced in the summer and consumed in the winter. Seasonal storage, which is never free and incurs energy losses, must be considered in grid design and could be factored into building standards, as the Passive House standard has done (69).

At the same time, there is a scientific debate about whether the remaining small energy needs of very low-energy buildings should be produced on-site or the right solution for this supply should be decided on a case-by-case basis based on the best supply option available, although both are

Supplemental Material >



Figure 9

Vienna Technical University energy plus building. Figure reproduced from Reference 124.

possible (151, 152). The key argument for PV power to be preferentially produced in large-scale installations is the economies of scale, and the avoided installation and per unit converter costs that occur for building-integrated PV solutions. Nevertheless, this is not how consumers face this dilemma: For them, their own PV installations compete with general power prices. In addition, many consumers have been opting to produce their own power for supply security and independence reasons. There has been a rise in prosumers, and they require a new utility model (153, 154). In summary, it is likely that building-integrated PV production is going to increase substantially, allowing for increased shares of net-zero energy buildings/neighborhoods (155–157).

Other RES options are also available for net-zero energy buildings, and they have been deploying also due to the mandatory 20% share of EU energy consumption coming from RES in 2020 (158). RES to be applied in net-zero energy buildings include photovoltaic/thermal (159, 160), solar/biomass hybrid systems (161) for heating, solar thermoelectric (162), and solar powered sorption systems (163) for cooling. Moreover, when including RES in buildings, both thermal energy storage (164–168) and advanced control (169, 170) become of extreme importance to achieve adequate performance and energy savings.

However, although single-family units can be fairly easily turned into energy plus buildings simply by installing PV panels, many building types (such as high-rise or commercial) are not easy to turn into zero-energy or energy plus buildings (171, 172). Such buildings can only be turned into net-zero energy or energy plus buildings if their energy demand is carefully minimized.

An exemplary energy plus retrofit from this perspective is the renovation of the Vienna Technical University building from 2014 (**Figure 9**). In order to be able to cover its approximately 800 kWh/(m²•year) total original energy consumption, the approximately 60 kWh/(m²•year) solar energy that could be generated even if all insulated surfaces were used for solar energy generation was only feasible after a tenfold reduction in all building energy uses (124). This required the optimization of 9,300 components by building physics experts, including those in tea kitchens, elevators, security systems, smoke detectors, etc., and as a result, the overall energy demand of the building was brought down to approximately 56 kWh/(m²•year), allowing the building to qualify for a net-zero certification.

As this example also demonstrates, the key to the large-scale realization of net-zero energy buildings, beyond widely accessible and affordable building-integrated renewable energy generation options, is the substantial improvement of energy efficiency of all energy uses in the building (173). This means that throughout the whole building, not only heating/cooling related energy

uses but also plug loads need to be minimized through efficiency, optimization, or smart solutions, as a precondition to wide-scale net-zero energy building deployment.

The concept of efficiency first appears not only for the higher end net-zero buildings, but also for the poorest population segments (117). For instance, in India, a leading scholar catalyzing the spread of solar energy to increase energy access for the poor has coined the principle “avoid, minimize, generate” (shortened to “AMG”), which clearly sets out the order of priority (174). Even in poor conditions, more services can be provided with the same locally generated PV energy if energy demand is minimized (174).

Although making each building energy self-sufficient with current technology remains a challenge for some building types (175), and may not even always make the most environmental or economic sense, widespread building-integrated generation of energy, with some buildings generating more energy than they consume, is possible today (176), and its consideration on a larger scale can change the energy paradigm (177). Large-scale building-integrated energy generation can be especially important for a closer integration of (electric) mobility and buildings in which building-integrated renewable electricity in periods of lower building energy demand is stored in vehicle batteries, and thus balancing loads with an increased penetration of renewables (178, 179). Energy storage can also contribute to achieving these goals (180). Whereas net-zero energy targets may be disputed to be the most environmentally or cost-effective solutions, their advantage is that in many buildings these levels can only be achieved if all energy demand in the building is minimized, thus forcing very high levels of energy efficiency and optimization. Another attraction of net-zero energy targets for policymakers is that these are fairly easily understood and communicated to voters as opposed to, for instance, Passive House or other more complex energy and carbon standards.

5. MOVING BEYOND OPERATIONAL ENERGY OPTIMIZATION: MINIMIZING EMBODIED ENERGY/CARBON AND CARBON STORAGE IN BUILDINGS

According to the IEA (181), in 2017 the manufacture and use of materials for buildings construction and renovation accounted for 11% of the global overall energy- and process-related CO₂ emissions. We refer to this as embodied carbon in buildings. More than 50% of these embodied emissions come from steel and cement production, due to the large amount of material used and to the carbon-intensive production processes. Other contributors are materials such as aluminum, glass, insulation, plastics, and copper. Although traditionally building energy policies have been concentrating on operational energy and resulting emissions, with the improvement of building energy efficiency, embodied energy and emissions are becoming more important in a relative sense. However, how important embodied energy and emissions are exactly in the life cycle environmental footprint of a building depends on many factors, and although the science on this is fast-growing due to the great diversity of findings depending on assumptions, calculation methods, building types, geographies, occupancy, etc., it is not possible to draw a simple, broadly valid conclusion. **Figure 10** illustrates this conclusion with a comparison of the potential of using bio-based products in the different parts of a building versus more conventional materials, showing the high uncertainty of such estimations (182). Bio-based materials could, in principle, represent a double win in construction: first, by replacing energy- and carbon-intensive materials and second, by storing the carbon temporarily. However, the science is still emerging on the magnitude of the climate impact of temporarily delaying the emission of CO₂ by delaying the decay of these bio-based materials built into the building infrastructure.

Chastas et al. (183) carried out a comparison of more than 90 low-energy buildings with respect to their embodied energy demand. They showed that the share of embodied energy in the total life

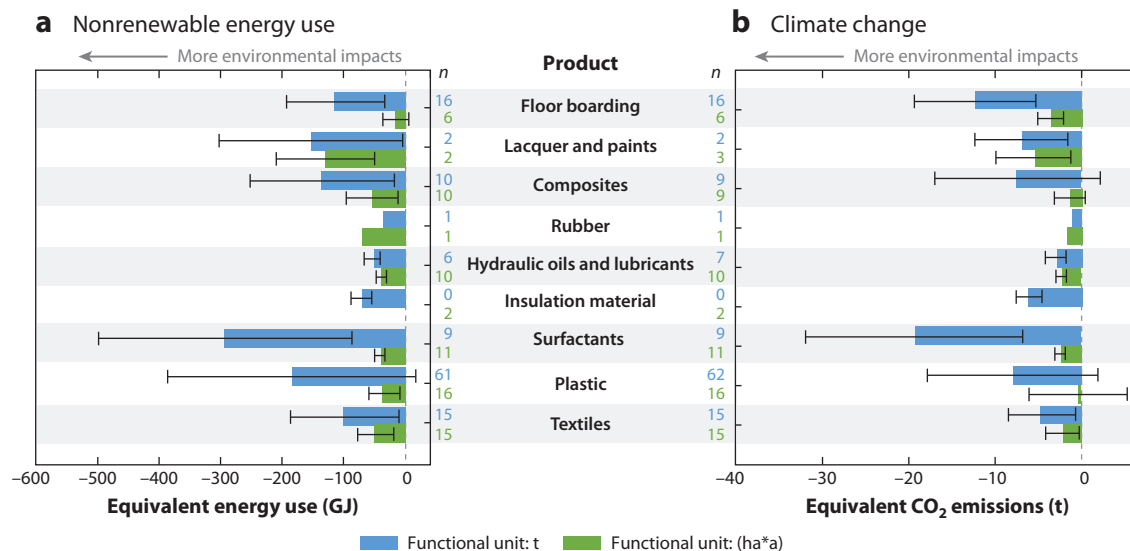


Figure 10

Average product-specific environmental impacts [in equivalent nonrenewable energy use (a) and in equivalent CO₂ emissions (b)] of bio-based materials in comparison to conventional materials. Uncertainty intervals represent the standard deviation of data. Blue and green numbers indicate the sample size for the functional units per metric ton and per hectare and year, respectively. Figure adapted from Reference 182.

cycle energy in low-energy buildings ranged from 5% to 83% and in Passive House buildings from 5% to 100%, whereas in conventional buildings it ranged from 5% to 36%. In low-energy and Passive House buildings, embodied energy and embodied carbon become more important, in part because of the reduction of operational energy requirements. The decrease in embodied energy includes building methods, the use of recycled building materials, or other materials produced in less energy-intensive production processes and transport are not always included and not clearly reported.

Moncaster et al. (184) evaluated quantitative and qualitative details of 80 buildings' embodied impacts, considering different stages of the life cycle (product stage, replacement, and end of life), new and refurbished buildings, and different building frames. This study found that in the analysis performed, the embodied impacts were predominant in the product stage in most cases, followed by the replacement stage (this stage being the stage where materials or components of the building are totally or partially replaced).

Most literature notes that Passive House buildings use slightly more materials than conventional ones (185–187), although the reduction in operational energy (heating and cooling energy use) compensates the potential increase in embodied energy, reaching a reduction of total life cycle energy demand of approximately 30% in Passive House buildings compared to conventional ones. Such calculations, however, are very sensitive to assumed building and renovation lifetimes. This also points to the importance of durability and longevity as strategies to improve the energy and resource performance of buildings (188). In addition, the authors' experience is that many Passive House buildings are ordered or built for environmentally conscious occupants, and thus they increasingly rely on low-carbon construction materials such as straw panels, wood, etc., providing the combined benefits of energy efficiency and low embodied carbon. Some professional associations helping Passive House designers, for example, are members of the Embodied Carbon Network to better facilitate the exchange of information.

Carbon storage:

refers to the storage of carbon dioxide in products or materials that hold the carbon out of the natural carbon cycle on the climate-relevant time horizon; therefore, building (material, component, and structure) longevity and durability, as well as the scale of bio-based materials used in the building stock, are relevant for determining whether the carbon stored in building materials can be considered to be relevant for the time horizon of climate change or the carbon cycle

In an effort to reduce the global carbon footprint of construction, low-energy buildings must use low embodied energy and low embodied carbon materials and construction methods to decrease their impact. Lupíšek et al. (189) proposed different strategies to decrease both embodied energy and carbon through three steps: (a) reduction of the amount of materials needed throughout the entire life cycle through optimization of the layout plan, optimization of the structural system, low-maintenance design, flexible and adaptable design, and components service life optimization; (b) substitution of traditional materials for alternatives with lower environmental impacts with reuse of building parts and elements, utilization of recycled materials, substitution for bio-based and raw materials, and use of innovative materials with lower environmental impacts, design for deconstruction, and use of recyclable materials; and (c) reduction of the construction stage impact.

One of the examples that Lupíšek et al. (189) present shows that substituting a masonry structure designed according to current standards by a masonry structure in a Passive House building increased the embodied energy by 8% but decreased the embodied carbon by 9%, showing that embodied energy and embodied carbon show decoupling in their accounting. Moreover, if the building is constructed with a light reinforced concrete with timber envelope, the embodied energy decreases 10% from the reference building and the embodied carbon by 32%.

The use of timber and other bio-based materials is an option to replace carbon-intensive materials such as concrete and steel (190). Today, mid-rise wood-framed buildings are common, and industry leaders are designing and constructing mass timber high-rise buildings. Wood-framed low-energy buildings, especially high-rise ones, can represent a triple carbon win: operational emissions reduction, reduction in embodied carbon from replaced steel and concrete, and the wood storing carbon instead of releasing it back to the atmosphere. These can be significant. For instance, according to industry calculations using methodology by Sathre & O'Connor (191), Brock Commons, the world's first 17-storey timber-hybrid frame building, avoided more than 2,432 metric tons of CO₂ equivalent emissions (192), equivalent to the annual emissions of approximately 150 Canadians. Out of this, the carbon storage represents the larger part: 1,753 tons, while 679 tons were avoided through reduced cement and steel use. In Brisbane, Australia, Monash University constructed a mass timber student residence building to the Passive House standard (193). In Europe, design and prefabrication firms exist to deliver low-energy homes built from natural materials such as straw and wood (194, 195).

The embodied carbon and energy in insulation materials has been thoroughly studied. For example, Bojic et al. (196) showed that the selection of the optimal insulation material and insulation thickness should be carried out using a life cycle assessment approach and considering the embodied energy of the different insulation materials. In their study, they compared the use of mineral wool [with an embodied energy of 16.6 MJ/kg and a thermal conductivity of 0.038 W/(m·K)] with the use of polystyrene [with an embodied energy of 86.4 MJ/kg and a thermal conductivity of 0.028 W/(m·K)]. The results show that it is better to use a thicker insulation layer with mineral wool than a thinner polystyrene if the required space is available.

Pittau et al. (197) studied the potential of fast-growing bio-based materials such as hemp and straw to capture and store carbon when used as insulation material in residential buildings in Europe. Those materials have a rapid CO₂ uptake when growing in crop fields, increasing the capacity to storing carbon using thicker insulated walls. In the calculations carried out in this paper, straw used in construction showed the potential of removing 3% of the CO₂ equivalent emitted by the entire construction sector in 2015 in Europe. Hemp showed similar potential but at a much later stage, around 2100. This study shows that timber does not show significant potential to reduce CO₂ emissions for the building sector when it is used only as structural material, given that a low amount of wood is used; more potential could be found if it is also used in the envelope as walls.

Finally, the use of polystyrene in building retrofitting in Europe would decrease the operating energy used in the buildings, but would not contribute to active removal of CO₂ from the air. While research on the impact of building with low embodied energy and carbon materials is relatively new, the scale of the threat created by emissions from the production of building materials makes it important to monitor and regulate embodied carbon to effectively reduce total emissions from the building and construction sectors.

Beyond bio-based materials, other methods are also important for the reduction of embodied energy and carbon. Material efficiency and process/system optimization to maximize material efficiency (198), material reuse and recycling, and carbon capture and utilization in materials are all important avenues. However, this field needs urgent and widespread research to understand the opportunities, costs, potentials, impacts and trade-offs on other areas and competition for resources for other purposes, such as for land and biomass (199, 200).

6. BENEFITS OF AND RISKS AND BARRIERS TO ADVANCED BUILDINGS

The IPCC 5th Assessment Report in a detailed assessment of cobenefits and adverse side-effects (trade-offs) of different mitigation options concluded that demand-side mitigation strategies are associated with more cobenefits than trade-offs, whereas this is not the case for supply-side strategies (201, 202). Within the demand-side options, high-efficiency buildings (with heat recovery ventilation) are probably associated with the greatest cobenefits. However, despite their significant financial, social, environmental, economic, and health benefits, high efficiency in buildings has not been widely implemented in building codes due to barriers that hamper their wide-scale penetration, especially for retrofits. This section introduces the most important benefits, risks, and barriers related to advanced buildings. The following section provides examples of how these barriers have been overcome in different contexts.

6.1. Benefits of Advanced High-Efficiency Buildings

The transition to low- and net-zero energy buildings delivers multiple objectives, beyond that of lower energy consumption in the built environment. These beneficial outcomes are well documented in the cobenefits/multiple objectives literature, which bring forth the significant complementarities, synergies, and trade-offs between the different domains of economic, social, and environmental priorities (202, 203). Co-benefits or multiple objectives offer entry points to policy- and decision-making through their multiple impacts across sectors, such as for energy services, energy and economic savings, energy security, jobs, and healthy local environments, while also yielding benefits for addressing climate change (204). Specifically for low-energy buildings, the range of direct and indirect beneficial effects entail improved energy security, sectoral, worker, and personal productivity, local/sectoral employment, improved indoor air quality, improved health, enhanced thermal comfort and better work conditions, safety and disaster resilience, reduced ecosystem impact, and reduced water use and pollution (202, 205, 206). A growing research base supports the evidence of such benefits, thereby illustrating well-being pathways that move away from carbon-intensive production and consumption patterns in buildings (207).

Low-energy and “better” building policies and strategies are therefore often motivated not by climate change mitigation or reduced costs, but rather by a much more diverse set of observed market drivers where better means a variety of different characteristics for different stakeholders. For instance, by making buildings efficient enough, their interior surfaces remain at a stable and comfortable temperature, delivering sustained thermal comfort. The importance of, and

motivation for, more comfortable buildings is illustrated by the Passive House standard, which is not defined in terms of energy efficiency but rather in terms of the following (70):

A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions—without the need for additional recirculation of air.

Furthermore, while comfort levels resulting from the absence of a chill from cold surfaces, thermal stratification of the air and cold drafts is not something most buildings offer even though it is fundamental to the quality of life for building inhabitants. Using comfort and health benefits as one of the most impactful entry points for advanced buildings, new Passive House projects in China display the indoor PM_{2.5} measure to interested visitors, suggesting that for Chinese buyers the building health benefits from avoided air pollution could be among the most attractive benefits of the buildings. The supply of fresh air in such buildings consumes very little energy and operates silently, without drafts.

Another key benefit of advanced buildings with a balanced mechanical ventilation system is maintaining healthy indoor air. If a ventilation system is required, adding heat recovery to the system is a small additional cost, and the greatest health benefits of high-performance buildings arise from well-maintained ventilation systems offering constant fresh, filtered air and removing stale air. The European Commission–funded research project “Healthvent” was the first systematic and large-scale effort to analyze the health effects of different levels of ventilation in buildings. The project found adequate, well-maintained ventilation greatly reduced the frequency of disease that arises in buildings by removing outdoor air pollution by filtration and exhausting indoor pollutants or other health risks. However, people become sick while indoors from nonfiltered air supply that brings in polluted outdoor air, especially in cities where most time is spent indoors. The Healthvent project found that the largest absolute numbers of disability-adjusted life-years (DALYs) lost are avoided through the significantly reduced risk for cardiovascular diseases (208) (**Figure 11**). However, important benefits also occur for lung cancers,

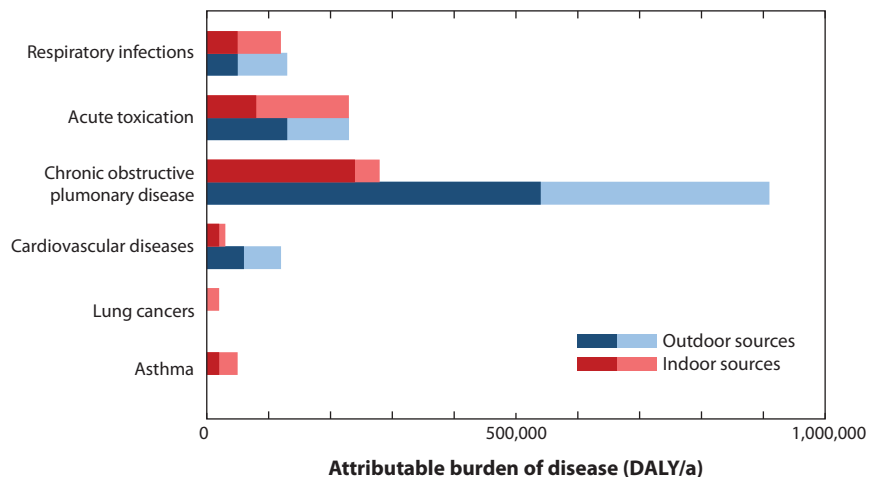


Figure 11

Attributable burden of disease due to indoor exposure in 2010 in EU26. The lighter shade represents the maximum fractions reducible through high-efficiency buildings with well-functioning ventilation systems. Figure adapted from Reference 208.

asthma, and chronic obstructive pulmonary disease. Respiratory tract infections and allergies also get reduced, significantly improving productivity (209, 210), but these are not captured by DALY figures.

Another evidenced benefit of building energy efficiency is the improved energy resilience of buildings. That is, advanced buildings better withstand interruptions in energy supply and level out demand on the grid, particularly when combined with dispersed short-term energy storage. If efficient buildings with on-site PV and battery storage are widely spread, the measure of resilience is greatly enhanced and multiple buildings can operate normally during extended interruptions in grid energy supply. This is particularly important in cold (or hot) climates and has been a key rationale for several cities to adopt stringent building energy efficiency targets and policies, such as One City Built to Last in New York City (211) and The City of Toronto Zero Emissions Buildings Framework (139).

In Toronto, studies indicated high-rise residential buildings achieving the top tier of efficiency remain at 19.7°C after 72 hours without power and 18.3°C after two weeks. Furthermore, the Toronto Community Housing Corporation is planning a multi-billion-dollar deep energy retrofit of hundreds of mid- and high-rise social housing projects not only to reduce emissions, but also to lower operating costs and offer residents a vastly improved quality of life.

Low-energy buildings also provide the valuable benefit of shelter providing thermal comfort longer for residents during extreme weather events (212). This is due to their better insulation techniques such as external shading and improved windows, which maintain the habitability of indoor environments during abrupt temperature changes and multiday power outages, coupled with the very low-energy consumption that prolongs the use of energy supply from backup or renewable supplies.

For example, the Namasia Ming Chuan Elementary School in Taiwan, rebuilt after serious damage caused by a typhoon, is now a shelter for local villagers. Its campus building has a thick thermal-insulation rock wool, placed on the roof, and the façade of the building is made of heat-resistant paint containing expanded clay aggregate to achieve high-performance insulation. The school is additionally equipped with a solar photovoltaic off-grid system of up to 22 kW/a capacity, energy storage and power conditioning system. The integration of energy preservation, green generation, and backup power makes the school disaster management more robust and helps sustain operations with a stable energy supply (131). Between 2012 and 2019, the school admitted more than 5,000 displaced residents during typhoons.

A further health benefit of advanced buildings is that they prevent mold and mildew. This is because inside surface temperatures are maintained above the dew point by adequate, thermal bridge-free building envelopes (213). The continuous supply of fresh, filtered air and the extraction of contaminated air maintains low CO₂ levels and reduces other health risks. This has motivated schools to opt for retrofits involving heat recovery ventilation; additionally, due to the low CO₂ levels, the efficacy of teaching does not decrease toward the end of the class (214–216).

However, air quality improvements are not a given for all energy-efficient buildings. Buildings built after the oil crises in the 1970s were increasingly insulated and air tight, without ventilation or adherence to basic building science principles, leading to many issues with air quality, mold and mildew growth, often referred to as the sick building syndrome (217–219). Mechanical ventilation and proper building envelope design eliminate these issues and are fundamental to any good building, not just energy-efficient buildings.

The various benefits described above arise as a result of the application of fundamental principles of building physics for the most efficient buildings. Maintaining interior comfort, health, and air quality in such a stable interior environment can be achieved more accurately and often with smaller, simpler mechanical equipment, which also reduces embodied energy/embodied carbon

in components. The high-quality components required for very low-energy buildings often have a longer lifespan than conventional products. The result is not only energy savings but substantial savings in operating and replacement costs of equipment. As identified in studies cited above, these benefits often do not necessarily increase construction costs, and where they do, overall affordability is still improved due to substantial savings in operating costs and significant noneconomic benefits. Furthermore, early market data on net-zero buildings suggest that consumers prefer such buildings compared to conventional buildings when they are given the required information regarding costs and benefits and a choice in selecting their building type (220). Importantly, increased sale or rental value and/or reduced time to sale offers additional incentive and benefits from net-zero buildings and demonstrates that consumer demand is vital for private developers.

6.2. Barriers to Advanced High-Efficiency Buildings

Despite the many advantages of very low-energy buildings, care is required to avoid pitfalls or potential risks, and there are significant barriers to their wide proliferation. As discussed above, in developed countries the priority for turning the building stock into a low-energy sector is deep energy retrofits of the existing stock. In developing countries, the focus is on the fast pace of new construction. However, deep retrofits show the least progress among high-efficiency buildings, despite the long-term financial benefits, social welfare, health, productivity, and other gains. The several barriers to be addressed by policy or other interventions in developed and developing regions are discussed below.

One key barrier is financing. As with most sustainable energy-related options, deep energy retrofits involve a significant upfront investment and reap the benefits over their lifetime. Although at a societal level deep energy retrofits are typically very cost-effective, paying back in 10–20 years, i.e., well within the building lifetime, dwelling owners typically do not have such a long investment horizon. Most real estate investors or financiers also expect shorter returns on investments. In addition, most dwelling owners do not have the relatively large capital available needed for deep retrofits. Therefore, interventions and/or policies need to bridge this payback time gap, recognizing that the deep retrofit of the building stock is of societal interest, similar to carbon capture and storage and other mitigation measures that expect the return on their investments based on some sort of climate finance.

In order for deep retrofits to scale, it is likely that climate finance, or other innovative methods of finance, is needed. Private financing, energy service company (ESCO)² arrangements or other on-the-bill financing schemes are unlikely to be sufficient to bridge the financing gaps, as involving third parties introduces further costs, making the payback gap even larger and withering the circle of overall cost-effective retrofits. In general, ESCO-based arrangements in the building sector can be problematic when the lock-in effect is considered, given that such commercial arrangements prioritize low hanging fruit, or finding the most cost-effective solutions and leaving out the less attractive ones (221). However, it is the less attractive elements of building envelope refurbishment that provide the greatest long-term benefits and without which true deep energy retrofits are not possible. A systemic approach to deep energy retrofits is also cost-effective, but the longer payback times and thus reduced return on investment (ROI) results in investors cherry-picking incremental solutions rather than the systemic ones.

Another barrier to deep retrofits is the so-called nuisance factor and the hurdles associated with its arrangements, which amount to a significant impediment. First, deep retrofits need to

²These commercial enterprises implement energy efficiency options by providing the investments and recover their capital from client savings on energy bills.

involve a multitude of permits, companies, financing, etc.—and often the interested owner does not know where to start or how to coordinate such a process. In order to overcome these obstacles, there are initiatives in the EU to offer “one-stop-shop” solutions for interested building owners that simplify the process for them (222). In multi-unit buildings a further hurdle is that all unit occupants and owners need to agree to the retrofit and potentially also its financing, which has been a challenge for energy-efficient retrofits for decades (223–226). Finally, these major retrofits often involve such major interventions, and tenants need to move out or suffer other significant inconveniences. This can be a factor in holding back relevant decisions, or in opting for more shallow retrofits with less hassle. Partial solutions have been offered and developed to overcome these barriers as outlined for the Energiesprong program (227) where buildings of a frequent typology can be retrofitted by prefabricated and prepared elements in days, to avoid the nuisance factor and permit the tenant to remain in place.

There are other less systemic obstacles as well. For instance, reports (228, 229) indicate that project teams in heating-dominated climates can overlook the importance of designing to ensure summer comfort in addition to winter comfort, resulting in overheating in the summer. With a changing climate, however, it is imperative to design for the anticipated future climate in a region (230). For example, although active cooling may not be required at the time of construction, future-proof building design should incorporate ample shading elements and consider future installation of mechanical cooling.

Passive House and other low-energy buildings have been noted as being more comfortable and avoiding indoor thermal problems such as overheating. In another example, in the warm Mediterranean climate, adequate shading is required (75). In those buildings, it becomes important to also manage internal loads and their resulting heat gains through adequate natural and mechanical ventilation to remove excess heat, potentially supplemented with active cooling.

The construction industry reports difficulty delivering cost-effective low-energy solutions using conventional practices for the design, tendering, and construction of buildings. Although it is well recognized within the construction sector that integrated design and construction enhances the ability to deliver cost-effective, innovative projects, true integration does not occur in most public procurement processes. Changing procurement practices can be particularly difficult for large institutions and governments, often placing them at a cost disadvantage. An exception is the impressive cost effectiveness of the projects submitted to the Pennsylvania Housing Finance Authority or others cited above (139). It would be interesting to know if the cost effectiveness is the result of having integrated project teams. In another example, the dramatic cost reductions achieved by the Energiesprong program (64) arose from innovation in the procurement model, assembling a large volume of projects and integration of design and construction.

Collectively, these barriers lead to a great risk, which is the failure to maximize efficiency when the opportunity to do so cost effectively arises. It is always cheaper and easier to design and build an efficient new building than to retrofit it later, making it essential to maximize efficiency in new buildings as rapidly as possible. Existing buildings offer few opportunities during their life cycle for deep energy retrofits. When those opportunities arise, taking them avoids large lock-in effects (11). Although some buildings are entirely retrofitted at one time, many can only be affordably upgraded step by step over time, as components reach the end of their useful life. For example, it is costly to remove windows that are still functional, even if inadequate in terms of thermal performance. However, when those windows begin to fail, the incremental cost of replacing them with truly high-performance windows rather than lower-performing windows is greatly reduced. In this manner, an existing building that merits the investment required to modernize it can be transformed over time. As a renovation rate of 2–3% per year is adequate to upgrade most existing building stocks (40), methodically completing deep energy retrofits at the appropriate stages in

each building's life cycle is a viable climate mitigation strategy. The timing of retrofits in a building's life cycle is thereby a crucial element of a retrofit strategy so as to capture opportunities for deep energy retrofits as they arise. Incentivizing the retrofit of buildings prior to building elements reaching the end of their useful life requires far more resources, thereby delaying progress.

Although the issues outlined in this section are sometimes cited as reasons to delay or avoid implementing programs for very low-energy new and existing buildings, experience in many jurisdictions demonstrates how solutions have been developed for each challenge. A commitment to an outcome and willingness to innovate are essential elements of a successful strategy.

For example, the Austrian region of Tyrol offers subsidies for investors who opt for deep retrofits rather than shallow ones, also if these are implemented in a step-by-step way that enshrines the systemic solution and not the optimization of a few components (231). The following section identifies further policies regarding how different jurisdictions are making an effort to overcome these barriers.

7. POLICIES AND PROGRAMS TO ACCELERATE THE UPTAKE OF NET- AND NEARLY-ZERO ENERGY BUILDINGS

Recognizing the climate, energy, health, and social welfare benefits of advanced buildings, and the strong barriers inhibiting their uptake on a market basis (many of which are detailed in the previous section), many jurisdictions have successfully applied policies and introduced programs to kick-start or catalyze a broader market transformation toward net or nearly-zero energy buildings.

Among these, building codes have been the most widely used, and are also identified by the IPCC among the environmentally most effective climate policies (232, 233). Although they mostly apply to new buildings, the EU has instituted efficiency regulations also for major retrofits. Despite their environmental effectiveness, building codes are still applied to a limited extent, and their implementation faces many challenges even where in force (234).

Shen et al. (235) reviewed the building energy efficiency policies of seven major economies and found that “Eastern countries,” e.g., China, Japan, and Singapore, were more likely to apply “mandatory administrative instruments” (e.g., building codes) than “Western countries” (e.g., Australia and the United States), who, in turn, rely less on mandatory administration instruments but rather on voluntary schemes. The United Nations Economic Commission for Europe (UNECE) (236) recently reviewed and evaluated building regulations in its 56 member states from Russia in the East to Canada and the United States in the West. It highlighted that many jurisdictions do not have efficiency requirements for buildings systems; there is often a lack of knowledge, incomplete statistics, insufficient studies evaluating the actual performance of buildings, and inconsistent assessment methodologies; and there can be a lack of enforcement, training, and monitoring. The report assessed building energy codes and performance certificates in UNECE member states. It concluded that many new buildings in the UNECE region still have no insulation or exterior shade control and have single-glazed windows, with the market maturity of high priority building envelope components varying significantly between states.

However, as reviewing energy efficiency policies in buildings is a topic alone for many papers and reports, in this article we focus the rest of the discussion on policies to showcase exemplary policies and actions worldwide that have proven to catalyze market shifts toward nearly or net-zero buildings in their jurisdictions—nations, regions, and cities. Although this topic alone is worth its own paper, the academic literature documenting these exemplary policies and actions in recent years is very thin; this article has space only to highlight a few exemplary cases and best practices.

A large-scale illustration is the EU Energy Performance of Buildings Directive, which is working to transform European buildings, with a target of nearly-zero building codes across Europe by 2020. Reports indicate implementation varies, but the transition to low-energy

buildings is becoming mainstream in some jurisdictions. For example, Ireland initiated its progress toward the Nearly Zero Energy Buildings program with a 2012 planning report (237) and is now implementing the program (238).

Although a source of the most rapidly expanding emissions from buildings, China illustrates how a nation can influence the development of highly efficient buildings and the required technical components such as windows and heating, cooling, and ventilation equipment on a short timescale. China adopted building energy efficiency standards in stages from 1986, starting with an energy design standard for residential building in cold and severe cold climate zones of China, to improve building envelope performance. Passive House technologies were imported from the German Energy Agency in 2011, and demonstration projects were established with international collaboration after then. The promotion of ultra-low-energy buildings was first raised as a national goal in *13th Five-Year Planning on Building Energy Efficiency and Green Building* (239), by the Ministry of Housing and Urban-Rural Development in 2017. The first voluntary guiding standard on ultra-low-energy building was published in 2019 (240), requiring a heating demand lower than 18 kWh/(m²•year) (severe cold zone) and less than 15 kWh/(m²•year) (cold zone), translating into a reduction of five times the current standard EPI in China. As of October 2019, 7 million m² of ultra-low-energy buildings were completed (241), making China the global leader in the total floorspace of buildings meeting such stringent efficiency standards. No other jurisdiction in the world is constructing as many zero-energy buildings as China at this time, an outcome their clear and well defined standard has likely facilitated.

In the early 2000s, the Capital Region of Brussels had among the least efficient buildings in Western Europe and decided to improve their buildings by adopting the Passive House standard as a target for their existing and new buildings. In 2015, seven years after initiating the process, the building code came into effect requiring that level of performance. However, with the industry having had ample notice, by 2014, the year before the code became compulsory, Brussels had more than 800,000 m² of Passive House buildings plus other low-energy buildings. Heating energy use per capita dropped by 25% and greenhouse gas emissions by 16% between 2004 and 2014. Building performance boosting policies and actions went through three phases: first, awareness, incentives, and demonstration projects; second, support and large-scale implementation; and finally, a massive investment in new and retrofitted buildings (242).

The Capital Region of Brussels is perhaps the most compelling illustration of the transformation that is possible, moving from the worst performing buildings in Western Europe to the most efficient building code seven years later. They achieved this result through a combination of voluntary measures to support and encourage industry leaders to innovate and demonstrate what was possible, showing others the way. Increasing mandatory standards came into effect and industry capacity and component supply increased.

The City of Vancouver, Canada, is another example of rapid transformation arising from civic leadership. At the end of 2015, the city had one single-family Passive House building. By the second half of 2017, only 18–24 months later, 20% of all rezoning applications³ in the city were for certified Passive House buildings. Numerous single-family homes and duplexes were also initiated without requiring rezoning. These results not only enable the City to achieve its emissions reduction targets, but also drive development of the local low-carbon economy, with an anticipated \$3.3 billion market in high-performance building products in Metro Vancouver from 2019 to 2032 (243).

³ Rezoning is a process to obtain permission from the City to build where the existing land use zoning does not permit the proposed building. In the City of Vancouver, the development of most projects (other than small projects such as single-family residences) requires a rezoning application.

The approach of New York City has been in many ways similar to Vancouver and Brussels in pursuing whole-building energy efficiency in their policies, with the realization of some of the multiple benefits of energy efficiency, such as resiliency, part of the motivation. New York City, as with Brussels, Vancouver, and many other cities, initiated their policy development with a review of best practices. They launched a Buildings Technical Working Group comprised of more than 50 subject matter experts and numerous City staff in a data-driven exercise to evaluate global best practices, undertake research, and identify how to place their buildings on a path to achieve their climate goals. The result was a series of recommendations, including the adoption of clear, ambitious targets for energy efficiency and emissions reductions, driving innovation and a competitive advantage for local industry. With this background knowledge, in 2014 the City adopted One City Built to Last, its strategy in relation to buildings to address climate change (211). The introductory letter from Mayor de Blasio explicitly references the benefits of reduced energy costs, cleaner air, comfort, building quality, and economic development associated with energy-efficient buildings. The projected 2.7 MtCO₂ emissions reductions are estimated to save building owners approximately \$900 million annually in energy costs (211). The city research identified that energy use in existing buildings needs to be reduced by 40–60% to achieve its target of 80% overall city emissions reductions by 2050. Their research further identified those reductions in energy use were achievable with the technology and strategies available in 2014. A driving motivator for New York City's clear action was Hurricane Sandy, which devastated the city in October 2012, placing resilience, including the ability to shelter in place during energy outages, high on the city's priority list.

On April 18, 2019, the City of New York followed up by passing the Climate Mobilization Act to align with the city's 1.5°C Climate Action Plan (244). That Act includes Bill 1253 requiring, among other things, the owners of existing building to pay a substantial fee if their emissions exceed defined limits. The legislated limits will decline over time and extend to an increasing number of their buildings.

The Passive House Institute lists 33 jurisdictions that have adopted the whole-building energy use intensity approach as a model for new and existing buildings on their website (69). Although each nation, region, and city has specific challenges, and not all will achieve their goals, the numerous successful projects and market transformation policies make it clear such highly efficient buildings are both feasible and affordable as demonstrated by several jurisdictions.

Public sector leadership is often identified as being an essential component of market transformation. In developed nations, most governments directly or indirectly support a large enough share of the construction market to motivate much of the sector to develop the required skills and building components simply by limiting public funding of buildings to those buildings delivering the required outcomes.

The EU, China, Ireland, Brussels, New York City, and Vancouver are six of many cities, regions, and nations setting and achieving ambitious targets and collaborating with each other to capture lessons learned. They have made substantial progress in transforming their markets toward net-zero buildings and demonstrated strategies for widespread regulatory adoption. As a result, they also drove the additional costs of these very high-performance buildings to little or none, as pointed out in earlier sections.

8. CONCLUSIONS

The evidence in this article demonstrates that it is possible to reliably and affordably achieve net- or nearly-zero energy building outcomes in most building types and climates with systems,

technology, and skills that already exist and at costs that are in the range of conventional buildings. Programs such as Energiesprong demonstrate the opportunity to reduce costs through innovative project delivery, as well as through policies incentivizing large-scale deployment of such new buildings and retrofits, such as in Brussels. Overall, there has been much progress in the deployment of such buildings and relevant policies/programs since the seminal 2013 Harvey (7) review in this journal.

Although the fundamental building science principles have been known for decades, it is mostly in the past decade or two that buildings with very low operational energy demand, representing a savings of up to 95% compared to conventional buildings, as well as buildings producing more energy on an annual basis than what they demand, have been built in larger numbers. We found that this acceleration was due to the recent advances in know-how as well as some cities, regions, and nations introducing ambitious policies/programs to encourage a transformation of the construction sector toward net-zero buildings.

Although we had space to highlight only a few examples, these and the data in the **Supplemental Material** underscore the versatility of net-zero, energy plus, or nearly-zero energy buildings in different building types, end uses, climates, and cultures. The literature and data reviewed demonstrated that these buildings can typically be built in the same cost range as their counterparts, or at minor cost premiums; sometimes even at lower costs. Given that in most regions these do not yet have a significant market share, with technology learning and economies of scale, their costs can still be expected to decrease.

In the developed world, the majority of the buildings that will determine our emissions in mid-century already stand, therefore in these regions retrofits are far more important from an overall climate and total energy demand perspective than new construction. The case studies highlighted in this article demonstrate that deep retrofits can also achieve similar energy performance levels as new construction, even for historic buildings under monument protection, or in many cases can even be turned into energy plus buildings.

Whereas nearly-zero energy buildings exist around the world, and net-zero or energy plus buildings also in many localities, the review of the literature and relevant databases has signaled that even the technical feasibility of turning the world's building stock into a climate-neutral—or net-zero energy—sector still raises questions. The key challenge is cooling, and especially dehumidification-dependent climates where even the highest-performance buildings may use as much as 90–180 kWh/(m²•year) for cooling, as opposed to the 15 kWh/(m²•year) that is feasible for heating everywhere in the world. This means that high-rise buildings with limited insulated surfaces in warm and humid climates to net-zero energy level is still challenging even from a technological perspective, although research and development is ongoing with some promising areas such as radiative cooling materials.

With higher levels of operational energy efficiency in buildings, the attention of the scientific and environmental communities has turned to the embodied energy and embodied carbon in the building infrastructure. Advances in recent years have been remarkable in the opportunities to replace energy- and carbon-intensive construction materials with recycled, bio-based materials, or improve material efficiency and utilize captured carbon. Another important and rarely emphasized strategy to improve the environmental, climate, energy, and resource sustainability of buildings highlighted in the article is to push the durability and longevity of building materials and components. The article showed that many of the advanced buildings typically apply high-quality components to meet stringent efficiency standards and as a result often last longer—with many of the buildings erected in the 1970s still functioning and delivering the original energy savings.

Supplemental Material >

Beyond operational efficiency regulations, warranty period standards may also help in delivering lower embodied carbon emissions in the long term.

Whereas early energy-efficient buildings had many issues with air quality and so-called sick building syndrome, by today well-designed, built and maintained net or nearly-zero energy buildings bring a broad range of cobenefits, including increased thermal comfort, improved indoor air quality, health, productivity, social welfare, reduction of energy poverty, as well as a higher level of resilience against climate impacts or other disruptions or disasters. In China, many buyers of Passive House apartments choose this solution due to the control of PM2.5 pollution.

Despite their numerous benefits, net and nearly-zero energy buildings are just starting to make inroads into most markets and are taken up by consumers only slowly under regular market conditions. Beyond information, knowledge, training, and expertise deficits, there are many barriers inhibiting the fast market-based uptake of these buildings, including the high upfront costs of deep retrofits.

Nevertheless, after recognizing their significant social, environmental, climate, health and economic advantages, many jurisdictions have successfully adopted and industry has delivered programs to provide a series of examples of how barriers to market transformation are overcome toward a very low energy demanding, or potentially a net energy producing, building sector. The experience of successful jurisdictions demonstrates how rapidly this transformation can occur. Perhaps the most notable is China, where in just eight years more than 7 million m² of ultra-low-energy buildings were erected, achieving a more than fivefold reduction in specific energy consumption as compared to standard practice. Other areas, such as Brussels, New York City, Vancouver, and Tyrol, have also achieved important transformations in their building markets toward net-zero performance levels. Net-zero energy buildings are perhaps even more important in poorer regions where the negligible operating energy costs have crucial social benefits, so many jurisdictions chose to first mandate Passive House standards in social housing.

The 2017 UN Framework Guidelines for Energy Efficiency in Buildings (236) capture many of the findings in our article, as stated in the following:

Economic growth and the quality of indoor environments have depended on increased primary energy use. Shifting that reliance to renewables requires a holistic, systems approach to building design, delivery and operation and a paradigm that envisions buildings as energy producers and not solely or primarily as energy sinks. At costs equal or close to those of traditional buildings, it is possible with today's technology to transform buildings to align with the highest standards of health, comfort, well-being and sustainability, including improving energy productivity and reducing CO₂ emissions.

The energy required by buildings can be reduced to a level that can be supplied largely, perhaps exclusively, by non-carbon-based energy. While further improvement in renewable energy technology and electrical and thermal storage is to be expected, the results will be more immediate and robust if buildings are transformed fundamentally in terms of their energy performance. . . . (p. 1)

This article has outlined how leading jurisdictions have taken action to transform their building stocks and highlighted specific exemplary policies and programs, overcoming perceived and real barriers in the process. However, if we want to limit global climate change to levels avoiding major impacts as stipulated in the Paris Agreement, we need to aim toward net-zero energy buildings, where possible, in both new construction and retrofits. Our article demonstrated that the key to achieving net-zero energy buildings is a radically improved efficiency in all energy uses within the building, and maximizing locally generated energy production opportunities comes only second. Given the urgency and the long lifetime of the building infrastructure, every building

we build or retrofit from today that does not take full advantage of the technological opportunities outlined here locks us into a warmer climate.

SUMMARY POINTS

1. The transformation of the building sector toward net-zero energy and low embodied carbon buildings is a key component of meeting climate neutrality targets, because the building sector contributes approximately 36% to final energy demand and 39% to process-related greenhouse gas emissions.
2. Recent advances in building design, know-how, construction, operation and retrofit, as well as low-carbon or even carbon storing building materials suggest that the building sector could become climate neutral in itself.
3. There is a wide range of net- and nearly-zero building terms, standards and definitions. Our article provides a summary figure that navigates the reader to understand the differences among these.
4. The evidence from the reviewed literature indicates that it is possible to reliably and affordably achieve net or nearly-zero energy building outcomes all over the world in most building types and climates with systems, technologies and skills that already exist, and at costs that are in the range of conventional buildings.
5. The evidence shows that the key to net-zero targets is the maximization of energy efficiency for all building energy uses, with the remaining energy loads to be covered from locally produced renewable energy sources. The greatest technological challenges to net-zero energy buildings are in high-rise commercial buildings in hot and humid climates as well as for retrofitted historic heritage buildings, but solutions and best practices exist for these, too.
6. Although net and nearly-zero energy buildings increasingly achieve market success, there are many significant barriers worldwide to their wider adoption. However, recognizing their environmental, climate, social, health, productivity, economic, and other advantages, many jurisdictions have successfully introduced policies and incentives to overcome these barriers and thus increase their market penetrations. China alone has built more than 7 million square meters of Passive Houses with significantly more under construction; New York City, Vancouver, Brussels, Tyrol, and other jurisdictions have introduced innovative policies and incentives to catalyze market transformation toward Passive House standard buildings.
7. Strategies to minimize embodied energy and carbon in building materials are gaining significant attention and include material efficiency, recycled and reused materials, durable components, design and new materials, replacing carbon-intensive materials by bio-based ones, as well as carbon capture and utilization.
8. The review of literature for this article reinforced the existence of the significant gap and time lag between the advanced professional knowledge and scientific documentation, and thus recommends strengthened research and publication in co-production among these communities in order to enhance the broader uptake of these advanced solutions as well as their wider inclusion in climate and energy policy portfolios and modeling.

FUTURE ISSUES

1. A significant gap and time lag exists between the work of professionals, the industry and policy leaders and its scientific documentation. Strengthened research and publication in co-production among these communities (science, building professionals, policymakers) will enhance knowledge co-generation and dissemination of advances.
2. Although the knowledge and technology currently exists to deliver net-zero buildings, their performance can be improved and cost reduced through innovation in design, project delivery, and building components. Targeted research can support rapid advances.
3. Due to the major gap between acceptable social and private payback times, deep retrofits delivering the major climate benefits discussed in this article require innovative financing mechanisms that bridge long-term climate interests and finance with individual building-level private retrofit decisions.
4. Further and more granular understanding is needed related to the possibilities and challenges to carbon storage in building materials, especially through bio-based materials, given the complex interactions of land, water, and biological productivity availability for food, feed, and fiber production considering the high demands on fertile land, ecological considerations for the share of biomass removal from the production sites, as well as competition for different biomass products for other purposes.

DISCLOSURE STATEMENT

R.B. is employed as Advisor, Projects and Policy, with Passive House Canada. The authors are not aware of any other affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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RELATED RESOURCES

1. Global Alliance for Buildings and Construction (GlobalABC). <https://globalabc.org/>; provides a wide variety of policy resources and links
2. Sinfonia Low Carbon Cities for Better Living. <http://www.sinfonia-smartcities.eu/>; reports on a five-year EU initiative to deploy large-scale, integrated and scalable energy solutions in mid-sized European cities