PEMBINA institute

Accelerating Market Transformation for High-Performance Building Enclosures

State of market, policy developments, and lessons learned from the Passive House movement

Tom-Pierre Frappé-Sénéclauze | Dylan Heerema | Karen Tam Wu

September 2016

photo Sonia Zouari

Accelerating Market Transformation for High-Performance Building Enclosures

State of market, policy developments, and lessons learned from the Passive House movement

Tom-Pierre Frappé-Sénéclauze • Dylan Heerema • Karen Tam Wu

September 2016

Editor: Roberta Franchuk

Recommended citation: Frappé-Sénéclauze, Tom-Pierre et. al. *Accelerating Market Transformation for High-Performance Building Enclosures: State of market, policy developments, and lessons learned from the Passive House movement*. The Pembina Institute, 2016.

The Pembina Institute
219 19 Street NW
Calgary, AB
Canada   T2N 2H9
Phone: 403-269-3344

Additional copies of this publication may be downloaded from the Pembina Institute website, www.pembina.org.

About the Pembina Institute

The Pembina Institute is a national non-partisan think tank that advocates for strong, effective policies to support Canada's clean energy transition. We employ multi-faceted and highly collaborative approaches to change. Producing credible, evidence-based research and analysis, we consult directly with organizations to design and implement clean energy solutions, and convene diverse sets of stakeholders to identify and move toward common solutions.

pembina.org

twitter.com/pembina facebook.com/pembina.institute

Acknowledgements

The authors would like to thank Nicole Flanagan (2016 Loran Scholar intern) and Bassam Javed (2015 PICS intern) for their invaluable research assistance in the preparation if this report.

These reviewers provided comments on the final draft of this report; we are grateful for their insight:

- Rob Bernhardt, Passive House Canada
- Christina Bollo, University of British Columbia
- Patrick Enright, City of Vancouver
- Graham Finch, RDH Building Science Inc.
- Mark Frankel, New Buildings Institute
- Katrin Klingenberg, Passive House Institute US
- Micah Lang, City of Vancouver
- Chris Mattock, Habitat Design + Consulting Ltd.
- Monte Paulsen, Red Door Energy Design Ltd.
- Jieying Wang, FPInnovations

The authors would also like to thank the 21 practitioners and policy makers who provided insights and perspective on the market during interviews conducted in August 2015; their names are listed in Appendix A.

This study was made possible by a Carbon Neutral Cities Alliance Innovation Fund grant from the Urban Sustainability Directors Network and a Greenest City grant from the Vancouver Foundation.

Accelerating Market Transformation for High-Performance Building Enclosures

State of market, policy developments, and lessons learned from the Passive House movement

Contents

List of Figures

List of Tables

Executive Summary

The challenge

Commercial, institutional, and residential buildings are responsible for about a third of carbon pollution in the U.S., and about a fifth of carbon pollution in Canada, constituting the largest source of emissions in North America.[1] Worldwide, they account for about a third of energy-related emissions[2], and continue to grow: over 80 billion square metres (900 billion square feet), will be built and rebuilt in urban areas by 2030, an area roughly equal to 60% of the current global building stock.[3]

As countries around the world strive to reduce climate impacts and urban air pollution, this construction spurt offers both challenges and opportunities. If construction standards do not evolve rapidly, inefficiencies will be locked in and could lead emissions from the building sector to double by 2050. At the same time, the nearly $80 trillion to be invested in this urban development represents a unique opportunity.

Enclosure-first approach

Heating and cooling loads generally account from a third to a half of energy use in buildings. Reducing these loads though enclosure improvements alone will therefore not be sufficient to meet deep energy reductions in the building stock; other end uses such as domestic hot water, lighting, ventilation, auxiliaries and plug loads will also need to be addressed. There are, however, several reasons to prioritize an enclosure-focused approach to energy efficiency:

- Building enclosures are long lasting and costly to refurbish, unlike other systems that can be more easily replaced as better technologies become available.
- Enclosures are simple systems; their performance does not depend on complex energy management systems and they are more tolerant to delayed maintenance.
- Reducing heating and cooling demand early in the design process allows for reduction of the size of space conditioning systems, reducing construction cost and ongoing energy demand.
- High-performance enclosures also offer significant non-energy benefits, such as thermal comfort, acoustic isolation, durability, and increased resiliency to power outages and extreme temperature events.

The Passive House standard

High-performance enclosures rely on relatively simple products and practices, most of which are already familiar to builders. Nevertheless, assembling these components to get maximal performance while ensuring durability and comfort represents a significant shift for the industry.

The international Passive House Institute and the Passive House Institute US are two of the main organizations driving innovation in high-performance building enclosures. These groups administer separate Passive House standards, both of which offer stringent guidelines for building energy efficiency including:

- maximum heating energy demand;
- maximum total site energy demand;
- minimum airtightness requirements, and
- requirements for thermal comfort.

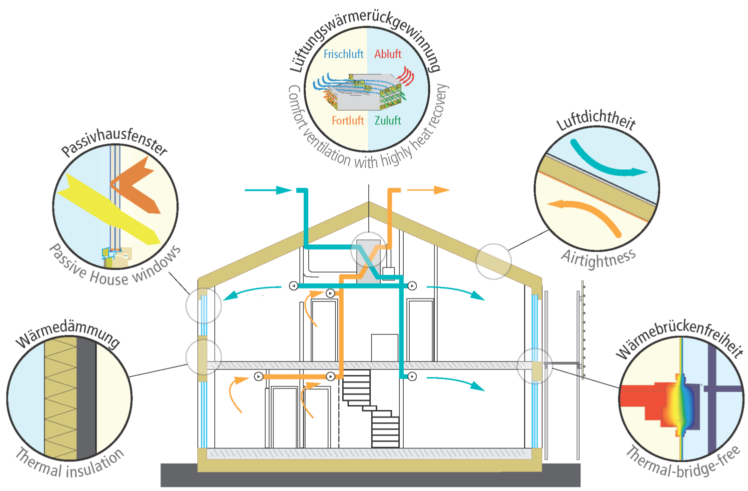


Figure 1: Passive House principles.

Source: PHI[4]

Buildings adhering to a Passive House standard use dramatically less energy than typical buildings, reducing heating energy requirements by **40% to 90%** (Figure 5) by utilizing an enclosure-first approach. Increasing adoption of these stringent standards for building enclosures represents the next step in a continuously evolving construction industry: an evolution, not a revolution.

State of the market

- Most passive buildings are residential projects (well over 3500 buildings worldwide and 300 in North America), but there is a growing number of commercial and institutional projects (over 500 worldwide and 30 in North America) (Figure 2).

- The number and size of certified Passive House projects has seen a rapid increase in North America in the last five years, and we expect this growth to accelerate. Mid-rise residential projects currently in construction will quadruple the number of Passive House certified units (Figure 3), and several more projects are expected to break ground in the next year. By the end of 2016, there will be nearly 2 million square feet of certified passive buildings in North America, three times more than in 2015.
- Demand and offerings for training of professionals and trades has also increased rapidly; there are currently over 1600 professionals and trades trained in Passive House design and construction in North America, with hundreds of new certifications expected in the next year (Figure 4).
- Several jurisdictions have put in place policies to support Passive House and high-performance enclosures in general, and there is growing political leadership on the role of standards and procurement policies to advance high-performance enclosures.

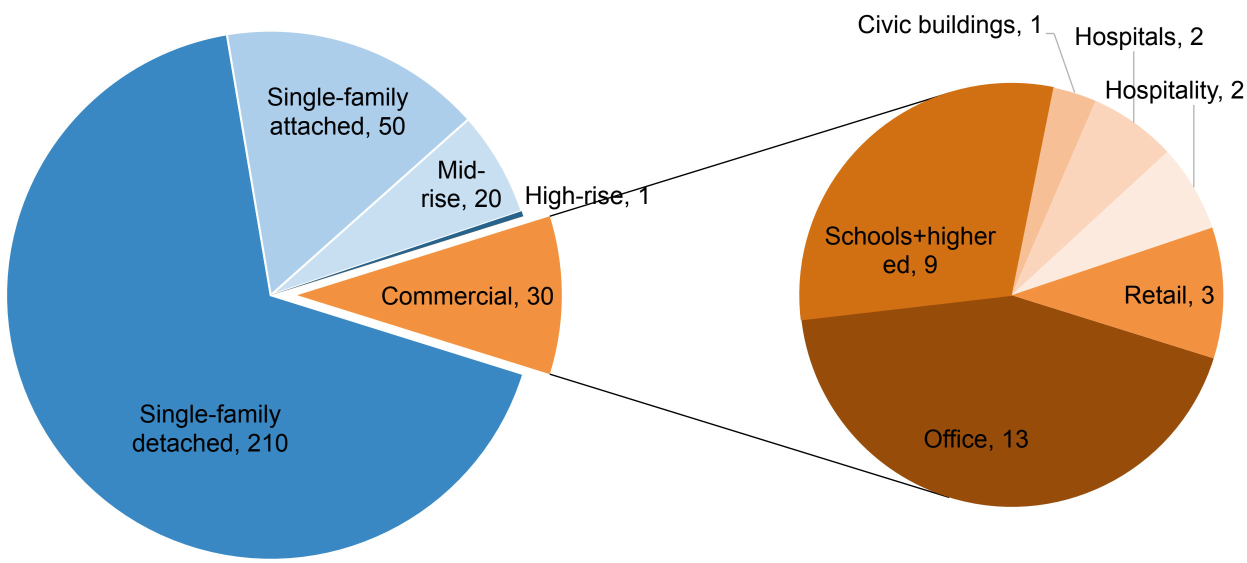


Figure 2. Estimate of the number and types of residential (left) and non-residential (right) passive buildings in North America (as of August 2016).

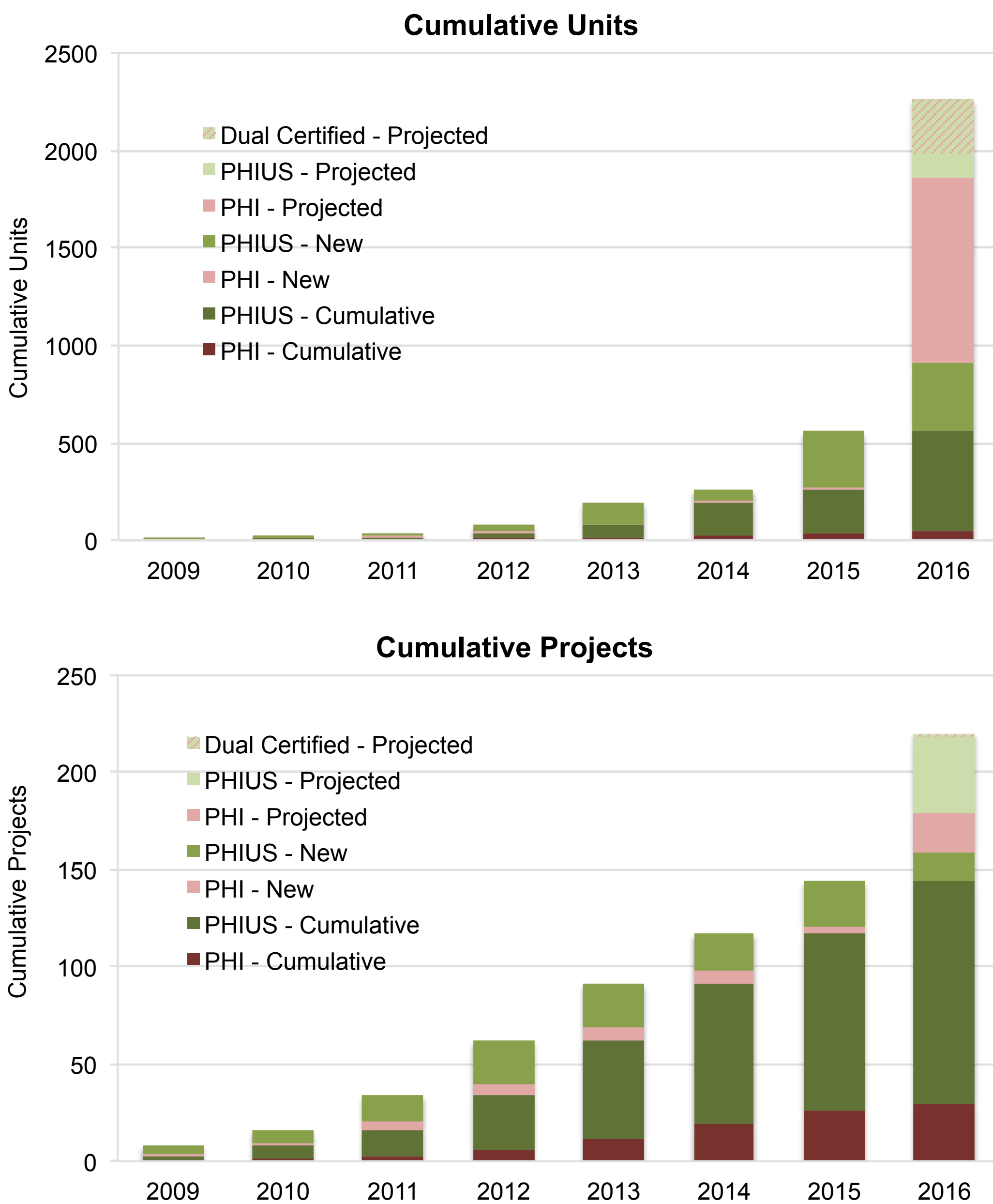


Figure 3. Growth in PHI and PHIUS+2015 certified Passive Houses in North America since 2009.

'Projected' data is for projects under construction and awaiting certification (based on data provided by PHIUS for PHIUS+2015 certification, and on a non-exhaustive list of projects compiled by the authors for PHI certification, which included 12 projects in Vancouver, 7 in Victoria, the Cornell Tech project in NYC, and a project in Kansas City seeking dual PHI/PHIUS+2015 certification).

Data sources: PHI, PHIUS and Passive House Canada

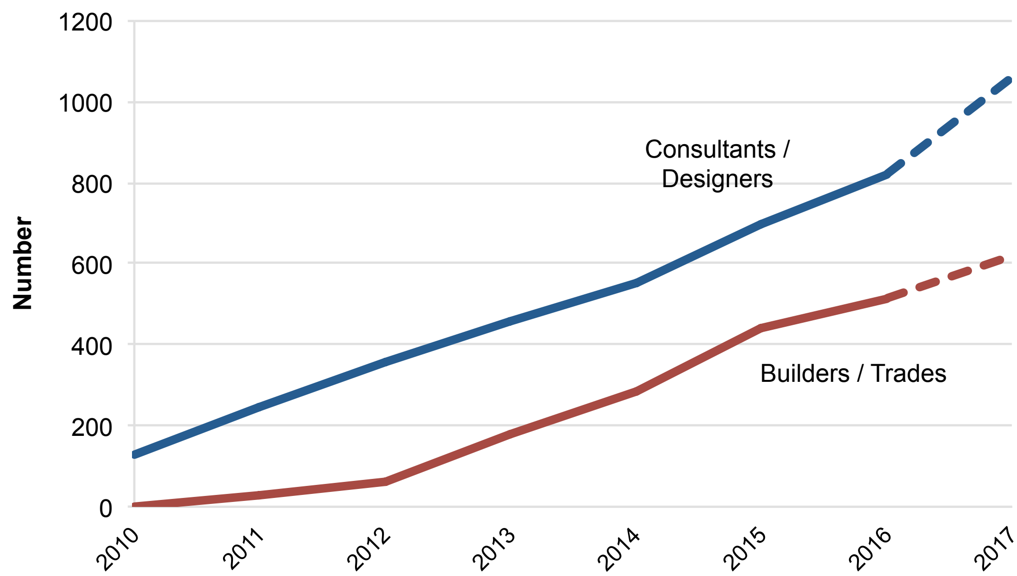


Figure 4. Growth in certified Passive House designers and trades in US/Canada since 2010.

Data: Passive House Canada and PHIUS[5]

Energy case for passive house

- Modelling studies show that passive design can reduce heating demand by 40% to 90% compared to typical current building practice. Monitoring of energy consumption in occupied units shows that heating loads for most projects studied are within ~10 kWh/m^2 of modelled values (Figure 5). As the systems involved are simple, the greatest source of variation generally comes from occupant behaviour.
- As the climate warms, passive strategies can be used to reduce cooling loads in conditioned buildings and reduce the risk of overheating in free-running buildings. These solutions can play a role in avoiding increased penetration of air-conditioning systems in regions where they historically had not been needed.

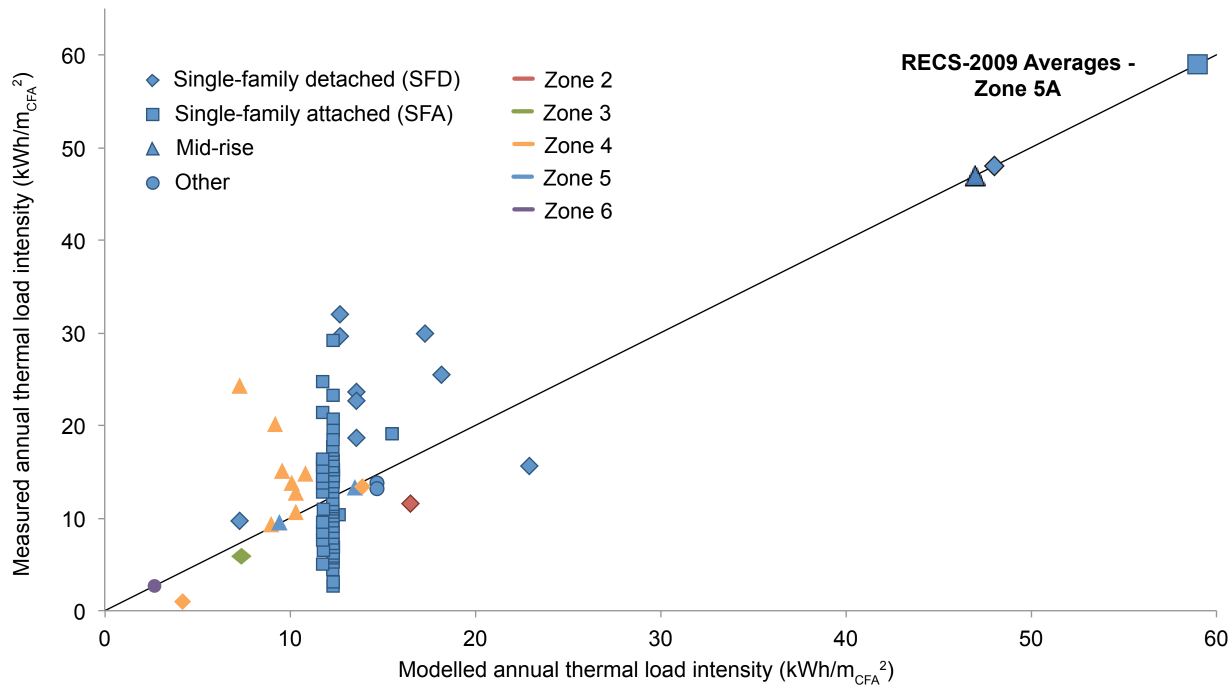


Figure 5: Comparison of measured to modelled thermal load intensity (TLI) for passive buildings.

The majority of buildings surveyed were located in climate zone 5A; the 2009 Residential Energy Consumption Survey (RECS) averages for this zone are shown to represent a typical U.S. building's performance in this climate. For most of the monitored project, the measured thermal load was within 10 kWh/m^2 of the modelled load. The average thermal load intensity (across all available measurement points) was 15.5 kWh/m^2: a 68% reduction from the RECS average. Points appearing in a vertical line result in cases where monitoring data is available for several individual units but the modelled thermal load intensity is only available for the buildings as a whole (and assigned as a default 'modelled' value for each unit).

Data sources: various, see references in Table 6

Business case for Passive House

- Detailed costing studies and anecdotal evidence from builders show that it is possible to build residential passive buildings within typical construction budgets; incremental cost estimates vary, but most are below 10%, and within normal budget variability.
- Given the low cost of energy in North America and continued failure to internalize the social cost of carbon, it can be difficult to make the business case for passive construction solely on the basis of energy cost savings. To complete the picture, we need costing studies that quantify potential maintenance cost savings associated with the higher quality components, as well as the decreased replacement costs resulting from simpler mechanical systems.

- While there is growing evidence of the fact that higher energy efficiency can increase sale values (see Section 11), better documentation of sales costs and time on market would help make the case for builders.
- Universal energy labelling would help provide validated information to compare the performance of different homes. This would also help communicate the relationship between quality construction, energy efficiency and non-energy benefits: comfort, air quality, durability and resilience.

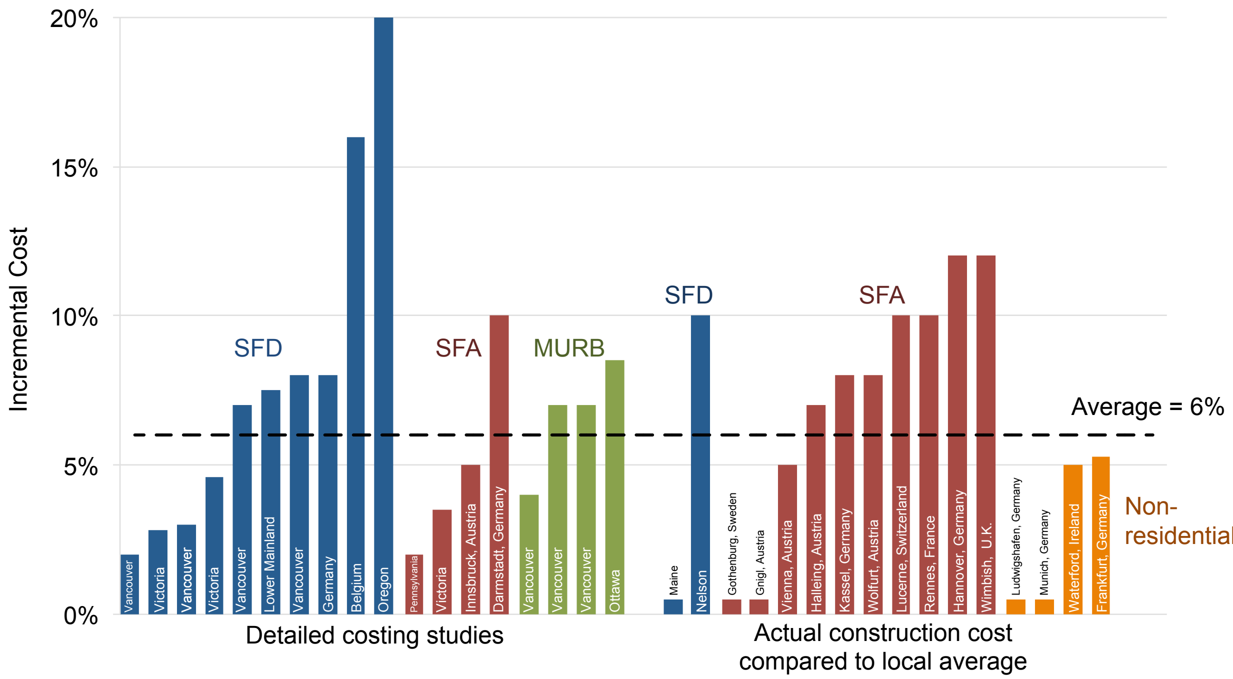


Figure 6. Estimated construction cost increment of passive buildings.

The average incremental cost, based on all studies and reported values found, was 6% of construction cost. Note that the baseline assumptions for what 'normal' construction practices (and associated costs) vary by location, and from study to study. See details in Table 8.

Data sources: various, see references in Table 8.

Quality control

Passive house construction raises the stakes: it provide great benefits if basic precautions are taken, but can also lead to underperformance if poorly executed. As passive approaches move from niche to broad adoption, certain quality controls will need to be integrated into building practices to mitigate the risk of moisture entrapment in walls and overheating, including:

- Air barrier testing, with strict airtightness requirements
- Proper accounting of thermal bridges and whole wall R-value calculations

- Involvement of a certified professional in the review of the enclosure design, or use of climate-appropriate pre-approved designs
- Design guidelines for passive cooling strategies including the sizing of south-facing windows, shading devices, cool roofs, etc.

Capacity building

Mainstreaming high-performance enclosures will require significant training across the construction industry, reaching beyond the occasional building code update seminar. Training capacity is in place, and is being scaled up to meet the growing demand. PHI and PHIUS provide a structure for training and networking of passive house practitioners in many areas of Canada and the U.S., and the number of Passive House trained trades and professionals is growing rapidly (Figure 4). Passive design is also being integrated into the curriculum of various trade, engineering, and architecture schools. This scale-up can also be supported by the creation of innovation excellence centres (such as BEEx in NYC, or that proposed by the City of Vancouver) that can act as clearinghouses for the dissemination of research and as hubs for education and outreach. These effort, however, are best coordinated when guided by energy codes roadmap, providing clarity on the next code iteration and on the end-goal performance they ultimately seek to achieve.

Accelerating change

Because retrofitting buildings is costly and complex, it is crucial that new buildings be built to the best standards as soon as possible. Each building allowed to be constructed at suboptimal efficiency is a 50+ year liability in a world that needs to be almost fully decarbonized within the next 30 years.

The pace of change that is called for to avoid this lock-in will be faster than what we have seen in the past — which will present both risks and rewards. The construction industry stands to gain in this transformation: as money moves from operational budgets to capital budgets, it also flows from the energy sector into the construction sector.

We have identified five early steps to be taken in supporting this market transition:

1. **Get more passive buildings on the ground.** Support the market segments that are already well underway (detached to mid-rise residential) or emergent (office, schools). Prioritize simple solutions that can be broadly applied, but also encourage projects that provide high visibility or break new ground: high-rise MURBs (multi-unit residential buildings), high-rise office, city halls, libraries. Collect basic data on the project economics and selected design strategy; work with research institutions to analyze this data and monitor energy use and indoor conditions after occupancy. Appendix C

summarizes policies implemented by North American jurisdictions to incent uptake of Passive House and remove some of the existing code barriers to the technology (listed in Appendix D).

2. **Ensure markets and decision makers have access to energy information.** The market can't value what it can't measure or see. Require benchmarking, reporting, and disclosure of energy use, starting with larger buildings and adding smaller ones over time. Put in place home energy labelling requirements for homes at point of sale and renovation. These will provides the feedback mechanisms needed to guide code evolution and facilitate valuation of energy efficiency for new and existing buildings.

3. **Free up additional capital to cover incremental costs.** Create the legislative structure to enable private industry to provide services combining lending and technical support (e.g. PACE model). Use government bonds to provide low-cost capital for loans and incentives and assess the potential for increased public revenues; the increased revenue and economic activity triggered will return more funds to public coffers (e.g. KfW model).

4. **Prepare the ground for regulation.** Set mid- and long-term targets to allow time for industry to prepare for policy development. Use information gathered from early projects to test economic and technical feasibility. Use benchmarking data to monitor impact of energy code change and market evolution.

5. **Create information sharing hubs offering training for industry and providing public education and outreach**. There is also need for a body to compile and analyze energy and costing data, to monitor the state of the market for high-performance components, and provide support for code development and design of demand-side management programs. These two functions can be joined, or assumed by different bodies, but in both cases they will likely play primarily a coordination role between various organizations providing the services.

Which building types to prioritize, and how

- From a 'proof-by-numbers' perspective, there is a strong case for the technical and financial feasibility of Passive House for ground-oriented, low-rise, and mid-rise residential buildings in North America. These market segments are rapidly growing and competing in the market, with limited incentives or policy drivers. With proper policy support and investment in builder training, passive approaches could be broadly adopted in the ground-oriented and mid-rise residential sector within a decade.

- Residential high-rise passive buildings are newly emerging but becoming more common, and more demonstration projects should be encouraged.
- For more complex building types, additional demonstration projects are needed to understand technical and market constraints. Public sector participation and leadership will be important (see Sections 9.1 and 11.2).
- Projects with high visibility that allow some access for the public are ideal candidates as they can increase awareness of passive design amongst the public and key market stakeholders. All social housing projects, community centers and civic facilities should be required to consider the feasibly of building the project to Passive House standard or comparable.

1. Introduction

Commercial, institutional, and residential buildings are responsible for about a third of carbon pollution in the U.S.,[i] and about a fifth of carbon pollution in Canada,[ii] constituting the largest source of emissions in North America.[6] Worldwide, they account for about a third of energy-related emissions,[7] and continue to grow: over 80 billion square metres (900 billion square feet), will be built and rebuilt in urban areas by 2030, an area roughly equal to 60% of the current global building stock.[8] Fifteen percent of this growth will occur in the U.S. and Canada.[9]

As countries around the world strive to reduce climate impacts and urban air pollution, this construction spurt offers both challenges and opportunities. If construction standards do not evolve rapidly, inefficiencies will be locked in and could lead emissions from the building sector to double by 2050.[10] At the same time, the nearly $80 trillion to be invested in this urban development[11] represents a unique opportunity. Countries and companies with the skills and knowledge to provide the needed building services while decreasing local air pollution and climate risks will have an important competitive advantage in local and global construction markets. Developing these solutions in North America is therefore not only an imperative from a climate and air quality perspective, but also a significant economic development opportunity.

One strategy to reliably reduce emissions from buildings at a low cost, while also improving durability, comfort, and resilience, is to improve the thermal performance of building enclosures. By increasing the insulation and airtightness of walls, roof, and windows, it is possible to reduce the energy used for heating buildings by up to 90% compared to common practice (Table 6). This 'passive' approach to thermal comfort—in contrast to active systems based on a constant supply of conditioned air by HVAC systems (Figure 7) —is the cornerstone of the passive house movement (see Box 1. Passive House basics) and a strategy used by thousands of green buildings around the world.

[i] 12% of direct emissions from commercial, institutional and residential buildings, rising to 34% of total emissions when including emissions resulting from the production of electricity used in non-industrial buildings (or 2,338 $MtCO_2e$ in 2014)

[ii] Counting both direct and indirect emissions from electricity use, buildings account for ~17% of Canadian emissions.

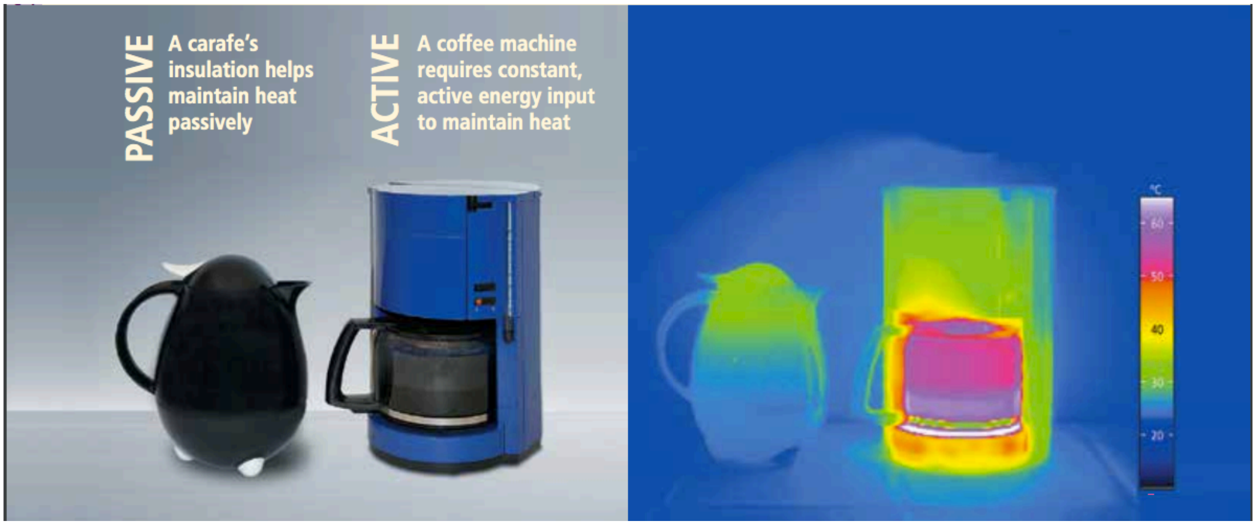


Figure 7. Passive vs. active approaches to climate control

Source: Passive House Institute[12]

Purpose, scope and structure of this report

This report investigates how public policy can be used to accelerate adoption of high-performance enclosures in the construction industry. To do so, we find it useful to consider lessons learned from the growth of the passive house movement in North America and Europe.

A couple of clarifications will help the reader in understanding the scope of this paper.

First, there are many 'passive design' strategies which can be integrated in high-performance buildings: daylighting, thermal mass, night ventilation, natural ventilation, shading, earth sheltering, cool towers, solar chimneys, earth tubes and phase change materials, to name only a few. Some of these strategies are directly addressed in the Passive House standards, others not. This report focuses on strategies related to enclosure design: level of insulation, airtightness, massing, orientation, and glazing. Other passive design strategies, such as shading and natural ventilation, will be briefly discussed for their role in mitigating the risks associated with super-insulated buildings such as overheating and moisture entrapment in walls.

High-performance enclosures are central to the Passive House standards, but they are also commonly used in high-performance construction more broadly, whether informed by other certification programs (LEED, R-2000, Built Green, etc.) or simply by construction best practices. Our discussion here is therefore not limited to the parameters set by the Passive House standards; for example, we discuss the value of airtightness measurement requirements in driving better enclosure design and construction practices, irrespective of the fact that the requirements implemented in North America to date do not specifically following Passive House methodologies or targets. That said, we see value in focusing more closely on lessons learned in the passive house community given its importance in policy development and capacity building in Europe, and given its rapid growth in North America. The Passive House standards also are the most rigorous with regards to enclosure performance; because the enclosure is among the longest lasting components of a building, maximizing its life cycle energy benefits will avoid locking in inefficiencies. Thus, to inform public policy, we are particularly interested in learning about the benefits and challenges of this ‘best in class’ standard. Many, if not all, of the lessons learned along the way will also be applicable to other high performance standards. Our primary concern here is not the adoption of a specific standard, but rather the dissemination of enclosure design best practices across the industry.[iii]

This report aims to provide decision-makers in government and industry a picture of the state of the passive house market (Section 2), an assessment of its energy benefits (Section 3), costs (Section 4), and risks (Sections 0 and 0), and a summary of barriers to market transformation and policy solutions advanced in Europe and North America (Sections 8 to 14).

Reducing emissions from buildings will require both de-carbonizing the energy supply and reducing energy demand across all energy end uses. This report, however, focuses primarily or the reduction of heating and cooling loads. The role of on-site renewables in reducing emissions and the need for strategies to address energy end uses beyond space heating (domestic hot water, lighting, plug loads, etc.) are briefly discussed in Box 2 and Box 3 below, but otherwise beyond the scope of this report.

Box 1. Passive House basics

The origins of passive house design date back over 40 years to the Saskatchewan Conservation House built in 1977 in Regina, Canada, by a team of researchers from the National Research Council and Saskatchewan Research Council.[13] The Saskatchewan Conservation House had an excellent standard of thermal insulation, an airtight building enclosure and one of the first heat recovery ventilation systems in the world. Tested 30 years later, the airtightness had not changed significantly, and the walls showed no sign of moisture accumulation.[14]

These design principles were codified and systematized by Bo Adamson and Wolfgang Feist, who

[iii] In this spirit, we will distinguish in this text the general design approach from the specific standards, by using Passive House (capitalized), to refer to the standards (and buildings meeting their certification criteria) and passive house (lower case) or passive building to refer to the general design approach developed by passive house practitioners across the world, irrespective of whether the resulting buildings meet all certification criteria.

founded the Passive House Institute (Passivhaus Institut) in 1996 in Darmstadt, Germany.

Buildings adhering to the Passive House standard use dramatically less energy than typical buildings due to a high level of insulation, high-performance windows with shading that modulate heat loss or gain, an airtight building enclosure, minimized thermal bridges, and continuous ventilation with energy recovery. Certification of Passive House buildings is based on quantitative performance targets and a series of specific requirements for thermal comfort, humidity, noise, and user satisfaction (Appendix A).

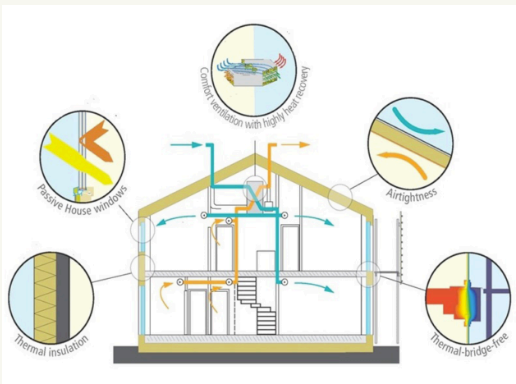


Figure 8. Passive House principles

Source: PHI[15]

Certification criteria (Passive House Institute)[iv]

Annual heating demand:	≤ 15 kWh/m^2 OR ≤ 10W/m^2
Annual cooling demand[v]:	≤ 15 kWh/m^2 + dehumidification contribution[vi]
Airtightness:	< 0.6 ACH @ 50 Pa
Total primary energy:	≤ 120 kWh/m^2
OR	
Total renewable primary energy (PER)[vii]:	≤ 60 kWh/m^2

[iv] These are the metrics for the 'classic' Passive House certification. New classes called Passive House "Plus" and "Premium" were introduced in 2015. These are energy-positive standards, decreasing further the maximum allowable PER, and requiring on-site generation greater than the expected annual use. See Appendix A for more details.

[v] Alternatively, a building can comply by showing the steady-state cooling load is < 10 W/m^2 and the total cooling demand remains below a (generally more flexible) limit calculated in PHPP based on climate data and air-change rates.

[vi] Variable limit value for the dehumidification fraction subject to climate data, necessary air change rate and internal moisture loads (calculated in PHPP).

[vii] In 2015, the standard shifted its total energy use intensity metric from 'primary energy use' to 'renewable primary energy (PER)'. Each standard combines the total site energy used for heating, cooling, dehumidification, DHW, lighting, auxiliary electricity and electrical appliances, but applies different factors to each of the energy supply sources. The PER factors were modified to better represent the complexity introduced by having a mix of intermittent renewables on the grid. Additional losses due to storage are considered when electricity is used at peak

In addition to these energy targets, certified buildings must meet specific requirements for thermal comfort, humidity, noise, and user satisfaction (see Table 27 in Appendix A).

Another major proponent of passive house design in North America is the Passive House Institute US (PHIUS.org), founded in 2007. Once a certifier for PHI, PHIUS now has a separate building performance standard, dubbed PHIUS+2015.[16]

Certification criteria (Passive House Institute US 2015)

Annual heating demand	< A kWh/m^2
Annual cooling demand (sensible + latent)	< B kWh/m^2
Peak heating load	< C W/m^2
Peak cooling load	< D W/m^2
Airtightness	≤ 0.05 cfm/sf enclosure @50Pa[viii,17]
Primary energy demand	≤ 6200 kWh/yr/person[ix]

Where A, B, C, and D vary by climate and energy costs (see Table 28 in Appendix A).

Other regional standards

The Passive House standard has also inspired other national codes or programs such as Switzerland's Minergie[18] and Brussels' 2015 building code (see Section 9.3). Canada's R-2000 certification for high-performance homes pre-dates the Passive House Institute, but is also inspired by a passive design approach (though the insulation and airtightness requirements are not as strict).[19]

Box 2. Focus on high-performance enclosure or on-site generation?

The benefits, and potential challenges, of highly insulated buildings vary by climate. While we try to address both cooling-dominated and heating-dominated buildings in this report, the majority of literature (and the geographic location of the authors) certainly bring a larger focus on the latter. And while we've attempted to capture the state of policy and markets across North

periods when renewable power is more limited (for example, during heating period in Europe). They are generally higher factors than primary energy factors, which explains in part the decrease in the target. At this stage, buildings can still certify using either metric. http://passipedia.org/certification/passive_house_categories/per

[viii] Conversion to ACH will depend on volume of the house, but is roughly equivalent to 1.3 ACH for a ~1,200 sqft home.

[ix] Where occupancy is determined by the number of bedrooms per unit, such that # occupant = # bedroom + 1

America, many of the examples discussed are from the Pacific Northwest, where the authors are based.

Achieving deep emissions reductions in the building sector will require improving the energy efficiency of buildings and supplying the remaining demand through low-emissions energy sources. How far we should push for energy efficiency, versus developing renewables, depends on the availability, costs and environmental impacts of each.

Given the significant decrease in PV costs, this is no longer solely a question of energy policy, but has also become a practical question for net-zero builders aiming to optimize cost effectiveness and constructability. The bulk of the construction industry, however, is still far from that intersection point. The solar potential of different buildings also varies greatly based on roof area, shading, and insolation. Even in areas where grid electricity is relatively low-carbon, such as in B.C. and Québec, the significant environmental and social impact of new supply, and its increasing marginal cost, maintain a strong incentive to conserve, and to continue to raise standards for energy efficiency in buildings. Even as we do so, we will need to consider how to integrate on-site generation, and how trade-offs between efficiency and on-site generation can be negotiated.

Box 3. Focus on reducing heating and cooling, or other end uses?

Heating and cooling loads generally account from a third to a half of energy use in buildings (depending on building type and location; see Figure 9). Thus, enclosure improvements alone will not be sufficient to meet deep energy reductions in the building stock; other end uses such as domestic hot water, lighting, ventilation, auxiliaries and plug loads will also need to be addressed.[20] Passive House standards address other end uses indirectly by putting a cap on the total energy use intensity of the building (Box 1) – a performance-based approach also used in certain energy codes (see Section 0). Other strategies for reducing other end uses include energy efficiency regulations for DHW equipment and plug loads, provision of hot water from low-carbon district energy systems, prescription of maximum power densities for lighting, daylighting, dynamic energy feedback systems for occupants, rate structures, etc. These approaches are complementary to enclosure improvement, and beyond the scope of this document.

There are, however, several reasons to prioritize an enclosure-focused approach to energy efficiency. First, building enclosures are long lasting and costly to refurbish, unlike other systems which can be more easily replaced as better technologies become available. Second, enclosures are simple systems; their performance does not depend on complex energy management systems and they are more tolerant to delayed maintenance — a known source of under-performance in buildings that are not continuously optimized (i.e. most buildings). Third, reducing heating and cooling demand early in the design process will allow to reduce the size of space conditioning systems, reducing construction cost and ongoing energy demand. Fourth, high-performance enclosures also offer significant non-energy benefits, such as thermal comfort, acoustic isolation, durability, and increased resiliency to power outages and extreme temperature events (particularly for non-conditioned buildings).

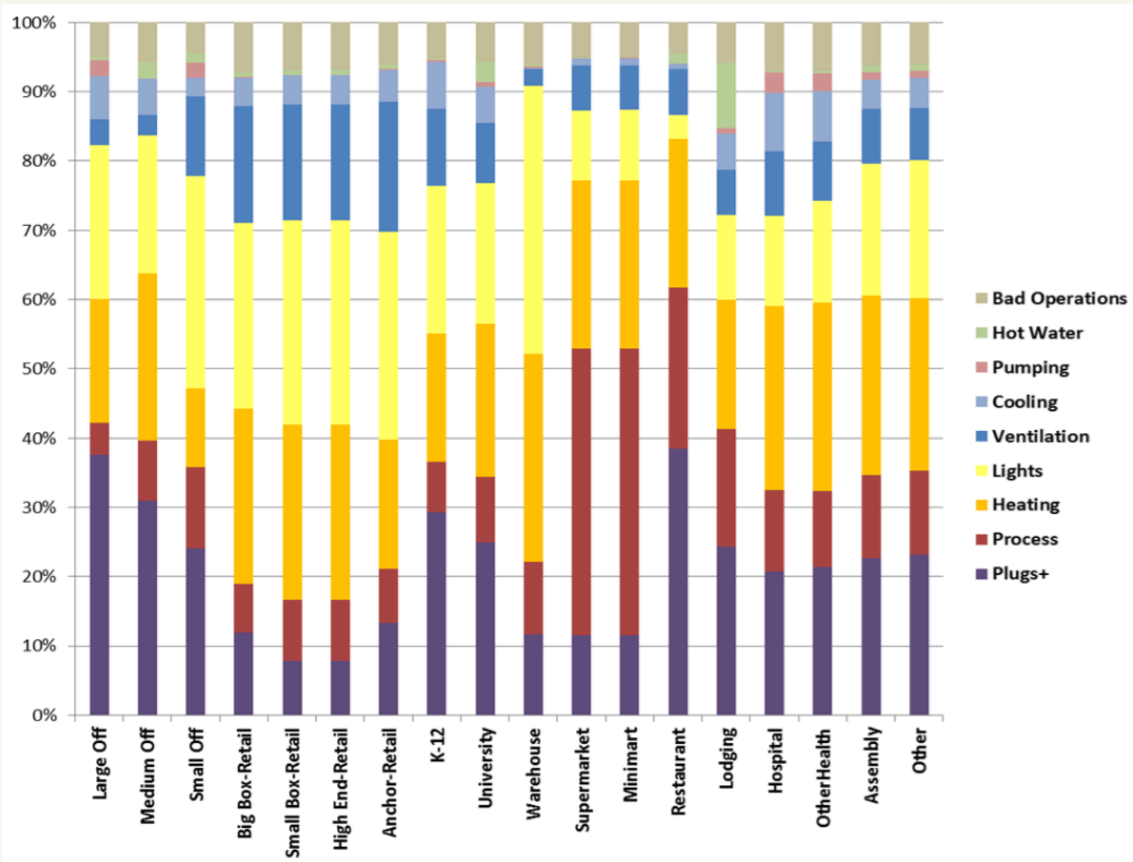


Figure 9. Energy end use for commercial buildings in the Pacific Northwest.

Energy end use is shown as a percentage of total energy use.

Source: New Buildings Institute[21]

PART 1: THE CASE FOR PASSIVE HOUSE

2. State of the market

Summary

- The number and size of Passive House projects in North America has rapidly grown in the last five years. Several mid-rise residential projects currently in construction will more than quadruple the number of available units and triple the square footage of passive buildings. We expect a steady flow of such mid-rise projects to break ground in the coming years.
- Most passive buildings are residential projects (well over 3500 buildings worldwide and 300 in North America), with a growing number of commercial and institutional projects (over 500).
- Demand and offerings for training of professionals and trades has also increased rapidly; there are currently over 1,600 professionals and trades trained in passive house construction in North America, with hundreds new certifications expected in the next year. There are local PHI and/or PHIUS affiliated chapters in over 25 locations across the continents, providing services to over 1,500 members.
- Several jurisdictions have put in place policies to support passive house, and there is growing political leadership on the role of standards for high-performance enclosures.

Because the Passive House standard was first applied to small residential buildings, it is often assumed to apply only to one- and two-family dwellings. In fact, the standard has been applied (with some variations) to a broad range of building types, including civic and institutional centers, offices, supermarkets, swimming pools, and low- to mid-rise commercial and multifamily buildings.[22, 23, 24] The first high-rise residential passive building was a 16-storey tower retrofitted to Passive House standard in 2010 in Freiburg, Germany;[25] two years later, the first high–rise Passive House office was built in Vienna on the old site of the OPEC head offices.[26] A 26-storey student-housing complex is being built on the Cornell Tech campus in New York City, aiming for certification under the international Passive House standard.[27] Projects have also been certified in nearly every climate zone, from equatorial to Arctic.[28]

Before discussing the energy case for high-performance enclosures and concerns associated with super-insulated walls, we give an overview of what types of passive buildings have been built to date both internationally and in North America. This will help identify building types for which 'passive-house-like' requirements could be implemented in the near future, and those that would benefit the most from public investment in demonstration projects and monitoring studies.

2.1 State of the passive building stock

While passive design principles can be used advantageously for all building types, there is a larger body of experience in building certain forms easily and cost-effectively. Unfortunately, it is rather difficult to get a good picture of the state of the passive building stock. There are multiple certification bodies and standards (PHI, PHIUS, Minergie, etc.), and we know, based on conversations with practitioners, that only a fraction of passive buildings actually go through certification. While the International Passive House Association database[29] allows builders to publish their projects irrespective of their certification status, entry to the database is voluntary, and many projects do not end up being catalogued. Nevertheless, the iPHA database offers a reasonably representative sampling of the distribution of passive buildings of different types (Figure 10).

To get a better sense of the state of the North American passive building stock, we compiled data available from various sources: the iPHA public database, PHI's internal database, the PHIUS database and various publications, as well as tracking projects known by over 20 practitioners across the U.S. and Canada (Appendix A); care was taken to avoid double entries as these sources were merged. Based on this research, as of August 2016, we counted over 300 passive house projects in North America (Figure 11). The majority of them (282, 90% of total) were residential projects, providing over 700 units; 30 were commercial/institutional projects (10% of total). Two-thirds of the buildings identified came from either the PHI or PHIUS certification database, and one-third were non-certified projects flagged by interviewed practitioners. The actual number of non-certified passive house projects is likely much greater. This survey was done in the summer of 2015, with partial updates in 2016. Further effort is underway by Passive House Canada and NYPH to track existing and upcoming projects.

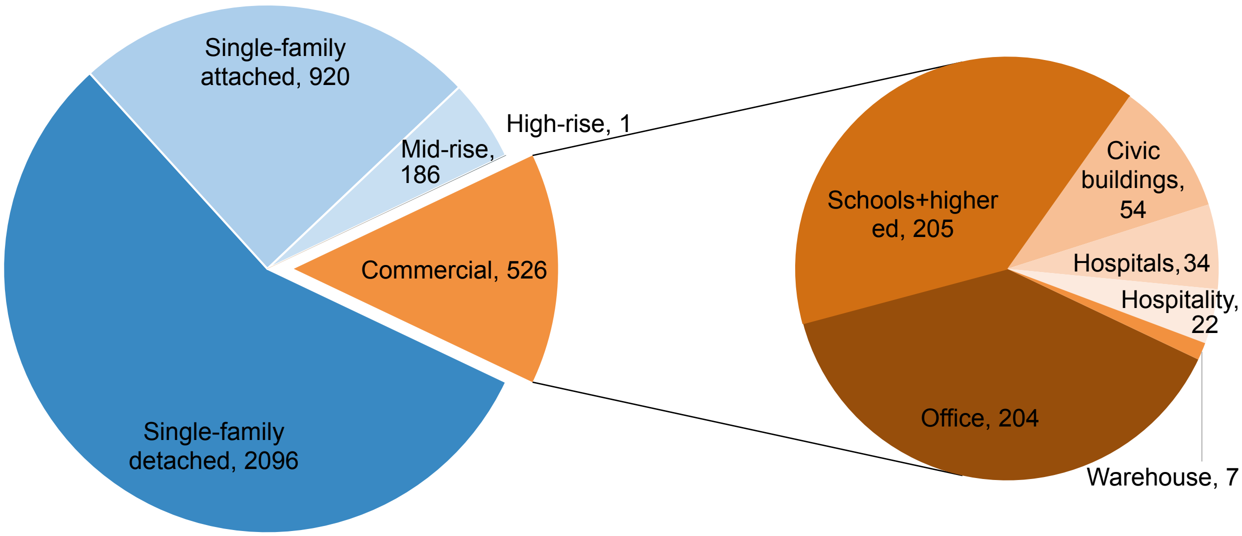


Figure 10. Number and types of residential (left) and non-residential (right) buildings registered in the global Passive House Database.

Of the 3700+ buildings in the database as of Aug 2016, 86% were residential, and 14% were commercial/institutional. The database specifies over 20 types of buildings; several of which were collapsed here to simplify the figure. Hospitality includes hotels and restaurants.

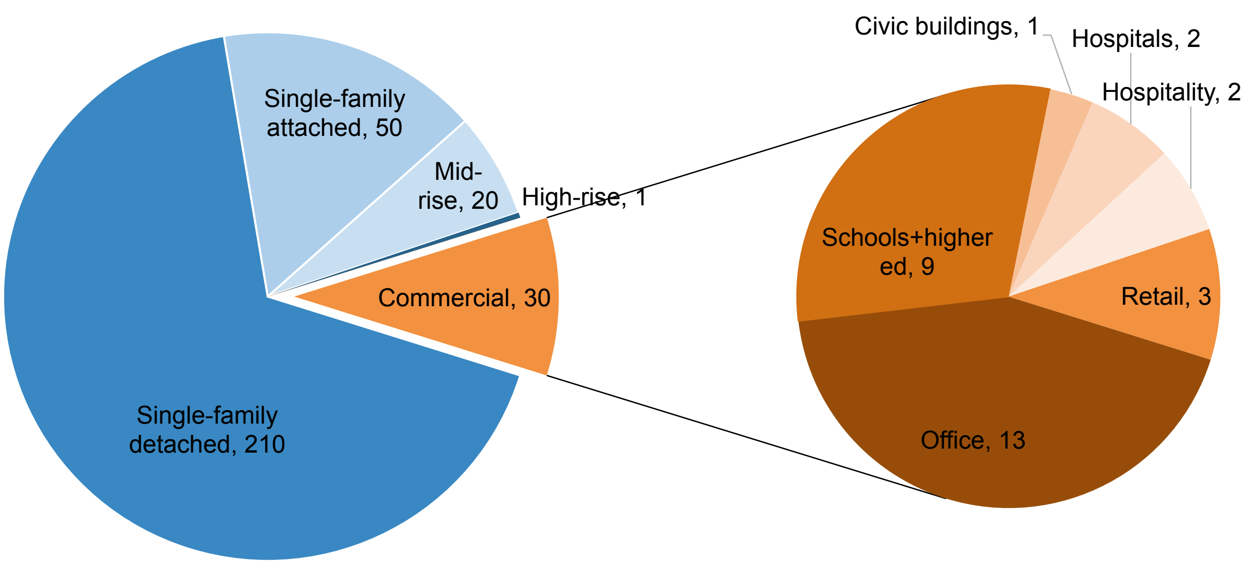
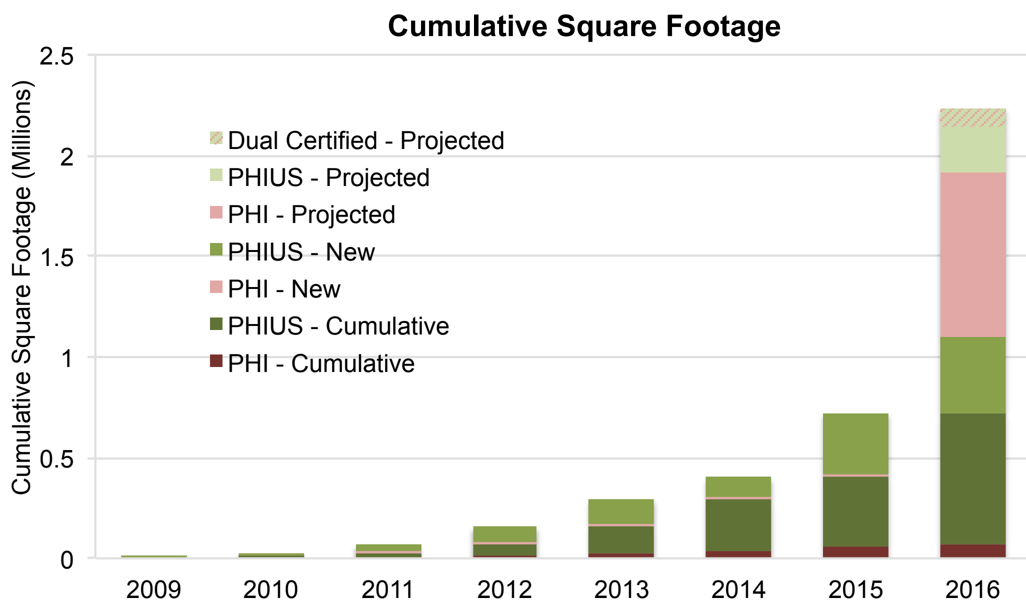
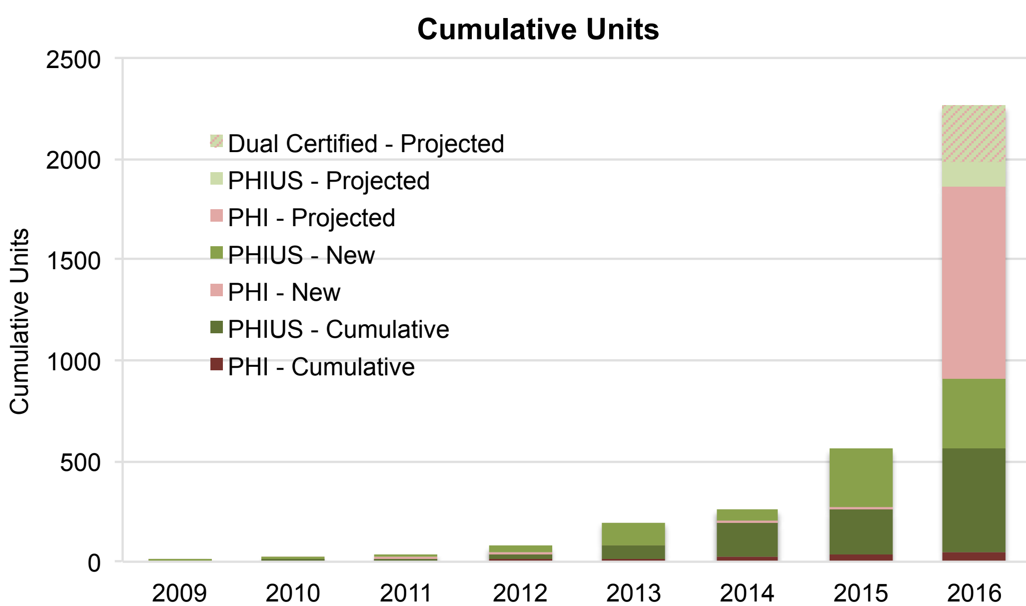


Figure 11. Estimate of the number and types of residential (left) and non-residential (right) passive buildings in North America (as of August 2016).

Based on a non-exhaustive compilation of databases and other sources, there were, in August 2016, at least 280 residential passive house projects (90% of total; over 700 units), and 30 commercial/institutional projects (10% of total). This only includes completed projects (see Figure 12 for projected growth in 2016.)


Cumulative Square Footage
Cumulative Square Footage (Millions)
2.5
2
1.5
1
0.5
0
Dual Certified - Projected
PHIUS - Projected
PHI - Projected
PHIUS - New
PHI - New
PHIUS - Cumulative
PHI - Cumulative
2009
2010
2011
2012
2013
2014
2015
2016


Cumulative Units
Cumulative Units
2500
2000
1500
1000
500
0
Dual Certified - Projected
PHIUS - Projected
PHI - Projected
PHIUS - New
PHI - New
PHIUS - Cumulative
PHI - Cumulative
2009
2010
2011
2012
2013
2014
2015
2016

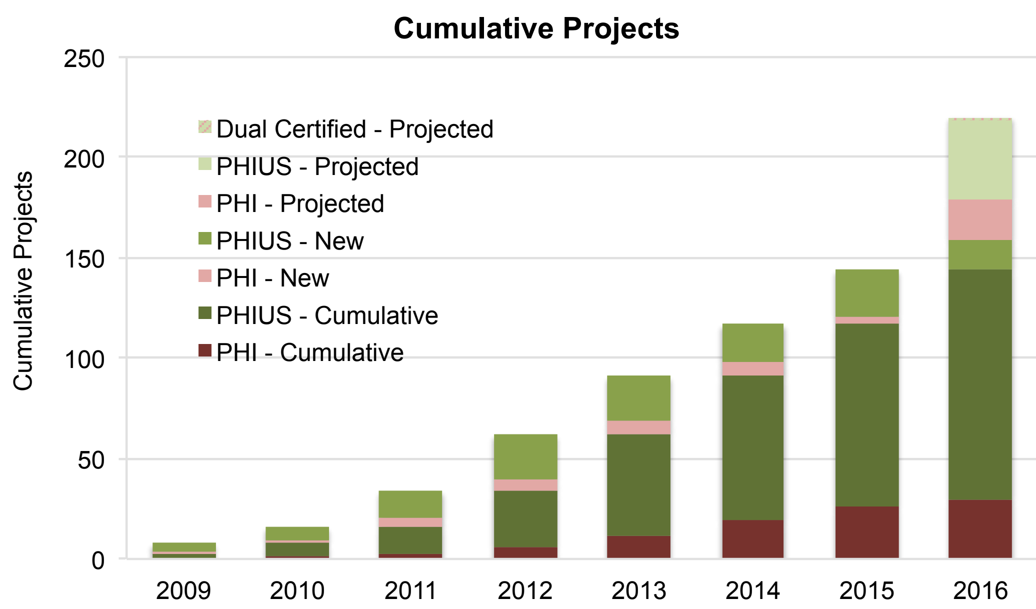


Figure 12. Growth in PHI and PHIUS+2015 certified Passive Houses in North America since 2009.

Source: PHI, PHIUS and Passive House Canada.

'Projected' data is for projects under construction and awaiting certification (based on data provided by PHIUS for PHIUS+2015 certification, and on a non-exhaustive list of projects compiled by the authors for PHI certification, which included 12 projects in Vancouver, 7 in Victoria, the Cornell Tech project in NYC, and a project in Kansas City seeking dual PHI/PHIUS+2015 certification).

The growth in Passive House certified buildings in North America during the last year has been particularly dramatic, more than tripling the number of available units and doubling the square footage. This is the result of some major high- and mid-rise residential developments in the United States, comprising hundreds of new units, and dramatic projected growth in the Vancouver area. Not surprisingly, the majority of passive house buildings are residential, most of these single family homes. Non-residential projects are less common, but this is not due to a lack of knowledge on how to adapt passive strategies to these market segments. Rather, it is a reflection of relatively few developments specifying highly efficient standards. Larger Passive House developments in cities like New York, Kansas City and Vancouver are beginning to challenge this status quo.

2.2 Design challenges for non-domestic buildings

The Sustainable Energy Authority of Ireland conducted case studies of several Passive House buildings in the commercial/institutional sector, including commercial offices, schools, and recreational complexes.[30] Reviewing these projects, they compiled a list of design challenges faced by non-residential projects and best practices to address them; their findings are summarized in Table 1.

A challenge common to most non-domestic projects is their more complex (and variable) occupancy schedules. For passive and non-passive house construction alike, this requires a more careful design of the ventilation system and the involvement of a mechanical engineer. A side effect which is more significant for projects aiming for Passive House certification is the fact that a fluctuating occupant load will also have a significant impact on heating or cooling energy intensity targets, because occupants are a significant heat source for well-insulated buildings. This may require strategies to redistribute heat between different areas of the building.

On the flip side, non-residential projects with regular occupancy schedules can simplify passive design for heating. Meeting heating targets for schools and offices, for example, is facilitated by the large number of occupants providing internal heat gain during daytime hours, when the space needs to be heated. The fact that heat delivery and fresh air delivery is often separated in passive design allows the system to meet the greater demand for fresh air, at a time when no additional heat might be necessary. On the other hand, large number of daytime occupants make it more difficult to meet cooling needs within the allotted energy budget, particularly in the shoulder season when some passive shading strategies can be less effective. A range of passive cooling strategies can be used to reduce cooling loads in conditioned building and to keep free-running buildings comfortable (see Section 0).

Buildings featuring numerous zones with varying ventilation and heating requirements, such as hospitals,[31] laboratories,[32] office buildings with server rooms,[33] recreational facilities,[34] and retail stores[35] also present design challenges to meeting passive house targets as the intersection of energy flows, building functionality and code requirements (fire safety) becomes more complex. Redistribution of heat from localized hot spots and differentiated delivery of ventilation increase the reliance on mechanical systems, which add to the energy load. Several case studies show that meeting passive house targets in these complex buildings is possible; but more importantly, they show how passive strategies can be applied to reduce energy use, irrespective of whether the certification targets are met (Table 1).

Table 1. Non-residential passive house challenges and current best practices

Design condition	Challenge	Best practices for mitigation

Larger treated floor area	Design requirements for mechanical equipment	Greater use of windows for ventilation; case-specific mechanical equipment choices[x]
Building use and occupant behaviour (e.g. computer servers, physical activity)	Greater internal heat gain	Thermal mass to reduce daily fluctuations (mixed or solid construction); energy efficient lighting and computers; concrete-core geothermal cooling; night cooling with automatic windows; fresh air cooling with reversible heat pump
Larger sun-facing exterior surface	Greater internal heat gain; glare	Exterior sensor-controlled shading
Periodic occupation	Frequent heat fluctuations	CO_2 sensors to control ventilation
Building regulations for fire protection	Passive House ventilation ducting may pass through multiple fire compartments	Fire-dampers, cold-smoke shutters
Additional building features (parapets, balconies, basements)	More interfaces for thermal bridging	Include in thermal enclosure with insulation layers, or exclude with a thermal break
Circulation spaces (e.g. stairwells, elevator shafts)	Additional design considerations	Separation from Passive House enclosure with thermal breaks
Common areas (e.g. lobby space)	Varied heating and ventilation requirements	Clustering common areas to reduce the number of individual mechanical systems
Specifically ventilated spaces (e.g. commercial kitchens, labs, gyms)	Ventilation design requirements	Use of separate ventilation system; greater use of windows for ventilation
Multiple temperature zones	Heating and cooling requirements	Use of radiators
Operational complexity	Difficulty in managing various building systems	Provide training where necessary; remove control where possible (e.g. centralized management for social housing and student accommodation)

[x] The decision to use centralized or decentralized mechanical systems depends on variety of factors. In the case of space heating, it depends on the number of living units (in the case of an apartment complex), the availability of district heating, cost-effectiveness of various types of space heating, the need for heat exchangers in the case of centralized systems, and the need for auxiliary equipment (e.g. fire protection).

Modelling complexity	Complexity beyond the scope of PHPP	Use of dynamic simulation software

Data source: Sustainable Energy Authority of Ireland[36] and interviews with practitioners

2.3 Certified practitioners and networks

As will be further discussed in Section 1, the training of professionals and trades in passive design is a fundamental condition for market transformation. Both PHI and PHIUS provide training and certification program for professionals and trades and support networks of practitioners. Demand and capacity for training has steadily increased in the last five years. Passive House Canada, for example, was recently constituted from the merger of canPHI and canPHI West. Less than three years ago the most active of the two organizations, canPHI West, had only one trainer conducting a handful of training per year; in fiscal 2017, Passive House Canada is scheduled to lead 52 trainings in B.C. alone, with a potential to reach 1,300 trainees.[37]

Table 2 provides a breakdown of the number of certified consultants/designers[xi] and trades in Canada and the U.S. as of August 2016.[38] The North American Passive House Network (naphnetwork.org) is affiliated with the Passive House Institute and provides support to a network of practitioners across North America, supporting various regional chapters (Table 3). PHIUS also supports a chapter-based network, the Passive House Alliance US, which has chapters in several American cities (Table 4).

These trained practitioners and network members are early adopters. There is evidence in certain regions of greater introduction into the established regime; for example, the cities of Vancouver and Victoria are getting building inspectors trained in Passive House and professionals in larger consulting firms are getting Passive House certified. More than 70 people, including some government staff, attended the Passive House Certified Designer/Consultant examination offered in Vancouver in October 2015 — numbers never seen outside of Germany. Over 500 more are registered or projected to attend Passive House Canada courses through the remainder of 2016 and the first quarter of 2017. Throughout key markets in Canada and the U.S., the sector is rapidly growing, as illustrated by Figure 12 and Figure 13. Table 2 shows the regional distribution of the trainees, as best estimated from location of

[xi] A certified passive house designer must have educational credentials in building science beyond the Passive House training (e.g. architects, engineers, master carpenter, etc.); a Passive House consultant meet the certification requirements from PHI/PHIUS, but might not have any further official building science training.

training or address of practice. In Canada, most practitoners are on the west coast, followed by Ontario and Québec. In the U.S., the East Coast has a large body of practice, along with California and the Pacific Northwest. This also mirrors the location of the NAPHN and NAPHA chapters, which provide facilitated and peer-led support to practitioners, with a joint membership of over 1,500 people (Table 3 & Table 4).

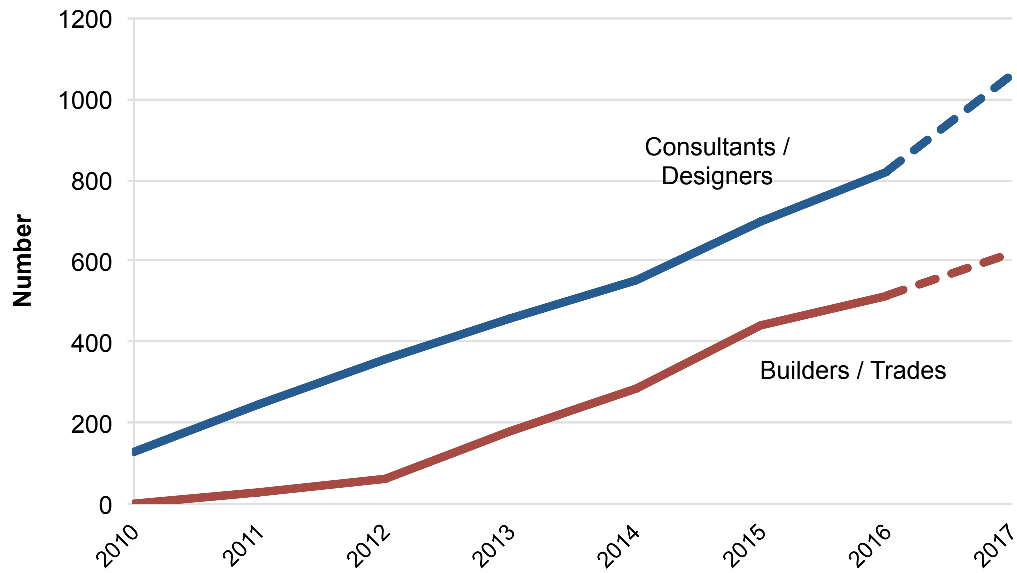


Figure 13. Growth in certified Passive House designers and trades in US/Canada since 2009.

Source: Passive House Canada and PHIUS

Notes:

a. The number of certified designers is not tracked by PHIUS – these figures were estimated from records of course registration and the historical pass rate on the PHIUS exam.

Table 2. Number of certified Passive House consultants/designers and trades (as of Aug. 2016)

	PHI			PHIUS		
Country/State/Province	Consultant/ designer	Trade	Certifiers[a]	Consultant/ designer	Trade	Raters/ Verifiers[b]
Canada	**169**	**21**	**3**	**19**	**10**	**2**
British Columbia	103	15	2			
Ontario	27	4	1	13	6	1
Québec	16	2			1	
Nova Scotia	8			2	3	1
Alberta	11			3		
Saskatchewan	2					
New Brunswick	1					
Yukon	1			1		

United States of America	**307**	**138**	**6**	**537**	**295**	**108**
New York	152	95	2	75	22	13
Pennsylvania	30	11		48	23	15
California	26	5		24	16	9
Vermont	16	7		15	17	4
Connecticut	11	3		9	8	4
Maine	11			9	3	1
Massachusetts	10	1		36	16	6
New Jersey	8	6		13	6	4
Washington	8	1		36	24	2
Illinois	5	3		25	12	7
Virginia	4	2		26	6	8
Minnesota	4			11	4	1
Colorado	3			28	21	4
North Carolina	3			8	9	4
Oregon	3		4	44	28	3
Arizona	2			4	1	
New Hampshire	2			5	7	
Ohio	2			12	7	4
Georgia	1			3		2
Iowa	1				1	1
Maryland	1	1		8	4	4
Michigan	1			9	2	
Missouri	1			8	3	1
Washington, D.C.	1			6	8	
Wisconsin	1			11	4	2
Delaware		2			4	
South Carolina		1				1
Alabama				2	1	
Alaska				2	3	1
Arkansas				1		
Florida				3	1	
Idaho				6	6	
Indiana					3	
Kansas				1		1
Kentucky				5	5	
Louisiana				1		

Montana			7	3	
Nebraska				1	1
Nevada				1	
New Mexico			3	2	1
North Dakota			2		
South Dakota			5	3	
Oklahoma			4	1	
Rhode Island			2	2	
Texas			14	4	4
Utah			5	2	
Wyoming			1	1	
TOTAL, certified professionals & trades	**1615**				

Data: PHI database, and PHIUS[39]

Notes:

a. The actual pool of certifiers for North American projects is larger, as anyone with Passive House Institute credentials around the world may certify a project. In some cases, an international certifier is chosen.

b. PHIUS raters/verifiers are third parties doing on-site verification of design specifications and construction practices. They report back to PHIUS certification staff, who oversee design review and onsite verification. Final certification is based on submissions from both phases.

Table 3. North American Passive House Network chapter membership (as of May 2016)

Chapter	Number of members
Passive House Canada	215
New York Passive House	209
Passive House Northwest	109
Passivhaus Maine	60
Maison Passive Québec	40
PH California	40
Ontario Passive House	30
Total	703

Source: NAPHN

Table 4. North American Passive House Alliance chapter membership (as of August 2016)

Chapter	Number of members
Atlanta	22
Austin	30

Capital (DC)	65
Chicago	70
Dayton	7
Denver	68
Houston	4
Hudson Valley	43
Kansas City	6
Kentucky	6
Lansing	13
Minneapolis/St. Paul	31
Northern Rockies	21
Portland	68
San Diego	12
San Francisco	42
St. Louis	8
Vermont	55
Not Affiliated	238
Total	809

Data: PHIUS

2.4 Supporting public policies

While growth in the North American passive house market to date has been primarily private sector driven, some public policies are starting to accelerate uptake by removing barriers or evening the field. The role of public policy is discussed in more detail in section 1, but to complete this 'state of the market,' we include here a brief overview of established and emerging policies which are supporting this accelerated adoption. We focus here on two leading jurisdictions: British Columbia (and the City of Vancouver), and the State of New York (and the City of New York).

BRITISH COLUMBIA

City of Vancouver Zero Emissions Building Plan (2016)

The City of Vancouver Zero Emissions Building Plan calls for a 90% reduction in emissions from new buildings by 2025, and achieving zero emissions for all new buildings by 2030.[40] While it does not explicitly require Passive House design or certification, this policy makes Vancouver the first jurisdiction in North America with a detailed roadmap and policy direction to encourage zero emissions buildings, the design of which will draw heavily on passive house principles and high-performance enclosures. In this plan, low-rise MURBs requiring rezoning will be required to meet the passive house thermal load intensity target of 15 kWh/m^2/year by 2020, with the requirement being extended to all new low-rise MURBs by adoption in the Vancouver Building Bylaw by 2025.

This builds on the existing City of Vancouver Green Rezoning Policy, which requires rezoning for large commercial and multi-unit residential projects to meet stringent thermal energy demand and greenhouse gas intensity targets, or else to achieve Passive House certification. This policy impacts 60% of square footage developed in the City of Vancouver (an estimated 2.6 million square feet of new development each year).[41]

Vancouver Passive House procurement policy: The 2016 plan also states that Passive House certification will be required for all new city-owned buildings, unless it is deemed unviable. A new fire hall is already being planned to achieve Passive House certification.[42] The Vancouver Affordable Housing Agency has also incorporated a requirement to assess projects against the Passive House standards as part of its RFP process. A new social housing unit is being planned as a passive house project.[43]

City of Vancouver thick wall exclusion (2010, 2015) **and setback allowance** (2016): Allows all building types to exclude the area used for insulation exceeding minimum code requirements in floor space ratio calculation. Maximum limit on exclusion was explicitly based on the amount of insulation deemed required to achieve Passive House. In 2016, Council granted the director of planning discretion to relax height and setback requirements to make use of the square footage gained from the wall thickness exclusion.[44]

Moodyville, North Vancouver (2016)

The City of North Vancouver's Moodyville redevelopment area comprises about 1 million square feet of buildable floor space. In order for new buildings to receive additional density beyond single-family or duplex development, the City's pre-zoning requires projects to either meet Passive House Certification, the highest tier of the Energy Step Code (similar to Passive House) currently under development by the province, LEED-NC Gold with 15% better than ASHRAE 90.1 2010 energy performance, or LEED For Homes Gold Certification with EnerGuide 86 Certification. Only developments designed to achieve Passive House certification will be exempt from a district energy connection for district heating, which acts as a indirect financial incentive for choosing the Passive House option at rezoning.[45]

BC Housing procurement policy (2016)

Passive House is now included as an option along with LEED for provincially funded projects. BC Housing has included targeting Passive House certification as a requirement in two recent

RFPs for three-storey housing projects of approximately 18,000 square feet, one in Merritt (climate zone 5) and one in Smithers (climate zone 7). Decisions as to whether these projects will apply for precertification is expected in the coming months.

B.C. Climate Leadership Plan (2016)

The new provincial climate action plan includes a target for all new construction to be net-zero ready by 2032 and announces the establishment of incentives for high-performance new construction as well as support for training and capacity building. A subsection is dedicated to the Passive House standard, which is receiving support from the province through funding for Passive House Canada training courses.

NEW YORK STATE

City of New York: Local Law LL31/2016 for new city-owned property (2016)[46]

Passed in March 2016, this new law requires that new capital projects for city-owned property (new construction, additions and substantial reconstruction) be designed to use no more than 50% of energy used today (called “low energy intensity buildings”). All projects must also consider the feasibility of providing at least 10% of energy from onsite renewables, and projects three stories or less must consider the feasibility of net zero energy use.[47] By reducing energy demand first, Passive House projects could be able to meet this 10% RE or net zero requirements at a lower additional cost.

State of New York: NYSERDA multifamily new construction program guidelines (2016)

This program is designed to offer incentives for new multiunit construction based on three tiers of energy performance. Four compliance and certification pathways are offered, including ENERGY STAR, PHI certified, PHIUS+ certified, and a modified prescriptive path. The three tiers offer incentives for energy performance of 15%, 25% and 35% better than the ASRAE 90.1 standard.[48]

City of New York: Zone Green thick wall exclusion (2012)

Zone Green allows for up to eight inches of wall thickness to be exempted from the calculation of floor area to encourage high-performance buildings without decreasing the amount of usable space in the building. This exemption applies where above-grade exterior walls exceed the thermal enclosure requirement of the New York City Energy Conservation Code by a prescribed percentage.[49]

Affordable housing policies in the U.S. (various locations)

In many U.S. jurisdictions, affordable housing development is funded through tax credits. This is a very competitive process, in which various developers compete for limited funds. Some housing agencies have started to award additional points for Passive House projects, which has spurred increased interest from developers. As an example, in the first year of the PHFA Passive House policy, 39 of the 85 projects submitted (35%) were passive. The agency funded eight Passive House projects, totaling 422 units. This is the largest concentration of passive buildings in the U.S.[50]

2.5 Conclusion

Whether it regards growth in construction, training, or emergence of new vision-setting and barrier-removing policies, all evidence gathered in this section indicate that we are at an important inflection point in the development of passive house markets in North America. The leadership of early adopters is now being followed by integration in established regimes, whether through development by larger scale developers, or integration by subnational government. Based on these signals, we expect the rapid growth observed in the last five years to be surpassed by development in the next half decade.

3. Energy case for passive design

Summary

- The measured energy use reductions in passive buildings compared to typical construction ranges from 40% to over 80% when considering total energy use intensity. Thermal load intensities were 33% to 98% below the average value for existing buildings of the same type and climate in the U.S., with most between 50% and 90%.
- There are some fundamental challenges with the methodology of ASHRAE 90.1 (and LEED by extension), which limit its potential in reducing energy use and greenhouse gas emissions. These include an emphasis on mechanical systems over building enclosure, and the conflict between fuel cost reduction and GHG reduction objectives.
- While reference building or "percent better" approaches allow more flexibility to address complex cases and allow baselines to reflect some of the 'natural' variability in energy demand between different building types and locations, the approach adds complexity and difficulties in modelling and communicating future progression of codes. Fixed-budget targets provide more clarity and predictability.
- Prioritizing passive building design, with an emphasis on improving building enclosures rather than mechanical systems, is expected to yield more reliable energy and carbon reductions, particularly in the residential sector and in heating-dominated areas.
- Adopting performance-based code requirements (which pair with a fixed energy budget approach) would allow the considerable efforts currently invested in maintaining prescriptive energy codes to be redirected toward the creation of design guidelines and providing support for builders, and will be simpler to implement than the detailed consensus-building of prescriptive solutions.

Current approaches to energy regulations in buildings have not consistently delivered the energy and greenhouse gas emissions reductions expected. In the Lower Mainland of British Columbia, for example, a study of energy use in a sample of mid- to high-rise MURBs has shown that those constructed after 1990 use on average more energy than those constructed in the 1970s and 1980s. The overall effective thermal performance of high-rise residential buildings has not improved significantly during that period, while ventilation rates (and associated space heating requirements) have increased.[51] This stalled thermal improvement performance is surprising, as energy codes regulating energy efficiency of these building has, in theory, increased in stringency during that period.[52]

A greater focus on enclosure and passive design could help address this gap, particularly in heating-dominated or mixed climates. To understand some of the issues with current approaches, we review published data on the performance of LEED buildings and discuss some of the limitations of the ASHRAE 90.1 standard in heating-dominated climates. We then review monitoring data from passive buildings, and in turn discuss some of the challenges of a fixed energy budget approach focused on thermal load intensity.

Box 4. Taxonomy of building energy regulations and certifications

Energy efficiency standards for buildings can be either prescriptive or performance-based. Prescriptive standards offer the builder, architect, or engineer a set of options with minimum performance metrics for various components. Common prescriptive measures include minimum R-values for insulation or wall assemblies, acceptable infiltration rates, and efficiency requirements for mechanical systems such as water heaters and HVAC equipment.

Performance-base code, on the other hand, requires the building as a whole to meet certain energy performance metrics. This whole-building approach provides more design flexibility, allowing for innovation and the integration of energy efficiency technologies. Compliance with the standard is established through energy modelling, which adds a modest cost to the design and/or compliance process. If integrated early in the design process, energy modelling can also lead to significant savings as it allows design teams to evaluate various strategies, components, and technologies and get the needed energy savings at the least cost.[53] Most beyond-code requirements use a performance approach, rather than a prescriptive approach: they rely on computer models to show that the proposed design should perform better overall than a baseline, rather than prescribing the performance of specific components. The desired level of performance can be expressed either as an absolute target — the fixed energy budget approach — or relative to a ‘reference building’, comparable in form and function to the design building but following the minimum requirements set by a prescriptive standard.[54] Performance-based approaches can be assessed using a range of energy performance indices (or metrics), which vary in the scope of end uses they include, and in the relative weighting they give to different fuel sources (Table 5).

Compliance with both prescriptive and the (modelled) performance-based standards can be assessed at the design stage and regulatory approved given before construction begins. Inspection after construction is sometimes used to ensure the building was built as designed, and therefore still meets code requirements. Most regulatory and certification processes end there; rarely is the developer/builder required to demonstrate that the building operates, once occupied, to the level of performance estimated at the design stage.

Thus, these forms of assessments are sometimes called asset ratings — they depend on the physical assets the building is built from, not on its operation. Asset ratings ('as designed') are based on modelled energy use (taking into account physical measurement of relevant characteristics of the building) with uniform conditions of climate, schedules, plug loads, occupancy, and energy management. The alternative is an operational rating ('as operated'), which relies on metered energy use to assess the performance of the building. They therefore take into account not only the physical characteristics of the building, but also the level of energy service provided (which might differ from modelled conditions), occupant behavior, building maintenance and operation, and possible variation in actual equipment performance.[55] Operational ratings can be used to develop outcome-based standard, where compliance (or certification) is established only once the building is shown to perform, in practice, as expected. Figure 14 summarizes these four approaches to energy regulation and provides some examples of each.

Approaches to energy regulations

Prescriptive

Component-specific performance requirements based on climate zone and construction type

ASHRAE 90.1; IECC; NECB; NBC section 9.32 and 9.36

Performance-based

'As-designed' performance assessed using energy models

Reference-building approach

Energy model of proposed design is compared to the energy model of a mock 'reference building' of same shape and function but built to code

LEED, ASHRAE 90.1, IECC; NECB, NBC 9.36.5, Title 24

Fixed-energy budget approach

Energy model of proposed design is compared to an absolute target

Passive House, Minergie, Denmark energy code

Outcome-based

'As built & occupied' performance assessed using actual energy use data

Living Building Challenge; Seattle outcome-based energy code*

Figure 14. Taxonomy of energy efficiency requirements

* Note that the targets for this pilot outcome-based code were set using a reference-building approach; projects were required to meet a total EUI target equivalent to at least 5% less than a modelled code-equivalent building.[56]

Table 5. Metrics for performance-based compliance

Scope	Weighting method
Thermal energy demand: includes energy needed	**Site energy:** energy use at the meter, irrespective of

for heating and cooling. It accounts for gains and losses through the enclosure but not for the efficiency of the heating equipment, ventilation, process or plug loads. Domestic hot water is sometimes included. Also sometimes called 'useful energy.' **Regulated loads:** includes most loads that can easily be affected by design: heating, cooling, ventilation, water heating, lighting, and sometimes, elevators. Details depend on standard use. **Total energy use:** includes all energy consumed in a building, including plug and process loads.	production or transmission loss. Fuels are weighted equally. **Cost:** weight of each fuel type consumed at site based on current utility rates. **Carbon** ($kgCO_{2e}/m^2/yr$): weight of each fuel type consumed at site based on global warming potential of emissions generated on site and at source (for electrical generation and district energy systems)[xii] **Source energy:** weight each fuel type consumed at site based on the efficiency of its production and transmission

3.1 Energy performance of certified LEED projects

LEED is commonly used to incent or require beyond-code energy efficiency and overall environmental performance. Across the U.S., over 40 laws reference LEED for incentives, programs and minimum performance criteria.[57] Several jurisdictions in the U.S. and Canada have LEED certification requirements for public buildings: British Columbia requires LEED Gold for public sector projects,[58] the City of New York requires LEED Silver for municipally funded projects,[59] and various U.S. federal agencies have LEED procurement policies.[60] The City of Vancouver also requires LEED Gold (or Passive House) for commercial rezoning, affecting much of the complex building development in the city.[61]

While LEED has contributed to improving the energy efficiency of the building stock overall, the outcomes met by individual buildings vary significantly. Figure 15 shows the results of a 2008 study reviewing actual energy performance of LEED buildings in the U.S. Of the 556 buildings certified between 2000 and 2006 under LEED for new construction (Version 2), 121 volunteered to participate in the study and provided at least a year of energy data. The study showed that overall the LEED certified buildings had a lower energy use intensity than the national building stock average from the 2003 Commercial Building Energy Consumption Survey (CBECS) (Figure 15 a). It also established that the average savings across the building sample was comparable to the expected average from the modelled performance.[62]

However, the study also showed a wide range of performance across individual buildings. Both the modelled EUIs (Figure 15 b, horizontal axis) and the capacity to meet modelled EUI in practice (Figure 15 b, vertical axis) varied broadly across the 121 buildings. Further statistical

[xii] One could argue that fossil fuel emission factors should include not only combustion at source, but also leakage in distribution and upstream emissions, though that is generally not the case.

analysis showed that on average LEED buildings used 18% to 39% less energy per floor area than their conventional counterparts (depending on building type), but that 28% to 35% of LEED buildings used more energy than their conventional counterparts. Furthermore, the actual energy performance of these buildings had little correlation with their certification level or even the number of energy credits achieved by the building at design time.[63]

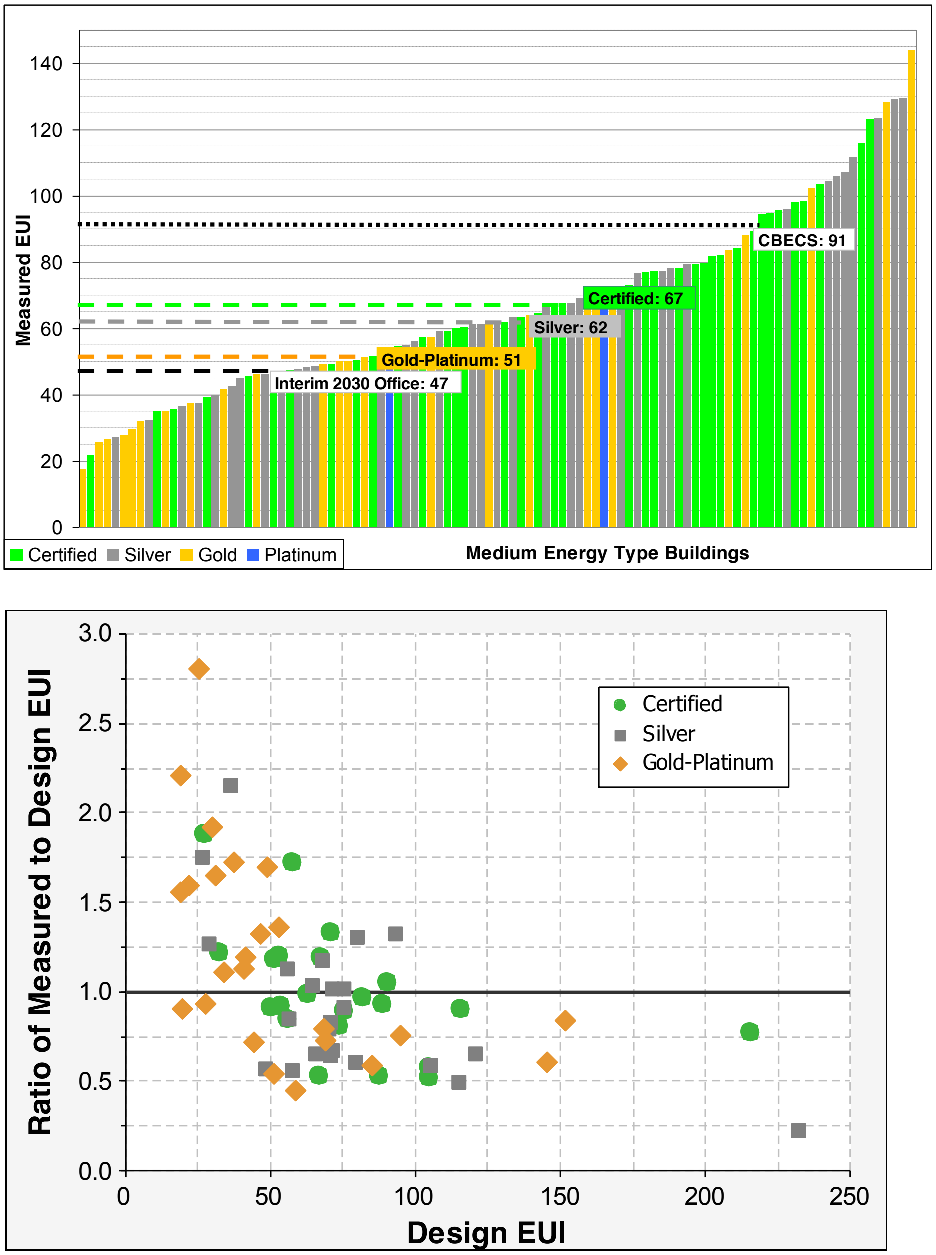


Figure 15. Perspectives on the actual performance of 121 LEED buildings: (a) range of measured EUIs and (b) comparison of measured and design EUIs.

On (b) the horizontal spread illustrates the variability of expected performance, and the vertical spread illustrates the performance gap between modelled and actual performance. (EUIs expressed in kBt/sf; 1 kBt/sf = 3.14 kWh/m^2/yr)

Source: Turner and Frankel[64]

Box 5. LEED certification

Leadership in Energy and Environmental Design (LEED) is a widely recognized building rating system that rates green buildings using a point scoring system, where points can be achieved for a variety of priorities including sustainable sites, water use, energy efficiency and indoor air quality. The accumulation of points across the various criteria determines what level of certification is achieved, ranging from Certified to Platinum.

To this date, four LEED versions have been introduced in the U.S. (three in Canada). Points are granted for energy performance based on a 'percent better than code' methodology outlined in ASHRAE 90.1 appendix G. The Canadian version allows proponents to use this method, or a comparable approached outlined in the National Energy Code for Buildings (NECB).

The latest LEED version, LEEDv4, requires energy efficiency 5% below ASHRAE 90.1-2010, with additional points awarded for better performance—up to 18 points for a 50% improvement over 90.1[65]. Figure 16 illustrates how energy performance requirements have increased over the current, and previous two, LEED systems. Furthermore, energy efficiency counts for more of the total number of points in the latest two iterations (18-20%) compared to the first version (14%), indicating that energy efficiency is becoming more important in the LEED rating system. Energy performance requirements are expected to increase in the future. The USGBC have set net-positive energy buildings as a vision for future versions of LEED. However, target dates or pathways to achieve this have not yet been published.

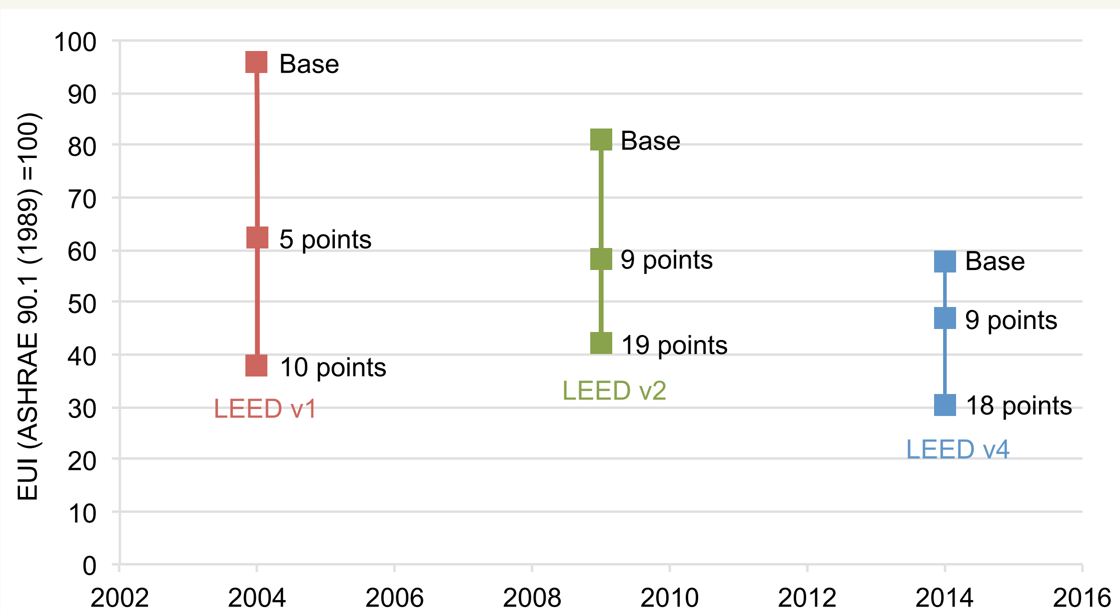


Figure 16. Evolution of LEED energy performance credits

EUI based on ASHRAE 90.1-1989. Each icon represents the assumed energy performance depending on the number of points for energy (out of 100 total). LEED NC1 has been normalized to a 100 point scale (70 in reality). For LEEDv4, most buildings can achieve 18 points from a max 50% improvement in energy performance; however, hospitals can gain up to 20 points for a 50% improvement in energy performance.

Data source: LEED Reference Guide 2004, LEED Reference Guide 2009, LEEDv4 for Building Design and Construction

This study showed that LEED can deliver energy savings at a societal level (i.e. looking at the averages of the buildings), but that the overall reduction potential is limited because of inconsistent outcomes across individual buildings. This inconsistency should also be of concern to owners and managers, who might not see energy benefits manifest as expected.

This study is almost ten years old now and unfortunately there has not been another comprehensive study comparing actual and modelled energy use in building required to meet beyond-code performance. So while there has been two major reversions of LEED since (v3 and v4) and ten years' worth of innovation in green building design, it is difficult to know if the issues raised by the 2008 study have since been resolved. However, there are some fundamental challenges with the 'percent better' cost-based methodology of ASHRAE 90.1 that limit its potential in reducing energy use and greenhouse gas emissions:

1. **EUIs of the reference buildings vary widely**. The energy use intensity of the reference buildings for the 121 projects reviewed in the Turner and Frankel study vary by almost an order of magnitude, ranging from 25 to 200 kBTU/sf (~75 to 625 kWh/m^2) (Figure 17). Even for a given prototype, varying some basic design options (HVAC system type, fuel source, roof type, etc.) can lead to variations of up to 13% in the final energy performance of the resulting reference building. With such varying baselines, aiming for an 'percent better' improvement will yield a correspondingly wide range of final performances (and energy savings, Figure 18).[xiii]

2. **Normalization of massing dis-incentivizes passive design**. Because the building shape is kept constant between the baseline and proposed models, the reference-building approach offers no incentive for optimizing form in order to reduce heat loss.[xiv]

3. **Thermal bridging is underestimated.** The energy standards referenced by LEED (NECB, 90.1) do not effectively address major thermal bridges such as slab edges, shelf

[xiii] This variability is also a strength of the reference-building approach; by allowing baselines to reflect some of the 'natural' variability in energy demand between different building types and location, it can offer a fairer distribution of effort. See discussion at the end of next section.

[xiv] ASHRAE 90.1-PRM (appendix G) does grant credit for optimizing orientation. The baseline has a fixed window-to-wall ratio, and the same fenestration orientation as the rated building, but it is modelled in four rotations and the average is used as the comparator. "A Classification of Building Energy Performance Indices," Table 3. Credits are also given for shading devices such as overhangs and blinds, as long as they are automated.

angles, parapets, window perimeters, etc. This is significant, since the contribution of these details can result in the underestimation of 20% to 70% of the total heat flow through walls.[66]

4. Baseline standards are focused on cooling-dominated climates. Being a consensus-based standard, AHRAE 90.1 reflects the concerns and priorities of its collective 'center of gravity.' Historically, it has tended to focus more on reducing cooling loads than heating load. Comparing 90.1-2010 with the Canadian NECB-2011, for example, shows the latter to place much more onus on provisions that affect heating, e.g. insulation, heat recovery, furnace/boiler efficiency.[67]

5. Energy saving strategies focused on mechanical systems. Most LEED buildings have tended to rely more on complex mechanical systems than on enclosure to achieve the energy cost savings required for certification. Mechanical systems require proper maintenance and operation to achieve the expected energy savings, and are more susceptible to under-performance due to user/operator error or improper maintenance.[68]

6. Cost methodology conflicts with GHG reduction objectives. The fact that the performance path is based on minimization of energy cost (rather than energy or GHG emissions) prioritizes electrical savings over other fuel types. In jurisdictions where electricity has a lower greenhouse gas intensity profile than natural gas, this bias works against GHG reduction objectives.[69]

These challenges don't negate the energy benefits of LEED projects; as discussed above, the 121 projects reviewed in the 2008 study still had average energy consumption 18% to 35% lower than their typical contemporary counterparts. But they do point to ways in which the 'rules of the game' could be better aligned to drive deep and predictable reductions in energy use and greenhouse gas emissions. Figure 17 and Figure 18 illustrate the wide variation in baselines and outcomes when considering a "reference-building" approach such as LEED. Uncertainty around the reference and realized performance of these buildings illustrates the value of a fixed energy budget approach, such as that used in the Passive House standard.

To test the assertion that a greater focus on passive design could help address some of these challenges, the next section provides a compilation of studies that monitored the energy performance of passive buildings in North America and Europe.

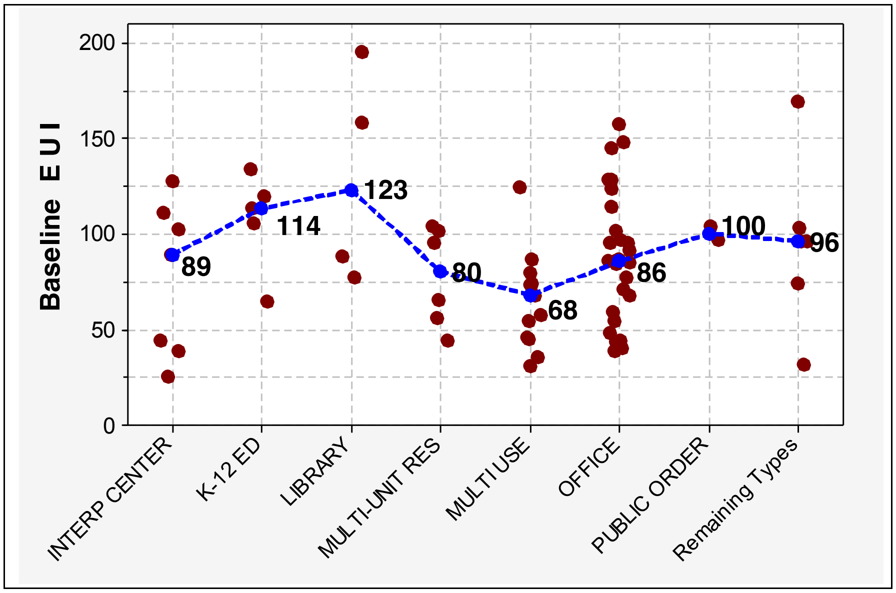


Figure 17. EUIs of the reference building for 121 LEED projects, by building type.

The dotted line marks average values. (Y axis gives Total EUIs in kBTu/sf, calculated by adding 25% riser on the regulated EUI to account for un-regulated loads).

Source: Turner and Frankel[70]

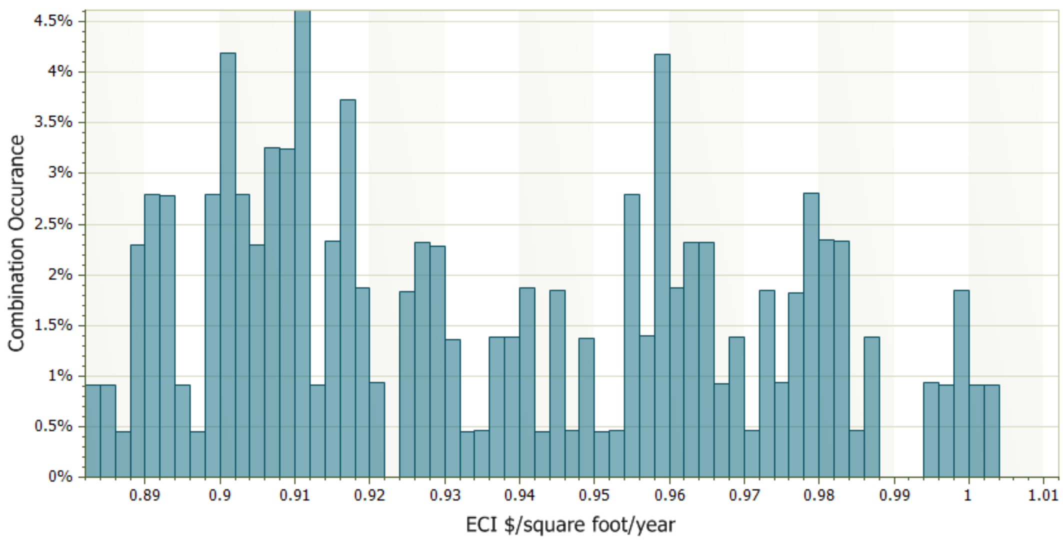


Figure 18. Range of energy outcome for 216 prescriptive options for a medium office building in zone 5A

While most design parameters were held constant, only five building parameters (HVAC system design, HVAC fuel type, Roof type, wall construction, window construction, and window-to-wall ratio) were varied to creating 216 possible medium size office buildings compliant with the prescriptive requirements of ASRHAE 90.1-2013. Energy cost intensities (ECI) for these 216 compliant designs vary by 13%, which is significant given that almost twice the energy savings were expected from transition from the 90.1-2010 to 90.1-2013.

Source: Rosenberg et al[71]

3.2 Energy performance of passive buildings

Like most energy codes and green building certifications, Passive House certification is based on 'as designed' performance: i.e. it requires the design team to show through energy modelling that, under standard operating conditions, the project should meet certain comfort and energy performance criteria (see Box 1 and Appendix A). Passive House certification does not require verification that the buildings actually meet these targets in operation.[xv,72] This raises the question: are Passive House buildings actually meeting their energy targets? Or is there, like for many LEED buildings, a significant gap between 'as designed' and 'as built and operated' performance?

To answer this question, we compiled results from a range of monitoring studies that tracked actual energy use in passive house projects in Europe and North America. For each project, we

[xv] The Living Building Challenge certification and Seattle's outcome-base compliance option are the only two programs (we know of) to require verification that targets are met not only 'as designed', but also 'as built and operated,' based on actual energy consumption after at least one year of occupancy.

compare the modelled and measured annual thermal load intensity (Table 6) and, when available, their total site energy use intensity (Table 7). To get a sense of the energy performance gains this approach can offer, we also compare these to the performance of similar buildings in the U.S., using as benchmark the median thermal load intensity of buildings of the same type and in the same climate zone in the 2009 Residential Energy Consumption Survey (RECS-2009; see Appendix E)[73] or the 2012 Commercial Buildings Energy Consumption Survey (CBECS-2012).[74]

Table 6. Measured and modelled annual thermal load intensity for passive buildings

Project		Climate zone	Annual thermal load intensity (kWh/m_{CFA}^2)[a]			Energy reduction compared to RECS-2009 average[b]	
			Modelled	Measured	Difference	Baseline (kWh/m_{CFA}^2)	% Reduction
Single family detached							
LeBois House, LA[75]	Heating	2A	8.8	0.66	-8	11	94%
	Cooling		16.5	11.6	-5	22	56%
Sonoma House, CA[76]		3C	7.3	5.9	*-1*	48	88%
Nebraska Passive House, OR[77]		4C	4.2	1.0	*-3*	41[e]	98%
Hood River Passive House, OR[78]		4C	13.9	13.4	*-1*	40	66%
Smith/Klingenberg Passivhaus, IL[79]		5A	7.3	9.7	*+2*	48	80%
Passive House Gaigg, AT (2 units)[80]		5A	17.3	30	*+13*	48	38%
Passive House Fügenschuh, AT (2 units)[81]		5A	13.6	22.7	*+9*	48	53%
Passive House Kitzbichler, AT[82]		5A	13.6	23.6	*+10*	48	51%
Passive House Krätschmer, AT[83]		5A	18.2	25.5	*+7*	48	47%
Passive House Samerberg, DE[84]		5A	12.7	29.6	*+17*	48	38%
Passive House Prantl, DE[85]		5A	12.7	32.0	*+19*	48	33%
Urbana Passive House, IL[86]		5A	22.9	15.5	*-7*	48	68%
Denby Dale House, UK[87]		5A	13.6	18.8	*+5*	79	76%
Single family attached							
Wiesbaden/Dotzheim, DE[88] (46 units)	average	5A	11.8	12.2	*+0.4*	59	79%
	min	5A	11.8	5.0	*-7*	59	92%
	max	5A	11.8	24.6	*+13*	59	58%
Hanover/Kronsberg, DE[89] (32 units)	average	5A	12.3	11.6	*-1*	59	80%

min	5A	12.3	2.8	*-9*	59	95%
max	5A	12.3	29.1	*+17*	59	51%
Stuttgart/Feuerbach, DE[90] (52 units) average	5A	12.3	11.6	*-1*	59	80%
min	5A	12.3	2.6	*-10*	59	96%
max	5A	12.3	24.1	*+12*	59	59%
Nuremberg/Wetzendorf, DE[91] (4 units) average	5A	12.6	10.4	*-2*	59	82%
min	5A	12.6	6.2	*-6*	59	90%
max	5A	12.6	13.8	*+1*	59	77%
The Linda's project, SE[92]	5A	15.5	19.1	*+4*	59	68%
Mid-rise						
Frankfurt, DE House A[93] (9 units)	5A	9.5	9.6	*+0.1*	47	80%
House B (10 units)	5A	13.5	13.2	*-0.3*	47	72%
Bahnstadt District, Heidelberg, DE (1000 units)[94] average	4A	9.6	14.9	*+5.3*	47	68%
min	4A	9	9.3	*+0.3*	47	80%
max	4A	7.5	24.2	*+16.7*	47	49%
Others						
Playing on the Passive House Hill, kindergarden, DE[95]	5A	14.7	13.6	*-1*	36	62%
Reidberg Passive House school, DE[96]	5A	14.7	13.2	*-2*	36	63%
Passive House Dental Clinic, VA[97]	6A	2.7	2.7	*0*	84[c]	97%

Notes:

a. Certification under Passive House Institute uses a European definition of Treated Floor Area (see Appendix A) to define energy densities; Treated floor area discounts several spaces generally included in conditioned (or heated) floor area. For a more accurate comparison with the RECS-2009 averages, which are expressed relative to heated floor area, we've assume TFA is 10% smaller than CFA and adjusted all heating demand intensity accordingly.

b. Averaged over all survey entries for the same building type in the same climate. The thermal load demand is estimated as: total heating BTU (kBTU) x 0.8 (to remove average equipment heating inefficiency) ÷ heated floor area (sqft) x 3.14 (kWh/m^2 per kBTU/sqft).

c. Average from CBECS-2012 for outpatient healthcare buildings in climate zone 6A.

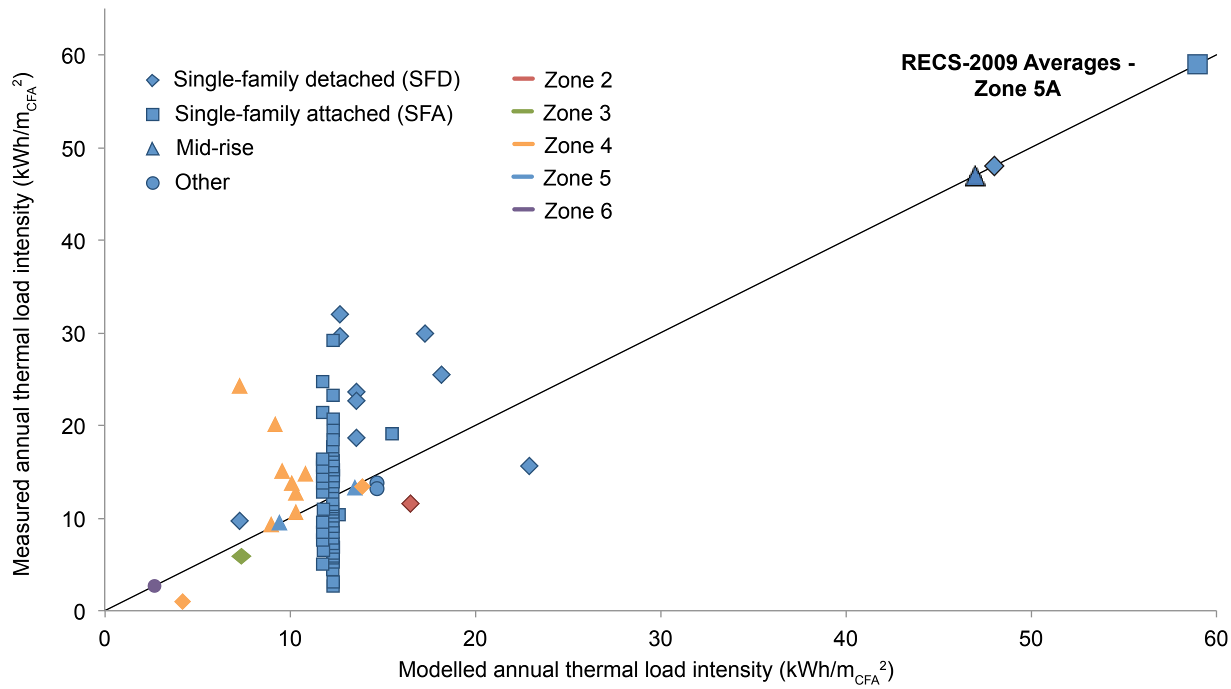


Figure 19: Comparison of measured to modelled thermal load intensity (TLI) for passive buildings.

The majority of buildings surveyed were located in climate zone 5A; the 2009 Residential Energy Consumption Survey (RECS) averages for this zone are shown to represent a typical U.S. building's performance in this climate. For most of the monitored project, the measured thermal load was within 10 kWh/m^2 of the modelled load. The average thermal load intensity (across all available measurement points) was 15.5 kWh/m^2: a 68% reduction from the RECS average. Points appearing in a vertical line result in cases where monitoring data is available for several individual units but the modelled thermal load intensity is only available for the buildings as a whole (and assigned as a default 'modelled' value for each unit).

Data sources: various, see references in Table 6.

Table 7. Measured and modelled annual site energy use intensity for passive buildings

Project	Climate zone	Annual site energy use intensity (kWh/m$_{CFA}^2$)			Energy reduction compared to RECS-2009 average[a]	
		Modelled	Measured	Difference	Baseline (kWh/m$_{CFA}^2$)	% Reduction
Single family detached						
Denby Dale Passive House , UK[98]	5A	79.1	96.4	*+17*	161	40%
Urbana Passive House, IL[99]	5A	102.0	79.8	*-22*	161	50%
Hood River Passive House, OR[100]	4C	63.6	28.9	*-35*	151	81%
Nebraska Passive House, OR[101]	4C	24.2	33.8	*+10*	151	78%

Sonoma House, CA[102]	3C	37.5	33.0	-5	151	78%
Single family attached						
Stellar Passive House Apartment Building, OR[103]	6A	48.6	55.9	+7	178	69%
The Linda's project, SE[104]	5A	33.2	35.6	+2	178	80%
The Orchards at Orenco Station. OR[105]	4C	66.0	66.3	+0.3	132	50%
Bernhardt Passive House, BC[106]	4C	48.2	67.4	+19	149	55%
Mid-rise						
Frankfurt, DE[107] House A	5A	57.9	57.5	-0.4	173	67%
House B	5A	57.9	63.3	+5	173	63%

Notes:

a. Averaged over all survey entries for the same building type in the same climate. The thermal load demand is estimated as: total heating BTU (kBTU) x 0.8 (to remove average equipment heating inefficiency) ÷ heated floor area (sqft) x 3.14 (kWh/m^2 per kBTU/sqft).

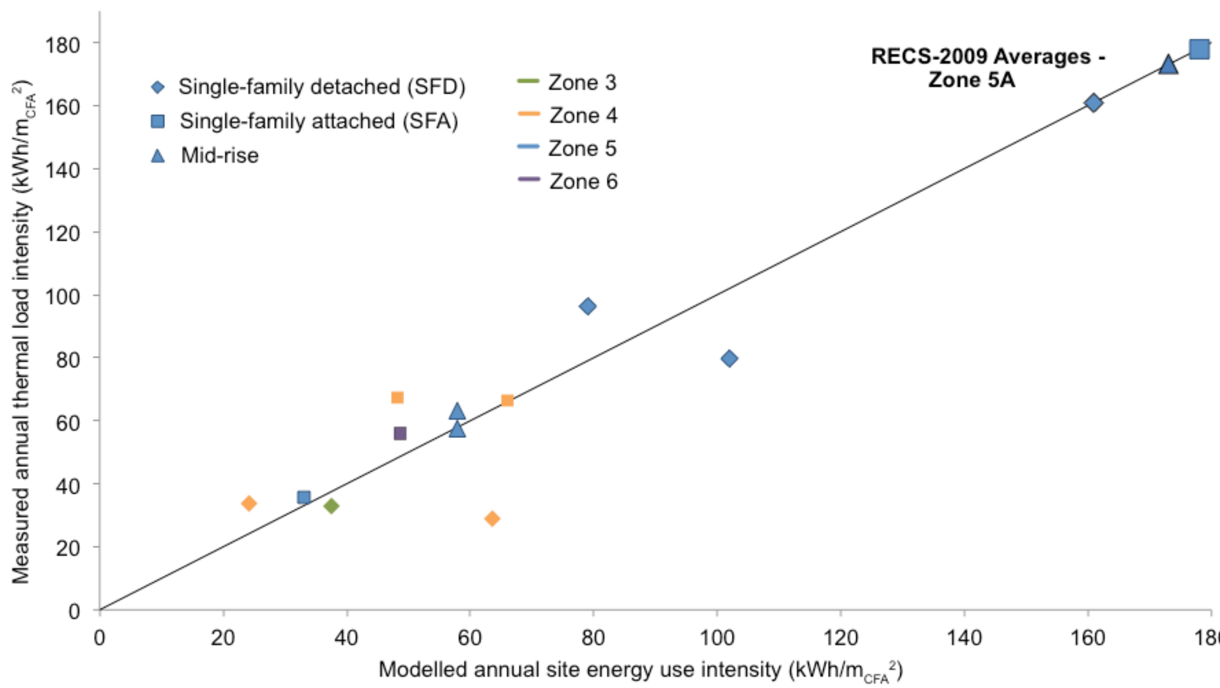


Figure 20. Comparison of measured to modelled site energy use intensity for passive buildings.

The majority of buildings surveyed were located in climate zone 5A; the 2009 Residential Energy Consumption Survey (RECS) averages for this zone are shown to represent a typical building's performance in this climate.

Most monitoring studies we could find were for ground-oriented and mid-rise buildings. For the majority of these projects, the actual energy use for heating was within a few kWh/m^2 of the modelled target. Given the diversity of studies considered here, this is a comforting result. A few saw significant departure from 'as designed' values, with variations of up to 20 kWh/m^2. In most of these cases, studies attributed the difference to occupant behaviour, mostly resulting from temperature set points being higher than in the modelling (the Samerberg and Prantl houses, for example, had thermostats set up to 3°C warmer).[108] Some studies showed that the gap could be reduced over time as occupants familiarized themselves with the functioning of the house and systems were commissioned.[109, 110]

Table 7 presents available data on the total energy use in passive buildings. Not surprisingly, there is more divergence between modelled and actual energy consumption. In only three cases, however, was the actual use greater than the modelled prediction, by up to ~20 kWh/m^2 annual, less than 15% of the RECS average EUI for single family homes in climate 5A. Total reduction in energy use range from 40% to over 80%.

Because of the lack of published monitoring data, it is difficult at this stage to comment on the performance of non-domestic passive projects. The three projects for which we could find monitoring data — a kindergarten, a school and a dental clinic — (Table 6) performed as modelled or better. Case studies published to date (see references in Section 2.2) showed a range of designs which met certification criteria, but we do not know how these buildings have performed in operation. It would also be useful to review projects that have opted for a passive design approach, but could not meet the fixed energy budget targets. It is worth noting that the certification process allows for some adjustment of the energy budget for buildings that have important additional loads (water heating in swimming pools, for example).[111]

Fixed-budget vs. reference-building approach

Distinct from the technical merits of passive design, but intertwined because of the structure of certification criteria, is the question of whether a 'fixed-budget' approach to energy regulation (i.e. based on maximum energy targets (Table 5)) is preferable to a reference-building approach (i.e. based on a 'percent better' than a prescriptive code). We discussed in the previous section how the reference-building approach led to a very broad range of EUIs for the reference buildings, and therefore uncertainty about the energy outcomes of a 'percent better' approach. This variability can also be considered a strength of the reference-building approach, allowing it more flexibility to address complex cases. By allowing baselines to reflect some of the 'natural' variability in energy demand between different building types and locations, it might also offer a fairer distribution of effort. Hitting fixed-budget targets, by contrast, might be much easier in certain context than others; so while it provides more clarity and predictability, it might create an uneven effort between projects of different types (though it still ensures that competing proposals for a given project face an even playing field). This challenge can be mitigated by clarifying exemption mechanisms, as did for example the City of Brussels when they adopted a passive standard in 2015 (see Section 9.4). Another approach might be to define fixed-budget targets for most common building types, and rely on a 'percent better' approach for other projects.[xvi]

Because it does not depend on an evolving prescriptive code, the fixed-budget approach can facilitate energy code development. The targets can be adjusted over time without requiring the creation of a new prescriptive code. This also makes it much easier to track code evolution on the way to long-term targets set by various jurisdictions, whether it is aiming for nearly zero, net-zero or net-positive buildings (in carbon, or in energy). The proposed adoption of ASRHAE 90-1-2004 as the baseline for all future 'better than code' performance program based on ASHRAE 90.1 would also help to simplify code development by providing a fixed baseline to build from.[112, 113]

Both of these solutions would, however, decouple entirely the evolution of performance-based approaches from the prescriptive codes. The consensus-based approach to prescriptive energy code plays an important role in defining an acceptable 'common ground' based on current market conditions.[114] This was the rationale behind using it as a baseline from which to define a 'better than code' increment. It is, however, a slow-evolving process. As policy and market pressure drive innovation, the number of technical solutions for energy efficiency is growing rapidly. The time will come (if it has not already) when the detailed cataloguing of acceptable solutions in a consensus-based prescriptive code will become impossible. Already, the predominance of LEED certification in various markets makes the use of energy modelling a de facto necessity, and this will only grow as environmental objectives drive for higher performance and greater transparency in the market. As the number of technical solutions becomes too large to codify, energy modelling might also become a requirement for compliance. This would allow the considerable efforts currently invested in maintaining prescriptive energy codes to be redirected toward the creation of design guidelines, providing support for builders but not meant to be legally binding compliance documents.

Selection of energy metrics

As performance-based design and compliance becomes more common, the selection of the energy metrics to be measured against will become more important than whether the

[xvi] This is the approach currently being considered in the creation of stretch code for British Columbia (under development).

thresholds are defined based on a fixed-budget or a reference-buildings approach. As discussed in the previous section, the cost-based approach of ASHRAE does allow optimization of economic benefits for owners, but it does not align well with environmental objectives as the cost of natural gas in most jurisdictions is much lower than that of renewable power. Targets based on carbon intensity use would be better suited to drive design towards reduced emissions, whether through efficiency or fuel switching. Primary energy use can also be used to factor in the relative merits of different fuels, though it fails to include the significant global warming potential of methane leakage in the transmission and production of natural gas.[115] The primary energy renewable metric recently introduced by Passive House Institute aims to better incorporate losses associated with storage of renewable energy, and therefore to benefit strategies that align demand for energy with availability of local renewables in order to minimize storage requirements.[116] It does, however, pose an obvious communication challenge.

Setting caps on thermal load intensity, as done by the Passive House standards, drives design towards optimization of the building enclosure, in terms of both reducing heat loss and optimizing solar gains. The existence of another metric for cooling (or for thermal comfort) ensures that the potential negative impact of solar heat gains on cooling loads is also considered (see Section 0). This is a positive outcome, and one which would gain to be more broadly adopted. It does, however, pose certain methodological challenges. First of all, one cannot measure thermal load; it has to be inferred from energy use, which requires making assumptions about the fraction of energy used for heating, and about the inefficiency of the heating equipment. Second, it requires standards to set strict modelling guidelines for factoring internal heat; otherwise, thermal load targets could easily be met by a greater fraction of heat provided 'for free' by internal heat sources. For compliance purposes, therefore, certain internal heat gains have to be assumed.[xvii,117] If these are very different from the expected internal heat gains, a different model should be used for design in order to ensure proper sizing of equipment and that the building will operate properly. This, therefore introduces further drift between compliance energy models and 'best guess' predictive energy models, further complicating design and analysis of performance data. While this is a fairly common problem with the use of energy modelling for compliance purposes, it is one that would be preferable to minimize. Both of these factors also make it more complicated to provide benchmarks for thermal loads, as neither energy use surveys nor modelling prototypes commonly report thermal load.[xviii]

[xvii] PHI recently modified its internal heat gain assumptions, to correct the fact that previous assumptions (based solely on floor area) under-represented internal heat gains in smaller unit sizes.

[xviii] In Table 6, we've approximated heat load intensities from RECS and CBECS data by using their thermal energy use data and assuming an average equipment efficiency ratio of 0.8. We were not, however, able to use the DOE

To mitigate some of these challenges, it would be useful to develop (or adopt) standard procedures for the estimation of thermal load from energy data, to integrate this metric in Energy Star portfolio manager and develop plug-ins to standardized its calculation in commonly used energy models.

prototype results, which would have provided a more useful benchmark based on modelled 'built to code' buildings, because their internal load assumptions were not in line with the assumptions made in PHPP models. Because internal gains in these building were assumed to be quite high, the fraction of heat to be provided by the heating systems was quite low (comparable to Passive House metrics, in some cases). This is not because the enclosures were of passive house quality, but simply because of different internal gains assumptions. An 'apples to apples' comparison would have required setting internal loads comparable to those assumed by certification requirements.

4. Incremental costs

Summary

- Passive buildings incur some additional construction costs due to the higher quality of components, increased insulation requirements, and additional detailing required. Some savings also result from smaller and simpler heating systems. Like for other innovative buildings, interviews with practitioners reveal that the incremental costs and risks of cost over-runs decrease after the first few projects.
- The majority of costing studies and construction estimates report that the cost increment of building to Passive House standards is less than 10%, with the average value being around 6%.
- Economic life cycle analysis has shown that residential passive houses could return net present value benefits to both builders—via increased sales cost— and buyers—via energy and maintenance cost savings; though the economics will vary based on location. More studies are needed to estimate the potential for ongoing maintenance cost savings, as well as replacement cost savings, as these are expected to decrease with higher quality components and simpler systems. These savings could be significant, particularly for institutional and commercial projects.
- The cost increment of Passive House construction is likely to decrease as industry capacity builds, as the supply chain for high-performance components improves, and as regulatory barriers are removed.

Higher quality windows and doors, additional insulation, high efficiency HRVs, and additional time for design and labour increase the construction costs of Passive Houses. However, reduced costs for heating systems due to smaller loads can offset some of that cost. Given the limited number of detailed costing studies done to date, it is difficult to accurately characterize the magnitude of these additional costs and cost savings. One often quoted rule of thumb pegs these additional costs at about 7–10% of construction costs, though costing studies and estimates by builders report a much wider range (Table 8).

Relatively few studies have explicitly estimated the piece-by-piece incremental cost of upgrading from a code-compliant building to a Passive House, and these studies are by nature location-specific, as both the construction cost of the 'minimum code compliant' building and the cost of higher performance components will vary. Other estimates compare the construction costs for the passive building as a whole to the average construction costs for similar building types. This approach provides a less accurate estimate of the cost of the energy efficiency measures, as the total cost reflects other design decisions, but it provides a good illustration of what can be achieved within given budget constraints.

Table 8 summarizes the data we could find on incremental costs. The method for estimation is not always explicitly stated in the source, but we have provided for each our best understanding of the baseline the cost increments were compared against.

Table 8. Summary of estimated construction cost differences between Passive House and conventional buildings

Buildings analyzed	Location	Cost increment	Costing methodology
Single family detached, duplexes			
13 duplexes, two triplexes, one quad	Maine, U.S.	0%	Actual cost comparable to standard construction costs[118]
Single family home (A)	Vancouver, B.C., Canada	2% to 7%	Detailed costing study. Estimated incremental cost compared to range of construction costs for house built to Vancouver building bylaw.[a]
Single family home (B)	Vancouver, B.C., Canada	3% to 8%	Detailed costing study. Estimated incremental cost compared to range of construction costs for house built to Vancouver building bylaw.
Duplex (Bernhardt residence)	Victoria, B.C., Canada	2.8% hard costs 4.6% soft costs	Detailed costing study. Actual cost of PH project vs estimated cost of same home built to common practice[119]
Single family home	Lower Mainland, B.C., Canada	7.5%	Detailed costing compared to a B.C. building code compliant home[120]
Single family home	Germany	8%	Estimated cost compared to German average[121]
Single family home	Nelson, B.C., Canada	10%	Actual cost, compared to standard construction costs[122]
Single family home	Belgium	16%	Estimated construction cost compared to estimated cost of same house built to code[123]
Single family home	Oregon, U.S.	20%	Estimate cost of additional enclosure + HRV measures compared to 2009 IECC requirements; not counting savings in HVAC system[b]
Single family attached			
Terraced (20 units)	Gothenburg, Sweden	0%	Costing methodology unknown[124]
Six-plex (North Park)	Victoria, B.C., Canada	3.5%	Detailed costing study. Budgeted cost compared to estimated cost of same building built to common practices[c]
Terraced (5 units)	Lucerne, Switzerland	10%	Costing methodology unknown[125]

Terraced (32 units)	Hannover, Germany	12%	Includes cost of solar water heater (exact costing methodology unknown)[126]
Terraced houses (14 units)	Wimbish, U.K.	12%	Actual costs compared to estimated cost of same building to code[127]
Low-rise (2-storey, 6 units)	Gnigl, Austria	0%	Includes cost of solar water heater (exact costing methodology unknown)[128]
Three low-rise (354 units total)	Innsbruck, Austria	5%	Compared to typical construction costs (estimated by housing agency)[129]
Low-rise (27 units)	Vienna, Austria	5%	Actual costs compared to actual costs of a low-energy building in same development[130]
Two low-rise (40 units)	Kassel, Germany	8%	Includes additional cost of PV array (exact costing methodology unknown)[131]
Two low-rise (10 units)	Wolfurt, Austria	8%	Includes cost of solar water heater (exact costing methodology unknown)[132]
Four low-rise (31 units)	Halleing, Austria	7%	Includes cost of solar water heater (exact costing methodology unknown)[133]
Low-rise (6-storey, 40 units)	Rennes, France	10%	Includes cost of solar water heater (exact costing methodology unknown)[134]
Two low-rise (3-storey, 73 units)	Darmstadt, Germany	10%	Estimated incremental cost above conventional cost of construction for low-rises in Germany[135]
32 affordable housing projects	Pennsylvania, U.S.	2%	Quoted construction costs of PH projects vs quoted costs of non-PH projects[136]
Mid-rise MURBs			
Mid-rise, wood-framed	Vancouver, B.C., Canada	0% / 4%	Estimated incremental cost above LEED requirement for rezoning / above Vancouver Building Bylaw base requirement[d]
Mid-rise, wood-framed	Vancouver, B.C., Canada	<7%	Detailed costing study compared to average construction cost[e]
Mid-rise, concrete	Vancouver, B.C., Canada	<7%	Detailed costing study compared to average construction cost[f]
Mid-rise, wood-framed	Ottawa, O.N., Canada	8-9%	Estimated cost increment above code requirements[137]
High-rise MURB-			
26-stories, 500,000sf, concrete, 37% fenestration.	New York, U.S.	results pending	Detailed costing study. Estimated cost compared to estimated cost of same building built to LEED Silver (requirement in NYC)[138]
Non residential[139]			
Office tower, concrete core w/ timber frame facade (Energon Offices)	Ulm, Germany	-20%	Actual construction cost compared to typical construction cost for offices in Germany

Office mid-rise, masonry (Lu-Teco Offices)	Ludwigshafen, Germany	0%	Actual construction cost compared to typical construction cost for offices in Germany
School (Aufkirchen)	Munich, Germany	0%	Actual construction cost compared to typical construction cost for schools in Germany
Big box retail (Tesco)	Waterford, Ireland	5%	Actual construction cost compared to typical construction cost for big box stores
School (Kalbacher Höhe)	Frankfurt, Germany	5.3%	Actual construction cost compared to estimated construction cost for a 'low energy school' in Germany

Notes:

a. Case Study House 1 is a two-storey house with a small third-storey mezzanine; GFA 3,215 sf, TFA 2,335sf. Incremental costs estimated at CAD$6.5/ft^2, 2-7% range based on range of baseline construction costs ($100 to $250 per ft^2). Total increment when considering land value was less than 2%. Building envelope costs were estimated to be 15% to 20% higher for Passive House, but mechanical cost were estimated to be 30% to 40% lower.[140]

b. Incremental costs estimated at USD$63,089 (out of a total budget of ~$320,000) but do not include savings due to equipment downsizing and if central forced air ducts are assumed in the base case and eliminated from the project house.[141]

c. Increment for total soft costs (construction and design): +4.1%[142]

d. Incremental cost for passive design over base requirements in Vancouver were estimated by the builder as 4% of construction cost. However, because rezoning was required, the building needed to meet a LEED gold standard. Typical approach to meeting the energy requirements is to use high efficiency natural gas boiler and hydronic systems. These systems have a similar cost (~CAD$8/sqft) than the passive strategy employed here, and therefore there was no net cost increment. Given the higher energy efficiency gains, the building is expected to meet LEED Platinum relatively easily.[143]

e. Incremental costs estimated at CAD$11.55/sqft ; assuming a $200/sf average construction cost for mid-rise in Vancouver.[144]

f. Incremental costs estimated at CAD$15.33/sqft assuming a $200/sf average construction cost for mid-rise in Vancouver.[145]

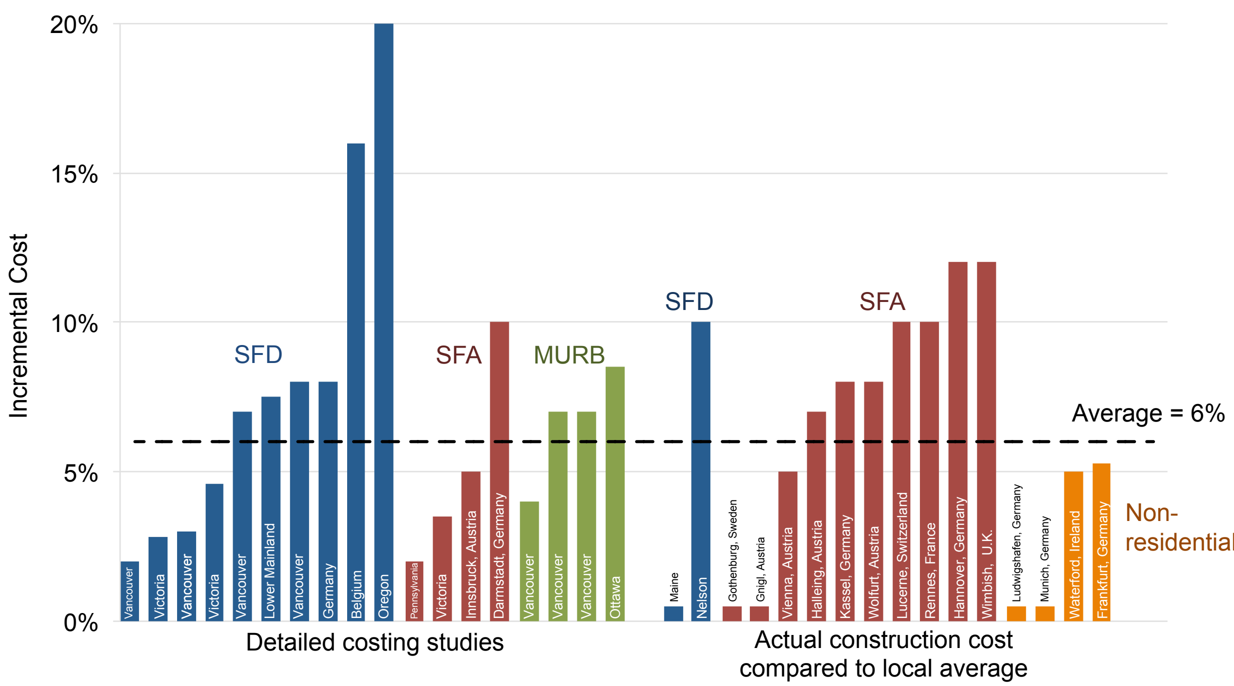


Figure 21. Estimated construction cost increment of passive buildings.

This figure illustrates the cost increments stated in 33 published costing estimates for different building types. Some are based on component-by-component cost increment estimates, compared to a 'built to code' or 'built to common practice' baseline; others are based on overall per-square foot construction costs, compared to typical construction costs for similar project in the area. The former is more rigorous, and often conducted by firms specialized in costing estimates, while the latter is more informal, based on builder and architects' professional judgment. Both methods involve uncertainty, and should be considered with caution. The average incremental cost, based on all studies, was about 6% of construction cost. Note that the baseline assumptions for what 'normal' construction practices (and associated costs) vary by location, and from study to study. See Table 8 for details. One outlier with an estimated negative incremental cost of 20% was not included.

These studies give a wide range of incremental costs, ranging from cost decreases of 20% to increases of up to 20%, but the majority report cost increments below 10%. Some of this variability will be due to material differences between projects (design choices, maturity of market for high-performance components, etc.), and some is certainly methodological (varying baselines being the most obvious, but also whether estimates include potential system cost savings, and possible trade-offs made by builders.).

Nevertheless, some general observations can be made on costs based on these study and observation of the market:

- For the most common building types (residential, offices, schools, etc.), there are several examples of passive house buildings built within typical budget for a given market. While there is generally an incremental cost for the additional energy efficiency measures, these costs can be minimized through design, and the remaining marginal cost can be offset through savings in other design features.
- As of August 2016, there were over 35 mid-rise residential passive buildings built (or in construction) for market and non-market housing in North America (Figure 11). Costing studies and anecdotal evidence indicate that incremental construction costs for these can be absorbed within typical construction budgets.
- Incremental costs for residential projects are mostly due to the added insulation and framing for the enclosure (~50%), windows and doors (~25%), HRV and ventilation (~15%) and about ~10% of miscellaneous energy conservation measures (lighting, shading, DHW, etc.). Alongside these additional costs, projects can see a reduction in cost for heating equipment covering about a third of those additional costs. Two studies also estimated additional soft costs (architecture, certification) at about ~20% of total incremental costs.
- Several projects (and their costs estimates) include on-site renewable systems, which add significant additional costs to the basic passive house enclosure package. Separating these costs would provide a better estimate of the energy efficiency measures.

- Cost is greatly reduced during design process by ensuring that massing, orientation, fenestration, and landscaping are optimized for passive heating, cooling and minimization of thermal breaks. An integrated design that includes early energy modelling can influence architectural decisions that lock in many of these passive elements.

While many of these studies estimated expected annual energy costs savings, only a few conducted a more thorough analysis of life cycle costs. A 2015 study by RDH Engineering assessed the business case for a Passive House six-plex in Victoria, B.C., from the builder perspective and from the homebuyer perspective.[146] Considering the added costs of energy efficiency measures, they show that the builder would require a price premium of ~2.5% to get a return on investment comparable to that of a regular building.

For buyers, on the other hand, energy savings would not return a positive net present value unless the price premium was less than 2%.[xix] The additional investment did return a positive net present value, however, if costs savings included an estimated ~$50/month (CAD) reduction in maintenance fees due to the simpler and more durable components installed in a passive house. In that case, the investment would return a positive net present value even if the price premiums were as high as 8%, showing that there is a wide range of possible sale price premiums (between 2.5% and 8% of construction costs) that would return net present value benefits to both builders and buyers.[xx,147]

[xix] This assumed utility rates and carbon taxes remained constant for the next 20 years and therefore certainly underestimated the savings as rate increases have already been scheduled and carbon pricing increases are likely.

[xx] An upcoming costing study being conducted for the New York State Energy Research and Development Authority will also include estimates of maintenance cost saving. It will review the business case for a (fictional) 26-storey concrete passive house MURB in New York City, considering capital, operational, and maintenance over 30 years.

Table 9. Breakdown of incremental capital costs for seven residential passive house projects

	SFD in Portland, OR[a]	SFD in Vancouver, B.C. 1[b]	SFD in Vancouver, B.C. 2[b]	Duplex in Victoria, B.C.[c]	Sixplex in Victoria B.C.[c]	4-6 storey multifamily in Vancouver, B.C.[d]	
						wood frame	concrete
Baseline construction cost $/sf$_{GFA}$	-	$100-350	$100-350	$156	$176	$175	$220
Additional costs $/sf$_{GFA}$	$26.7*	$9.9	$10.2	$14.0	$15.3	$11.2	$15.3
Cost savings $/sf$_{GFA}$	Not estimated	$3.8	$3.8	$5.3	$5.9	Not estimated	Not estimated
Net incremental cost $/sf$_{GFA}$	-	$7.0	$6.4	$8.7	$9.4	-	-
Net Incremental cost (% of construction cost)	-	3%-8%	2%-7%	5%	5%	< 7%	<7%
Baseline description	BEoptE+	VBBL	VBBL	BCBC	BCBC	VBBL	VBBL
Cost increment breakdown[e]							
Insulation & external enclosure	64%	59%	58%	54%	24%	21%	37%
Air tightness	9%	Not estimated	Not estimated	(included above)	13%	2%	2%
Windows & doors	12%	32%	31%	19%	23%	24%	18%
HRV & Ventilation	5%	9%	11%	-38%	21%	46%	33%
Heating system	Not estimated	-30%	-37%		-39%	Not estimated	Not estimated
Soft costs	Not estimated	Not estimated	Not estimated	28%	19%	Not estimated	Not estimated
Other	9%[f] (lighting/ shading)	-	-	-	-	7% (lighting/ DHW)	9% (lighting/ DHW)
Additional costs total	$53,599*	$31,829	$25,400	$54,000	$77,330	$134,400	$184,000[g]

Cost savings	-	$9,480	$9,480	$20,500	$30,000	-	-
Net incremental cost	$53,599*	$22,349	$15,920	$33,500	$47,330	-	-

Notes:

* USD. All other values in CAD

a. Hales, D. (2014, January). *Hood River Passive House* (Rep.) http://www.nrel.gov/docs/fy14osti/60999.pdf

b. *The Economics of Passive House - Project 4229.070* (March 8, 2016). RDH Building Science Inc. Red Door Energy Design.

c. *The Business Case for Passive House*. (2015, May 27). http://www.ryanhamilton.ca/Client/0052-SSi/PH_BusinessCase_2015.pdf

d. *Carbon Neutral 4-6 storey Multifamily Buildings – Project 7814.037* (March 18, 2016). RDH Building Engineering Ltd.

e. Expressed as percent of total *additional* cost

f. The project also included a domestic solar hot water system which cost $9490; to facilitate comparison with the other project we removed this from the incremental costs.

g. Calculated from cost per sf for a 12,000 sf building.

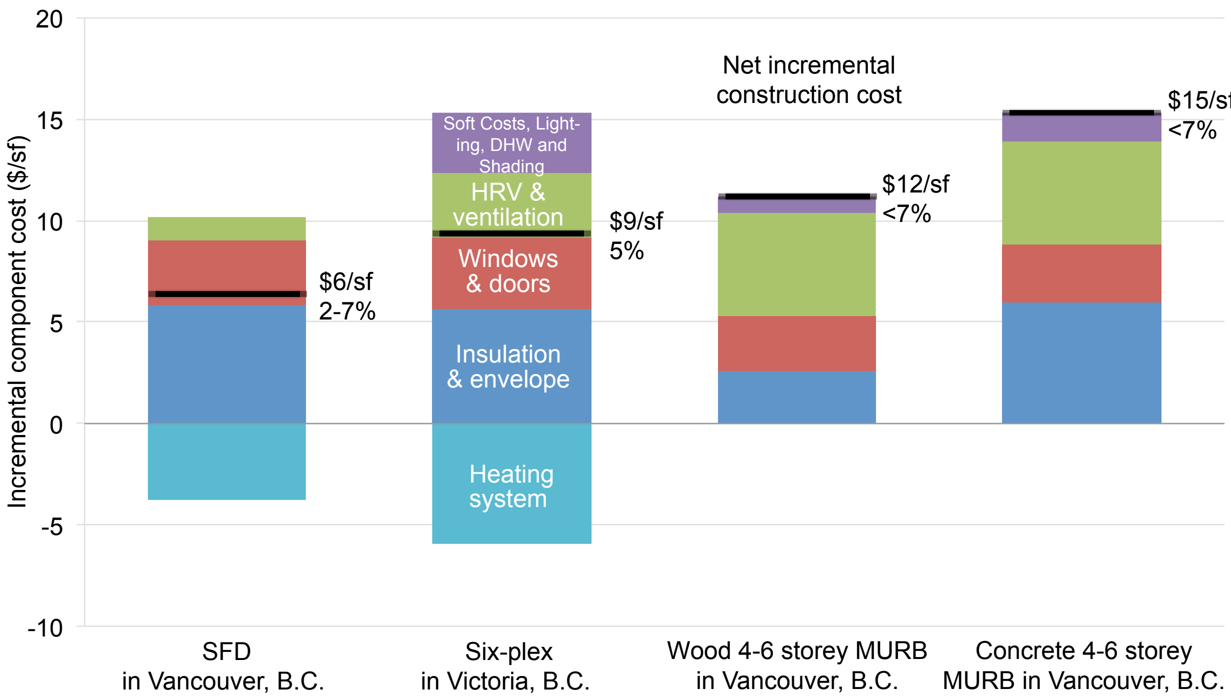


Figure 22. Estimated breakdown of incremental capital costs for passive buildings in four costing studies in B.C.

Note that the two MURB studies (on the right) mentioned there would likely be cost saving compared to standard constructions as well (e.g. smaller heating system), but did not estimate them.

5. Moisture control in highly insulated buildings

Summary

- Moisture concerns must be managed for all wall assembly types, but because increased insulation and airtightness reduces the capacity of walls to dry out, super-insulated walls reduce the margin for error. The amount, type, and location of insulation must be carefully selected to suit local climate and indoor conditions. More attention must also be given to wall details design (i.e. junctions between assemblies, roof-wall interface, penetrations, etc.) to ensure continuity of the water and air barrier and to minimize thermal bridges. Judicious use of vapour retarders and careful consideration of the permeance of sheathing membranes and outboard insulation is needed to enable some drying to both sides of the wall. Material selection also becomes more important to increase moisture tolerance.
- Many strategies for reducing moisture penetration (airtightness, elimination of thermal bridges, high quality fenestration, proper ventilation) overlap with those for achieving high thermal performance. Through careful design, detailing and review of these elements, passive buildings both reduce energy demand and improve durability by reducing the risk of moisture damage.
- Field measurements in inhabited houses and in testing facilities have shown that current construction best practices for thick walls perform generally well, even in the moist and rain-heavy Pacific Northwest.
- The Pacific Northwest is arguably a world leader in the management of moisture in enclosures, and there is significant research, engineering, and construction capacity in the area that can be called upon to assess new walls systems as they emerge, and to train trades and builders to design and construct durable, healthy thick wall systems. However, these best practices might not be common knowledge across the construction industry today.
- There are several design guides for high-performance wood-frame construction that can be used to train residential low-rise builders. There are fewer resources for high-rise and commercial buildings, but expert advice is available for this segment from enclosure engineers.

Accumulation of moisture in walls can occur because of leaks or condensation and can lead to mould growth and decay of structural components. To protect health of occupants and durability of the enclosure, wall assemblies must be designed to avoid moisture penetration and allow drying in case penetration occurs. Moisture control can be an issue in all buildings, but there is a common perception that moisture issues are exacerbated in highly insulated buildings. In reality, good detailing, air sealing, and ventilation strategies associated with passive design can provide effective moisture control and help the industry address these issues.

B.C.'s 'leaky condo crisis' of the 1990s brought into sharp focus the importance of proper moisture management in all types of construction; it also led to considerable change in construction practices and ongoing research and innovation on enclosure performance. This legacy provides a strong foundation to build from as we consider the possible mainstreaming of super-insulated building enclosures (Box 6).

Box 6. Leaky condo crisis: lessons learned and legacy

A major construction scandal through the 90s and continuing to this day,[148] the leaky condo crisis required the refurbishment of hundreds of buildings after water penetration led to rotting and degradation of building enclosures. In B.C. alone, over 900 buildings and up to 50,000 units were affected; at an average cost of about $20,000 per unit, the total cost of repairs was estimated at over $1 billion (CAD). The damage was focused in the Lower Mainland of B.C. — in part due to its very wet climate, in part because of the rapid development it saw in the 1980s and 1990s — but similar wall problems were observed across Canada[149] and in the Pacific Northwest.[150]

The Barrett inquiry commission was appointed in 1998 to review the causes of the crisis, to understand financial and social ramifications, and to recommend measures to ensure consumer protection and accountability in the construction industry going forward.[151] It concluded that "significant building enclosure failures in British Columbia since the early 1980s … is a result of numerous factors, including design features inappropriate for our climate; a reliance on face-sealed wall systems; a fundamental lack of awareness regarding the principles of enclosure design suitable for our climate; meaningful inspection at critical stages of construction; and a regulatory system which was unable to understand that failures were occurring and to redress them."[152]

The commission and other initiatives taken during the crisis led to ongoing research and to significant changes in construction practices and warranty provision.

Impact on construction practices

Study of leaky buildings revealed the main source of moisture to be rain penetration at the edges of claddings, windows, balconies and parapets, with subsequent infiltration through gaps in the weather barriers.[153] Commonly used face-sealed wall system (without a drainage cavity) lacked a means for water to escape, allowing it to seep into the walls. Ongoing wetting and lack of drying in the summer season led to rot and delamination of exterior wall cladding and sheathing, rusting in metal wall studs, rot in the wood structure, saturation of batt insulation, and development of mould and spores inside the walls and building interior. Most of the affected buildings were low-rise, three- to four-storey buildings framed in wood, but some were of steel, concrete, and metal stud construction types, including high-rises.[154]

These technical issues were addressed in subsequent revisions to building codes. The Vancouver Building bylaw (in 1996) and B.C. Building Code (in 2006) were modified to include specifications for drained rainscreen construction. Subsequent studies have highlighted the importance not only of preventing wetting, but also enabling drying, and recommended further changes to rainscreen designs to protect the sheathing from humid ventilation air, to enhance drying, and to increase the safe storage capacity of moisture sensitive materials.[155] Design guides were published by CHMC to provide guidance regarding good detail design and construction.[156,157]

The Vancouver Building bylaw and B.C. Building Code also added requirements for enclosure engineers to be involved in reviewing wall designs. This, and the introduction through the 1998 Homeowner Protection Act of a builder certification process, significantly facilitated adoption of better practices by the industry.

Impacts on warranty provisions

The leaky condo crisis also led to important changes in the structure of home warranties and accountability for construction, creating further incentives for the construction industry to adopt best practices.

At the height of the crisis in April 1999 the New Home Warranty of British Columbia & Yukon, the main source of warranties against construction defects for B.C. homebuyers, collapsed. This was a voluntary warranty program created by the residential construction industry in the seventies. At the time, approximately 60% of all new housing units were carrying warranty protection. This warranty failure led to a second inquiry commission, which recommended 100% compensation up to $25,000 per unit for repairs, with costs to be shared equally between the provincial government, the federal governments and the B.C. condominium construction industry.

In response to the crisis, B.C. implemented the Homeowners Protection Act in 1998. It was designed to protect homebuyers and improve the quality of residential construction by requiring certification of builders and a third-party warranty with minimum coverage of two years on labour and materials, five years on the building enclosure and 10 years on the structure of the home.[158]

Depreciation reports (a.k.a. reserve fund studies) were made mandatory in B.C. in 2011 (earlier in most other Canadian provinces),[159] providing a mechanism for the regular assessment of enclosure performance.

Impacts on training and research

The Homeowners Protection Act also established the Homeowner Protection Office (HPO), responsible for licensing builders, monitoring the provision of compulsory third party home warranty insurance, and providing ongoing research and education in building science.[160] Just a few years before, the Canada Mortgage and Housing Corporation created the Building Envelope Research Council (BERC) to act as a coordinating agency for the research of building enclosure problems and to change industry practices in Canada.[161]

Funding and infrastructure provided by the BERC and HPO contributed to the establishment of a solid research and engineering ecosystem in B.C. (FPInnovations, RDH, Morrison Hershfield, BCIT, UBC, etc.). This research infrastructure, alongside with the requirement for home builder certification and code requirements for building engineers, has significantly increased capacity and sophistication of the enclosure construction industry in Canada and particularly in the Pacific Northwest, making the region a global leader in the field.

Before we dive into the specifics of how high-performance enclosures such as those used in passive houses should be designed to avoid potential moisture issues, we find it useful to provide the reader with a basic introduction to the management of moisture risks. Note that this section is written primarily for the context of temperate humid areas, though some of the principles will apply also to warm humid areas. While high-performance enclosures require careful design of wall, glazing, roof, and basement (as well as the interfaces between these assemblies), for brevity, we focus the following discussion primarily on wall assemblies.

5.1 Moisture in building enclosures: the basics

Water leakage, high humidity levels and condensation within wall or roof assemblies can lead to mould growth and assembly decay. These durability risks depend on the balance between wetting, drying and moisture redistribution, as well as on the capacity of the wall materials to safely store moisture (Figure 23). Ideal conditions for mould growth vary by species, but most thrive between 20° and 35°C and a relative humidity in the range of 75% to 95%. The rate of wood decay also depends on the fungus and tree species, but onset generally happen when the moisture content of the wood product is above 26% (at or near fibre saturation point).[162]

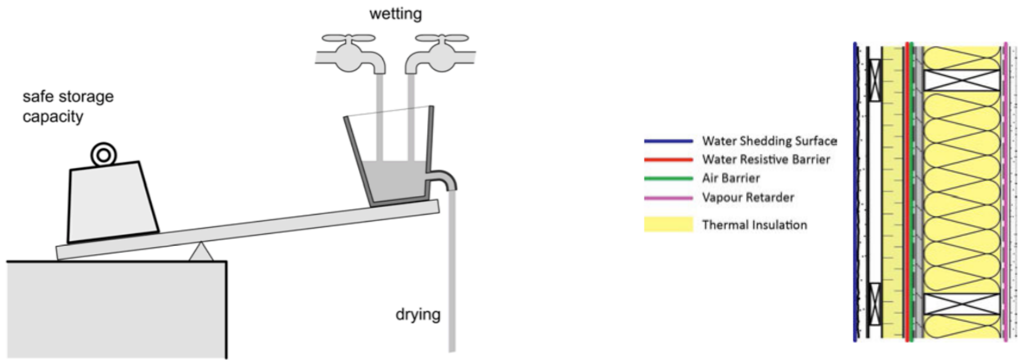


Figure 23. (a) Moisture risk schematic (b) Wall assembly cross section

The schematic (a) shows that moisture risk varies with the risk of wetting, drying capacity, and the water-holding tolerance of the wall assembly.

The wall assembly cross-section (b) shows, from left (outside) to right (inside): the rainscreen assembly consisting of the cladding (used for water shedding), drainage cavity (air gap allowing penetration or condensate to escape), and water resistive barrier (e.g. Tyvek, which similarly to Gore-Tex is impermeable and watertight, but allows water vapour to exit the wall). In this wall, some external insulation is added between the cladding and the water/air barrier, protecting the sheathing from the cold and thus reducing the risk of condensation. Next is the sheathing (typically plywood or oriented strand board), the wall cavity filled with insulation (e.g. batt, blown cellulose, spray foam), followed by drywall and a vapour retarder (e.g. poly or vapour-retarding paint), which reduces diffusion of moisture into the wall cavity during colder months.

Sources: Smegal and Straube; City of Vancouver and HPO[163]

There are five basic ways in which moisture can accumulate in an enclosure; each is mitigated by different strategies (Table 10).

Table 10. Moisture entry points and management strategies

Risk of moisture entry	Principal mitigation strategy
Rain penetration: rain enters the wall due to a failure in the outside cladding.	Exterior cladding, careful detailing of interfaces, drainage cavity to allow any penetration/condensate to leave the wall, and water resistive barrier to protect sheathing and interior wall elements
Condensation because of air leakage: moist air (from inside in winter, from outside in summer) enters the enclosure and condenses at a cold interface.	Air barrier detailing
Condensation because of vapour diffusion: even without air penetration, vapour can enter the wall through diffusion and condense at a cold interface.	Vapour retardant to prevent diffusion of interior moisture into the wall in cold climates
Site wetting: wall components may get rained on and	Protection of materials on construction site

enclosed into the wall assembly before they can dry.[xxi]	Drying to the interior after installation of water barrier and before drywalling
Plumbing issues: small plumbing leaks and more dramatic incidents (overflowing tub, fire sprinklers, etc.) can brings water into the enclosure	Drying by moisture diffusion to the outside and/or inside wall

Beside the role of air barriers and vapour barriers, the location and type of insulation also plays a key role in avoiding water damage. Greater levels of insulation means less heat transfer through the wall (the desired effect); however, this also decreases the temperature on the outside of the wall during the heating season, thus increasing the risk of condensation at the sheathing. This risk can be mitigated by moving some of the insulation to the outside of the sheathing, thus protecting it from the cold (see below).

5.2 Wood frame construction

There is a significant amount of research on wall assemblies for low and mid-rise wood frame buildings, providing a range of acceptable options for high-performance enclosures. The Province of B.C.'s Homeowner Protection Office recently published an illustrated design guide to R-22 effective walls; it provides guidance to meet the new 2014 Vancouver Building Bylaw requirements (R-22 effective), but also includes strategies to meet much higher insulation values (up to R-60 effective). The guide was informed, amongst other sources, by the research of Smegal and Straube, who evaluated 17 assemblies types for the Pacific Northwest climate providing whole wall R-values ranging from R-12 to R-37.[xxii,164] They scored each assembly on thermal control, durability (including both wetting prevention and drying capacity), ease of construction, cost, and material use (considering both the amount of materials needed, and their embodied energy). Heat flow and hygrothermal performance were analyzed using computer software and field studies.[xxiii] Table 11 summarizes key moisture management

[xxi] Water logging during construction is particularly an issue in the Pacific Northwest, where it is often not practical to schedule construction for dry periods. Traditional 'stick and frame' construction generally allows enough time for timber and other components to dry to the inside after the rain barrier is installed, but the increasing use of pre-fabricated wall units can increase the risk of moisture staying in walls, as panels are sometimes left out in the rain on site. Cellulose dense-pack insulation, a commonly used insulation product, also has relatively high humidity levels and must dry after installation.

[xxii] Whole wall R-value includes not only the effective R-value of each of the wall assembly components (including basic framing) but also the effect of thermal bridges of all additional structural elements (e.g. double studs, attachments, etc.), and typical enclosure interface details, including wall/wall (corners), wall/roof, and wall/floor.

[xxiii] THERM 5.2, a two-dimensional steady-state finite element software package developed by the Lawrence Berkeley National Laboratory at the University of California, was used for thermal analysis, and WUFI from the Fraunhofer Institut Bauphysik was used to determine the hygrothermal performance of the chosen wall systems, using climate

considerations for the four most common wall systems included in the R-22 guide. Some of their main characteristics and challenges are discussed below.

Benefits and risks of different wall systems

A commonly used strategy for highly insulated walls is the use of **deep cavity walls**, either using double stud walls or prefabricated I-joists (Table 11). These have the advantage of using a form familiar to most framers; the additional framing materials, however, make them a more expensive option than split insulation walls.[165] They also result in overall thicker walls, which may lead to reductions in the interior floor area if the exterior dimension of the buildings are constrained by property dimension and zoning (although this can be mitigated by proactive thick-wall exclusion policies; see Section 9.3).

From a durability perspective, the increased level of insulation with deep cavity walls increases the risk of condensation at the sheathing, but only if adequate airtightness is not achieved and thermal bridges are not eliminated. Field research conducted in Southern Ontario measured the moisture content of different assemblies as they were injected with indoor air at rates meant to simulate air leakage that could result from common construction practices; over the course of a year, moisture accumulation in deep cavity walls led to thousands of hours of high-temperature high-humidity conditions needed for mould growth, as well as thousands of hours with moisture contents favourable to decay.[166] It should be noted that total mould growing hours were also high on the upper plate of the typical 2x4 wall assemblies.[167]

These results show how critical air barrier details are to deep cavity wall systems, as they rely on airtightness to mitigate this condensation risk. It should also be noted that these tests were conducted in Southern Ontario and that climates with more temperate winters (and summers) might see the risks of condensation (and mould growth) further reduced.

The risk of condensation at sheathing and plates can be effectively mitigated by adding rigid insulation on the outside of the sheeting, such as in **split-insulated wall systems** (Table 11). Split-insulated walls tested in the Ontario study mentioned above performed exceptionally well.[xxiv,168] Some of these rigid insulation materials (e.g. extruded polystyrene (EPS), expanded polystyrene (XPS), and polyisocyanurate (PIC), however, have very low permeability, which

data for Portland, OR, (zone 4C). The study was also informed by field studies conducted in British Columbia, which has a comparable climate.

[xxiv] They tested and modelled three walls featuring a typical 2x4 cavity covered with an additional ~2 inches of outside insulation (extruded polystyrene (EPS), polyisocyanurate (PIC), and mineral wool). After a year of (forced) inside air exfiltratation, these walls showed no significant moisture accumulation, risk of mould growth, or risk of decay.

decreases the wall drying capacity. This increases the risk of moisture being trapped in the cavity in case of a failure of the rainscreen or other penetration (e.g. plumbing incidents). To allow drying to the outside, use of a more vapour permeable insulation material, such as rigid mineral wool or fiberglass, is recommended. Mineral wool (e.g. Roxul) is particularly effective as it is also hydrophobic, non-absorptive and moisture tolerant, and can drain if wetted. The vapour permeance of the water and air barrier must also be carefully considered, with breathable materials such as Tyvek contributing to the drying capacity of the system.

A **fully exterior insulated** wall is another option for preventing condensation on the sheeting, but the higher levels of rigid insulation required increase costs and complexity of detailing and construction; this approach is more often seen in retrofit situations but can be applied to new construction as well.

Irrespective of the wall systems, removal of excess indoor moisture is also key in reducing risks of condensation. This is addressed in passive buildings through the design of the mechanical ventilation system (and possible use of an ERV in very humid areas), which should ensure that indoor moisture levels are kept within acceptable bounds for comfort and durability.

A range of site studies confirm that these solutions can perform adequately in the field. Here are brief summaries of relevant studies:

- A 2014 study by FPInnovations assessed the performance of a Passive House home in B.C.'s Lower Mainland. The enclosure featured double-stud walls with an effective insulation value of about R-50 and with the air barrier located in the middle of the cavity, rather than on the outside sheathing. The south- and north-facing walls were instrumented during construction and have been monitored for four years to assess moisture and thermal performance. These measurements showed that the walls performed well, although there may be an occasional risk of moisture accumulation on the north wall.[xxv,169]
- A 2012 study revisited six double-stud houses built or renovated in the Saskatoon area between 1979 and 1992, with nominal insulation ranging from R36 to R60. New blower door tests indicated that the airtightness of these houses had not decreased

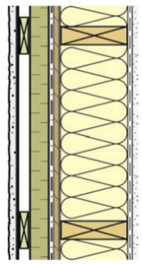
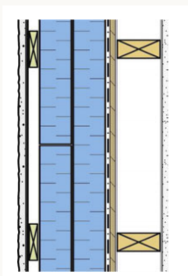
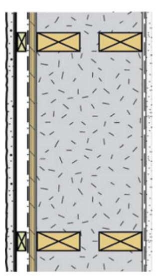
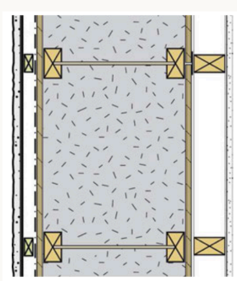
[xxv] Moisture content measured at the bottom of the studs remained generally below 15%, and the relative humidity measured on the interior side of the exterior sheathing ranged from 70% to 90% on the south wall, and from 80% to 100% in the north wall – which could lead to condensation. No steep vapour pressure gradients were observed between any specific layers, indicating the overall vapour permeable nature and good drying performance of the wall design. In the south-facing wall, a vapour drive was observed in the summer which should have good drying potential if wetting occurred. On the other hand, the partial vapour pressures were largely consistent across the north-facing wall, not showing a strong vapour drive from interior to exterior in this mild climate. The exterior sheathing would have poor drying performance if wetting occurred in this location because of condensation.

significantly over the years, and moisture content measurement taken at the bottom plate of north walls (most likely areas for water damage) were mostly below 20%, indicating proper moisture control in the wall.[170]

- A large study from the late 1980s and early 1990s that included 24 energy-efficient houses was conducted in Winnipeg, Canada. Assemblies included standard 2x6 wood-frame walls, 2x6 walls with rigid fiberglass or XPS outer insulation, double walls, and 2x6 walls with additional interior insulation. No substantial moisture accumulation was found in those building enclosure systems during the three-year monitoring period, and the more energy-efficient houses generally performed better than the less energy-efficient houses.[171]
- Similarly, a recent study of the first German Passive House, built in Darmstadt 25 years ago, revealed no sign of moisture build-up in the house.[172]

This is not an exhaustive list; there is a large body of literature available on this topic, covering not only walls, but other important enclosure components such as basements and roofs.[173] Nevertheless, these studies provide confidence about the long-term durability of highly-insulated wood-framed walls, at least in the cold and dry prairies (climate Zone 7A) and in mild Germany (climate Zone 5A). Field studies in the wet-temperate Pacific Northwest and in the mixed climate of central-eastern Canada and U.S. are more recent, and provide some confidence but also early warnings of possible complications with deep cavity walls. Further field studies are currently under way at the B.C. Institute of Technology, with results expected in 2017.[174] The University of British Columbia is also setting up a new high-performance thermal insulation laboratory, which will increase research capacity.[175]

Table 11. Key moisture management considerations for high-performance assemblies

Assembly type	Description	Key considerations
Split insulated 	Rigid or semi-rigid insulation placed on the exterior of a conventional insulated 2x4 or 2x6 wood-frame wall assembly.	The vapour permeability of exterior insulation and air/water barrier should be carefully considered (along with the interior vapour control strategy) so as not to intolerably reduce the ability of the assembly to dry. The use of thicker layers of external insulation (> 1") reduces vapour condensation but tends to increase the complexity of detailing around windows, doors and other penetrations.
Exterior insulated 	Rigid or semi-rigid insulation placed on the exterior of a conventional un-insulated 2x4 wood-frame wall assembly.	The method of cladding attachment is important to limit thermal bridging through the exterior insulation while adequately supporting the exterior cladding. The use of thicker layers (> 1") tends to increase the complexity of detailing around windows, doors and other penetrations.
Double stud wall 	Deeper cavity created by an additional framed wall installed to the interior of a conventional wood-frame wall; cavity filled with batt insulation, blown-in fibrous insulation, or spray foam insulation.	Decreased exterior sheathing temperature increases the risk of condensation and related damage: continuity of the outside air barrier and installation of an inside air barrier are necessary. Quality of insulation installation is critical to limiting convective circulation inside the wall.
Deep stud with service wall 	Deeper stud cavity created using deep studs (2x10, 2x12) or engineered wood I-joists (illustrated here). Adds an additional 2x4 service wall on the interior to allow for running of electrical, plumbing, and HVAC services.	As above. Use of the service wall adds an added layer of protection for the integrity of the interior air barrier, but also increase construction costs.

Source: City of Vancouver and HPO[176]

5.3 Non-combustible construction

There is a lot less experience in North America in constructing highly insulated non-combustible buildings. Significant changes would be needed for current design and construction practice to reach Passive House levels of performance, particularly with respect to the elimination of thermal bridges.

Review of failures from concrete constructions during the leaky condo crisis led to recommendations for improvements, most of which are addressed by today's non-combustible high-performance walls. A study conducted in 2000 by RDH Engineering for CHMC and HPO inspected over 100 assemblies in 35 buildings using eight different cladding materials. The results of the study indicate that, similarly to low- and mid-rise wood-frame buildings, the main cause of damage in high-rise buildings was rain penetration at details and at the interfaces between assemblies. It also found that windows were a focal point for moisture problems. Complexity of building form and overhangs, on the other hand, were not found to be a significant influence on performance. Noticeably, none of the walls that incorporated drainage cavities were found to have experienced problems.[177]

Key recommendations for improvement in design and construction practices included the need for better design of interfaces and details, the need for better guidance regarding environmental design loads, and the need for most building to have drained and ventilated rainscreen walls. The role of mechanical ventilation systems in controlling indoor moisture was also identified as an area requiring additional research and better application of known principles.[178]

These strategies and concerns are similar for highly insulated non-combustible walls and most learnings are transferable. This is an ongoing area of work, but significant improvements have been made in the last 15 years to address these issues. The main areas of research and development at the moment have less to do with moisture concern, and more with the cost-effective achievement of high R-value systems. As with wood-frame construction, the use of a continuous layer of insulation on the exterior of the wall assembly is an effective approach to reduce thermal bridging and increase overall thermal performance. In concrete construction, however, metal is typically used for flashings, window frames, slab edges, shelf angles, parapets and cladding attachments creating multiple small thermal bridges which can be responsible for 20% to 70% of the heat flow through walls.[179] Thus, reaching high effective R-values requires reducing the thermal conductance of these components, either by adding external insulation (on window frames, for example), inserting thermal breaks (e.g. fiberglass spacers in cladding attachment systems) or shifting to less conductive materials (e.g. fiberglass window frames).[180]

Ongoing research and piloting is needed to produce low-cost solutions for high-rise MURBs and ensure proper moisture management strategies. Ultimately, the risk of moisture damage in these projects is mitigated by the involvement of enclosure engineers, who should be able to assess the risks posed by different wall systems.

5.4 Conclusion

Moisture concerns must be managed for all wall assembly types, but because increased insulation and airtightness reduces the capacity of walls to dry out, super-insulated walls reduce the margin for error. The amount, type, and location of insulation must be carefully selected to suit local climate and indoor conditions. More attention must also be given to wall detail design (i.e. junctions between assemblies, roof-wall interface, penetrations, etc.) to ensure continuity of the water and air barrier and to minimize thermal bridges. Judicious use of vapour retarders and careful consideration of the permeance of sheathing membranes and outboard insulation is needed to enable some drying to both sides of the wall. Material selection also becomes more important to increase moisture tolerance.

Many of these strategies (airtightness, elimination of thermal breaks, high quality fenestration) are also fundamental to achieving high thermal performance, and have been carefully studied by the passive design community over the last 40 years. Field study of some of the oldest passive buildings have shown that the early designs aged well, providing some confidence for long-term durability — though these are ultimately small samples. Other strategies (location of insulation, breathability, use of moisture-tolerant materials) are more germane to moisture risk management, and might be overlooked if thermal performance is the sole focus. It is rarely economical to build an enclosure with no risk of wetting, so managing the risk is important. It is also, to some extent, a subjective decision requiring compromises between constructability, costs, and moisture management: the ‘right’ balance between these factors will vary based on climate, building use, and the builder/owner tolerance for risk.

The key questions, from a market transformation perspective, ultimately are:

- Is the knowledge of risks and mitigation strategies readily available?
- Are there quality controls to ensure these strategies are properly applied?
- Are there means for builders, inspectors, etc. to get up to speed as the demand for super-insulated buildings grow?

The range of currently available research and examples in the field suggest that the answer to all three questions can be ‘yes’; see below.

Light wood frame construction

Modelling studies validated by field measurement have provided a knowledge base to assess risks for most common wall systems and end uses, and current best practices for wood frame buildings have been compiled in readily available illustrated design guides (Box 7). However, while the general principles for these designs are based on sound building science informed by field testing, not all the proposed wall systems have been field tested at high insulation values. Future research might show that approaches that perform well at R-22 may not perform adequately when insulation levels are increased to reach R-30 and beyond. This is an ongoing area of research, and various labs are setting up site studies to test high-insulation wall systems.

There are, however, strategies that are known to significantly decrease moisture risks. The use of external insulation, for example, has been shown to decrease the risk of condensation on sheathing. Using rigid mineral wool as external insulation also increases drying capacity and provides further moisture tolerance. While outright requiring this approach might be unnecessarily restrictive at this point, policy makers and/or builder education agencies might consider how to steer builders towards these proven approaches until more data is available on alternatives.

Non-combustible construction

The state of knowledge for moisture management in non-combustible concrete and steel constructions has greatly improved following the leaky condo crisis, and many of the techniques developed are transferable to higher performance enclosures. The challenge there is less moisture management than reduction of thermal bridges. Technical solutions are available and generally understood by the industry, but their adoption is limited by demand and construction costs.

Quality control

Certain quality controls must be ensured to avoid problems with highly insulated building assemblies. It would be unwise to require such a level of performance without ensuring these processes are in place. This includes:

- Air barrier testing, with strict airtightness requirements and location of defects during testing
- Proper accounting of thermal bridges and whole wall R-value calculations
- Involvement of a certified professional in the review of the enclosure design, or use of climate-appropriate pre-approved designs
- Field review / testing of new assembly systems

Some experts would also insist on hygrothermal modelling of wall assemblies, at least in hot/humid climates. Some of these quality control mechanisms are ensured by Passive House certification, which provides a useful framework to bring builders up to speed. The involvement of enclosure professionals is already required for complex buildings in many jurisdictions and increasingly common for high-performance single-family residential constructions. As regulations evolve towards passive design, air-barrier testing and accounting for thermal bridges will need to be integrated into building permitting and inspection processes. Air-barrier testing is already required for different building types in Washington State and the City of Vancouver (see Section 10.4); and the methodology for accounting for thermal bridges has been developed and could be integrated into future energy codes.[181]

Capacity

There is significant research and training capacity already in place in the Pacific Northwest, and the number of Passive House trained trades and professionals is growing rapidly (see Section 2.3). Mainstreaming of passive design practices will require a significant scaling up of this training effort. Setting a clear target in advance for when this transition is to occur will allow for a smoother transition. This scale-up could also be supported by the creation of innovation excellence centres focused on training, research, and monitoring that would act as clearinghouses for the dissemination of research results and hubs for ongoing education.[182] See Section 1 for more details.

Box 7. Design guides for the Pacific Northwest

These guides contain examples of thermal resistance calculations, building assemblies, critical interface detailing, and appropriate material selection for above-grade and below-grade walls. They include assemblies meeting minimum requirements of the various energy-efficiency codes and standards in practice at the time, but also expand beyond this scope to include higher performance assemblies such as those used in passive house construction.

Wood frame one and two family homes

City of Vancouver and the Homeowner Protection Office, *R22+ Effective Walls in Wood-Frame Construction in British Columbia.* https://hpo.bc.ca/r22-effective-walls-wood-frame-in-BC

FPInnovations, *Pathways to High-Performance Housing in British Columbia.* https://fpinnovations.ca/Extranet/Pages/AssetDetails.aspx?item=/Extranet/Assets/ResearchReportsWP/3128.pdf#.V7ILpGXmvOQ

Wood frame low to mid-rise

G. Finch, J. Wang, and D. Ricketts, *Guide for Designing Energy-Efficient Building Enclosures in Marine to Cold Climate Zones in North America.* http://rdh.com/wp-content/uploads/2014/07/Guide-for-Designing-Energy-Efficient-Building-Enclosures.pdf

B.C. Homeowner Protection Office, *Building Enclosure Design Guide.* https://hpo.bc.ca/building-enclosure-design-guide

Thermal bridging (multiple building types and climates)

Morrison Hershfield, *Building Envelope Thermal Bridging Guide.* https://www.bchydro.com/powersmart/business/programs/new-construction.html#thermal

6. Cooling and the risk of overheating

Summary

- Well-designed highly insulated enclosures will decrease cooling loads in air-conditioned buildings and improve summer comfort in non-conditioned spaces. The risk of the higher levels of insulation 'trapping in the heat' and leading to overheating can be managed by avoiding over-glazing in south facing walls, shading, and carefully accounting for internal heat gains. Natural ventilation, nighttime flushing, and cool roofs are other passive strategies that can mitigate overheating risks.
- In climates with a long cooling season or high levels of humidity, these passive cooling measures may not suffice to meet comfort criteria, and mechanical air conditioning / dehumidification may be required. Even then, reducing cooling loads by minimizing infiltration and heat transfer through the enclosure through passive cooling strategies will reduce the size of equipment needed, its annual energy use, and its demand on the grid during peak cooling periods.
- In temperate climates, the greater application of passive cooling strategies could counteract the growth in demand for air-conditioning systems. Avoiding "locking-in" high-powered cooling equipment in regions where they have not historically been necessary would help mitigate summer peaks in electricity demand, reduce overall energy demand, and increase community resiliency.
- Passive Houses are not the same as passive solar buildings, which rely heavily on south-facing fenestration to provide winter heating and therefore often overheat in the summer. While solar gain contributes some heating (generally less than a third), most of the winter load is in fact provided by internal heat sources, making Passive Houses much less prone to overheating than passive solar buildings.
- The International Passive House standard requires modelling of ventilation and overheating potential, which ensures that the risks of overheating is at least assessed. As the market embraces high-performance buildings outside of certification programs, safeguards should be put in place to ensure the risks are mitigated. This could be done through prescriptive requirements (e.g. maximal ratios of southern windows to treated floor, shading, operable windows, etc.), or by assessing suitability of thermal comfort

through energy modelling based on comfort criteria defined in standards such as ASHRAE 55, BS EN 15231, and ISO 7730.

Space cooling is a significant use of energy in North America, consuming about 14% of total electricity sales in the U.S.[183] and about 4% in Canada.[184] A southward shift in population in the U.S., an increase in summer temperatures due to global warming, and the proliferation of household electronics are increasing demand for cooling.[185] This in turns increases annual electricity load as well as peak demand; a growing fraction of the continental grid is now summer-peaking. In addition to these grid impacts in cooling-dominated areas, there is also a risk of locking in future cooling demand because air-conditioning systems are more and more being installed in temperate areas where they have historically not been present, such as in the Pacific Northwest.

Increasing the insulation and airtightness of a building enclosure will, in most cases, reduce the demand for cooling (we discuss the few cases where that might not be the case in Box 8). On the other hand, attempts to capture more solar radiation to reduce heating in the winter can increase cooling loads in the summer. This can increase the energy used for cooling (in air-conditioned buildings) and increase the risk of overheating (particularly in non-conditioned, or 'free-running' buildings). A balance must be struck therefore between winter and summer solar gains, which requires a careful consideration of the orientation, size, and transmittance of windows, as well as the use of passive cooling strategies such as shading, air flow, and the reduction of internal heat sources.

The risks of overheating in passive buildings is much more discussed than their direct (and more certain) benefits in reducing cooling load; this might be in part due to the failure of many of the early 'solar home' or earth-ship experiments from the 1970s. Aiming to capture most of their winter heating load from the sun, these homes featured large amounts of fenestration to the south, and as a consequence, poor insulation and high thermal bridging. This combination of high solar gains and poor insulation from outdoor heat led to large indoor temperature differentials and frequent overheating. Lessons have been learned from these early attempts, and most passive designs today feature a different approach, relying less on solar heat gains to reduce heating load than on capturing internal heat sources (and modest solar gains) within a highly insulated enclosure.

To assess both risks and opportunities of passive cooling approaches, we first provide a quick overview of the most commonly used strategies for passive cooling. We then discuss the structures put in place by passive house certification processes to mitigate overheating risks, present some results from monitoring studies and put these in context with social science research on thermal comfort. We conclude by discussing what measures could be integrated into energy codes to mitigate overheating risks in passive buildings, and more broadly.

Box 8. Super-insulated buildings: trapping the heat, or retaining its cool?

We sometimes hear that passive buildings have a higher risk of overheating because they are too insulated and therefore 'trap the heat.' This is mostly a misunderstanding. It can happen, but in relatively rare circumstances.

A well-insulated enclosure prevents the transfer of heat between the inside and the outside. In the winter, insulation reduces heat flow to the outside; in the summer, it reduces heat flow to the inside, keeping the house cool when it is hot out (whether the cool comes from opening windows at night, or from air conditioning).

The only time when higher insulation can be a disadvantage is when the temperature outside is more comfortable than the temperature inside. This can happen in free-running buildings if internal heat sources are large, or if windows are not opened at night, allowing heat to build up over consecutive days.[186] It can also happen in the shoulder seasons when outside temperature are still relatively warm and heat loss through the wall might not suffice to balance these heat gains. For the northern U.S. states and most of Canada, this risk is most severe in October, where the sun is relatively low and shading strategies might be less effective in reducing solar gains. For free-running buildings in temperate areas, this can generally be fixed by opening windows.[xxvi] For conditioned buildings, this effect can extend the length of the cooling season. This extension will increase annual energy consumption, reducing (but very rarely surpassing) the annual gains from reduced in summer cooling loads and winter heating loads.

The risk of fall overheating is particular to buildings with high-performance enclosures. It is a unique problem that will require the attention of builders. But it remains a much smaller problem, both in terms of energy use and potential for occupant discomfort, than summer overheating. If minimal care is given to avoiding large internal loads, the primary impact of increasing insulation is in the vast majority of cases a reduced cooling load and a decreased risk of overheating.

[xxvi] Note that this does not work so well in areas which still have high humidity during the shoulder season, where the house might need active dehumidification in addition to cooling. Mechanical air conditioning might then be required.

6.1 Passive cooling strategies

To maximize sustainability and cost effectiveness, strategies to reduce cooling loads and overheating should be considered in a sequence:

1. reduce heat gains
2. optimize passive heat rejection
3. consider mechanical heat rejection
4. consider mechanical cooling.

Some of the most common passive strategies are:[187]

- **Avoiding over-glazing**: As discussed above, a balance must be struck between optimizing solar gains in winter and minimizing heat gain in the summer. Generally, with a well-insulated enclosure, internal heat gain will provide most of the heat needed, and there is no need for large southern fenestration. The optimal balance for a given climate and building can be found iteratively using energy modelling. Accurate estimate of solar gains requires dynamic hourly modelling, but peak cooling loads can also be estimated using static monthly-modelling models such as PHPP.[xxvii,188]
    - For northern states and southern Canada, modelling shows that a maximum of 3.5–5% of the heated floor area in south-facing windows can be accommodated by the thermal mass provided by typical wood-frame construction.[189] When more glazing is installed, as is often the case when desirable views are to the north, additional strategies will be needed to avoid overheating.
- **Decreasing internal heat sources**: High efficiency appliances and lights decrease electricity demand and cooling loads. Ensuring proper insulation of hot water pipes and boilers will further limit internal heat gains.
- **Low solar gain glazing:** Low-emissivity (low-e) coatings minimize the amount of heat radiated by windows, thus improving their thermal insulation. In addition to optimizing glazing emissivity to reduce heat loss, coatings can optimize its transmissivity to increase or decrease solar heat gain. Low solar gain glazing allows most visible light through, but blocks ultraviolet and infrared radiation, thus decreasing the amount of radiative energy entering the house and decreasing cooling loads.

[xxvii] An analysis tool called the House Comfort Design Checker for Winter Solar Overheating was also developed in the late 1990s by SAR Engineering Ltd. (Burnaby, British Columbia), to estimate appropriate glazing levels. The tool has been refined recently for a study for CHMC, but not publicly released yet.

- **Shading**: Overhangs, louvers, external shades, dynamic glass, and vegetation can be used to provide shade in summer months. Overhang size must be adjusted based on latitude; for northern states and southern Canada, an overhang of one-third to one-half of the window height is recommended. In these regions, the greatest likelihood of overheating will tend to occur in the late fall when outdoor temperatures are still warm and the sun is lower in the sky. During these times, adjustable interior or exterior shading may need to be used. For east- and west-facing windows, vertical exterior shading devices or the use of cooling, low-emissivity coatings are most effective.[190]
- **Nighttime flushing**: Cool air can be drawn indoor by opening windows, using fans, or by drawing air into the return-air plenum of a forced-air heating system.[xxviii] This will lower air temperature at night, and provide cooling for the next day. Flushing is most effective if a certain amount of thermal mass (e.g., cement floor, brick walls) can act as a heat sink and retain the cool throughout the day.
- **Airflow cooling**: Air flowing through the house can also provide cooling. Ventilation rates in most passive buildings are too low to provide airflow cooling but it can be achieved with cross-ventilation driven by wind pressure or stack effect (warm air rising), possibly supplemented by ceiling and task fans.[xxix,191]
- **Cool roofs:** A significant portion of the summer heat gain occurs through the roof of the building as asphalt shingles and other dark roofing materials absorb most of the solar radiation. High-albedo (high-reflectivity) roofing materials decrease the cooling load and the urban heat island effect by reflecting a larger fraction of solar radiation.[xxx,192]
- **Green urban spaces:** Local trees and bushes increase shading and reduce the solar energy absorbed by structures of the urban environment, reducing the urban heat island effect. Green spaces, even if not directly shading the buildings, can reduce cooling loads by reducing urban temperatures and the amount of low-range radiation radiated by surrounding structures.

In climates with a long cooling season or high levels of humidity, these passive cooling measures may not suffice to meet comfort criteria, and mechanical air conditioning / dehumidification may be required. Even then, reducing cooling loads by minimizing infiltration

[xxviii] A bypass feature on some HRVs also allows cool air to be drawn directly indoors.

[xxix] This is not possible in all climates. To be effective, airflow cooling requires air to be moving over the occupants at 1 to 2 m/s, the outdoor air temperature to be 28°C or less, and the relative humidity to be lower than 80%.

[xxx] Title 24 in California regulated the use of cool roof. It was introduced in 2001 as an energy efficiency option, made mandatory in 2008 for non-domestic buildings over 190 m^2, and made mandatory for all new building, additions and alterations above a certain size in 2014.

and heat transfer through the enclosure through passive cooling strategies will reduce the size of equipment needed, its annual energy use, and its demand on the grid during peak cooling periods. In some cases, cooling equipment can be reduced to a few mini-split air source heat pumps combined with an energy recovery ventilator (ERV), which ensures proper ventilation while dehumidifying and cooling incoming outdoor air.

Box 9. Passive cooling strategies in high-rise buildings

Some of the passive strategies outlined above are more difficult to implement in high-rise buildings, but alternatives generally exist. Overhangs would need to be strong enough to resist high winds and can complicate access for window washing. Their protuberance might also clash with the desired visual effect of a clear surface. In these cases, exterior blinds might be a better alternative. Low solar heat gain glass is a practical and cost-effective measure and should be considered, particularly in south-facing units. Dynamic glazing systems, which can change tint (via application of a small electrical current) based on light and temperature, or on demand, are in various stages of development and market readiness and could provide another alternative.[193]

Opportunities for airflow cooling by cross ventilation may be complicated by the fact that units may only have access to one side of the building. On the other hand, the additional height also offers greater opportunities for wind-driven ventilation, as wind increases with height and distance from other large structures. Taller structures also provide the opportunity for stack-effect driven ventilation, but this can cause issues with imbalances in ventilation between suites.[194]

It is not so much the lack of options but the constant effort to minimize construction and design costs that mean that passive cooling strategies are often overlooked in high-rise construction. Natural ventilation in these larger buildings will require more detailed dynamic analysis, but offers opportunities to reduce both fan power and cooling loads. The fact that overheating in south-facing units is very common in curtain-wall buildings, many of which feature floor-to-ceiling windows, highlights the need for greater integration of passive cooling strategies, including the need for better enclosure insulation and for operable windows.[xxxi,195]

[xxxi] Parallel opening and top-tilt windows, in particular, can be an effective and safe source of ventilation in tall buildings.

6.2 Standards for thermal comfort

Standards for thermal comfort such as AHSRAE 55 and the European equivalent EN 15251 offer methods for assessing thermal comfort and the risk of overheating in buildings at the design stage. The method varies depending on whether the building is conditioned or free-running.

For conditioned buildings, the "predicted mean vote" method estimates the percentage of occupants who would rate the building as comfortable for particular combinations of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. Different tolerances are set for different classes of buildings depending on their expectation for thermal comfort.[xxxii,196] This method treats all occupants the same, disregarding their capacity to actively adapt to adjust to different thermal environment, and their possible different climatic preferences. It basically states that the indoor temperature should not change as the seasons do, nor vary depending on where you are in the world.

In contrast, adaptive thermal comfort models are based on the principle that an individual's thermal expectations and preferences are determined by their experience of recent (outdoor) temperatures and a range of contextual factors, including their capacity to control their environment through means such as clothing, operable windows, fans, personal heaters, and sun shades. Research has shown that occupant's perception of their capacity to control their environmental conditions has a significant impact on their rating of thermal comfort.[197] Adaptive models are based on hundreds of field studies, and are commonly used to define acceptable temperature ranges in free-running buildings (Figure 24).[198]

[xxxii] The PMV index represent the predicted 'vote' of occupants rating their thermal comfort on a seven-point scale from cold -3 to hot +3, where zero is the ideal value, representing thermal neutrality. The PMV can also be used to predict the proportion of any population that will be dissatisfied with the environment — the predicted percentage dissatisfied (PPD). The thresholds for different conditioned building classes are set based on either of these metrics: Class A: ±0.2 (PPD ⩽6%); class B ±0.5 (PPD ? ⩽10%); and Class C ±0.7 (PPD ⩽20%).

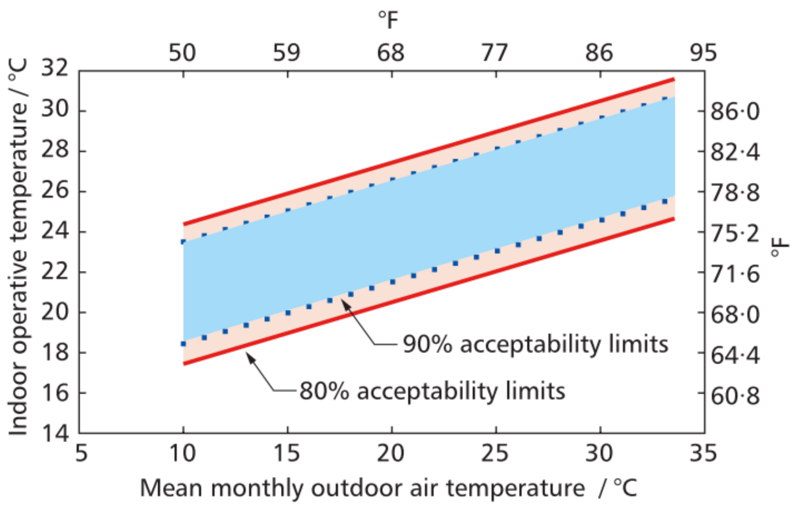


Figure 24. Acceptable temperature ranges for naturally conditioned (free-running) spaces (ASHRAE 55-2010).

Source: CIBSE 2013[199]

6.3 Thermal comfort in certified Passive Houses: monitoring studies

Certification under the Passive House Institute requires designers to show that no more than 10% of hours in a year have indoor temperature above 25°C, while maintaining cooling loads below 15 kWh/m² (with an additional tolerance provided for dehumidification; see Appendix A). The number of overheating hours is estimated using the PHPP simulation model.[xxxiii,200]

This requirement ensures that the risk of overheating is at least considered by the designer and that some mitigating measures are taken. 25°C is a somewhat arbitrary threshold, and should not be regarded as a definition of overheating; as discussed above, research shows that comfort thresholds are more complex, and largely track outdoor temperatures. Thus, this metric should be regarded as a rough design guide. Nevertheless, as 10% of annual hours can be nearly the entire summer, this threshold might be higher than occupant expectations — certainly so in regions accustomed to air conditioning.[xxxiv] By comparison, the 2006 edition of the Chartered

[xxxiii] There is no formal requirement to assess the risk of overheating under PHIUS+2015 certification, though running a three-zone dynamic model as a comfort analysis using WUFIplus (WUFI Passive dynamic side), or another dynamic energy model is recommended (but not required).

[xxxiv] It is possible for builders to size conditioning equipment to meet stricter requirements, even within the limits of the certification standard. This will increase the cooling load, of course, and could in practice bring the demand

Institution of Building Services Engineers (CIBSE) Guide in the U.K. recommended 25°C as an acceptable indoor design operative temperature for non-air conditioned office buildings in summer and suggested limiting the expected occurrence of operative temperatures above 28°C to 1% of the annual occupied period (e.g. around 25–30 hours).[xxxv,201] Ultimately, neither of these criteria can be regarded as a robust definition of overheating, but serve as rough design guide. More robust analysis can be based on methodology outlined in the latest version of ASHRAE 55 and BS EN 15251.

While these guidelines are crude, they do provide a structure to ensure some consideration of the risk of overheating. Results from monitoring studies are mixed; most of the studies we could find showed an acceptable thermal comfort in the summer, but some highlighted issues to be resolved.

Figure 25 present the results of monitoring study from three projects from the EU-funded demonstration project CEPHEUS. It shows that a temperature above 27°C is only exceeded in exceptional cases. 88% of occupants surveyed in the Hannover project reported being satisfied with the indoor climate in summer; in the Kassel mid-rise, the average satisfaction for summer thermal comfort was 5.2 on a scale of 0 (very dissatisfied) to 6 (very satisfied).[202] The Harmony House, a passive net-zero house in B.C., was designed to be cooled exclusively by natural ventilation. Monitoring over the course of a year showed the indoor temperature mostly stayed within the ASHRAE 55-2013 tolerance band, and occupants reported being comfortable year round, without the need for any mechanical cooling or ventilation during the warm periods of the year.[203] A survey of occupants from nine Passive Houses in Sweden, on the other hand, showed that several occupants complained of high temperature in summer. These buildings did not have external shading, which can explain some of the additional gains, but occupants also noticed how much cooking and other heat-generating activities affected indoor temperatures.[204]

In a survey of 50 occupants in 32 Passive Houses across Europe, almost half responded that indoor temperatures were slightly too high in summer, but only 6% considered them too hot for

beyond the 15 kWh/m^2 maximum. However, as long as the builder can show through PHPP modelling that the cap would be respected for a system providing a maximum of 10% of hours above 25ºC, the certification criteria can be met. The designer can use a different threshold to size the system, even if it means that in practice the building might exceed the 15 kWh/m^2 maximum. This 'workaround' allows builders aiming for certification some flexibility to meet customer expectations.

[xxxv] Recognizing the limitations of attempting to define overheating by a single temperature (even for a relatively uniform climate as in the U.K.), the CIBSE now recommends that the risk of overheating be assessed by three criteria: the number of hours where temperature exceed a threshold comfort temperature, the severity of overheating within any one day, and the absolute maximum daily temperature for a room. Failure of two of any of these is considered overheating.

comfort. Further field study of 18 of these buildings concluded that indoor temperature and relative humidity were within acceptable ranges set by standard EN 15251.[205] Authors of the study highlighted the importance of occupant behavior in managing summer temperature, as many of the passive cooling strategies used depend on adaptive measures taken by occupants: opening windows at night, keeping windows closed during the day, and closing external shades during hot days. However, even when informed of the importance of these measures, other priorities may lead occupants to act otherwise: when interviewed, the homeowners of a passive apartment block in Vienna said that they sometimes kept windows closed despite high temperatures in their units because of outdoor noise, perceived security, and insects. Some also expressed discontent at the need to close the blinds in summer because of the resulting loss of light and views.[206]

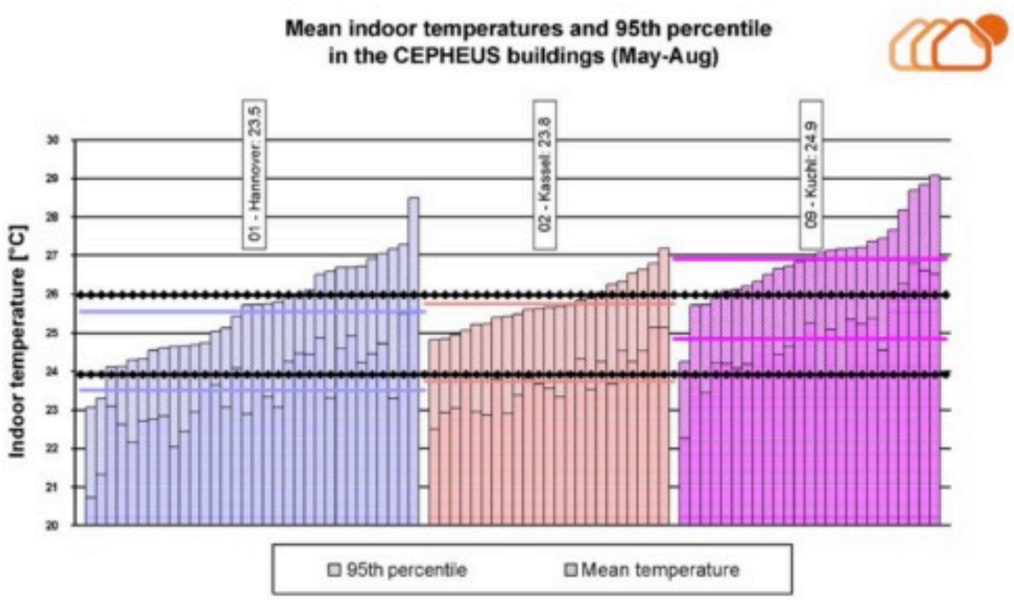


Figure 25: Mean indoor temperature from May to August for residential Passive House units.

The bars show the mean and 95th percentile temperatures for Passive Houses in Hannover (DE), Kassel (DE), and Kuchi (AT). Coloured lines cutting across give the average and 95th percentile values for each project, and the black lines give the over average (24C) and 95th percentile (26C) temperatures. Built in 2000, the Kassel project was the world's first mid-rise Passive Houses, comprising 40 units in two buildings (bars here show temperature in all units for one of the two buildings).

Source: Schnieders & Hermelink[207]

6.4 Conclusion

Highly insulated enclosures can decrease cooling loads for buildings with air conditioning, and provide a more comfortable summer indoor temperature for non-conditioned homes. To do so, a balance must be struck between maximizing solar heat gains to reduce heating load, and preventing the risk of overheating in summer and shoulder season. Internal heat sources must also be minimized, which may require some load shifting from the occupant (i.e. running high heat producing appliances in the evening rather than in the middle of the day.) Various passive cooling strategies can be used to mitigate overheating risks, some of which are independent of occupants (overhangs, low solar-gain glazing, cool roofs, etc.) and some which require their participation (opening windows at night, closing blinds, etc.). Fixed solutions are more robust, but strategies providing occupants more control on their environment are more adaptable and can provide both pleasure and a broader tolerance for temperature variations.

Monitoring of passive buildings shows a range of outcomes, with most performing exceptionally well, others less so. This can in part be attributed to the fact that many of the early passive designs were primarily concerned with heat conservation in winter, and less emphasis was placed on cooling in the warm months.[208] But overall, both building science and practice show that high-performance enclosures, paired with appropriate passive cooling strategies, can significantly reduce energy use for heating and cooling while providing superior thermal comfort year-round.

As the climate warms, the demand for cooling will increase. The choice between passive and active cooling strategies raises a more fundamental question: in a rapidly changing environment, are we better off investing in creating controlled environments, or in increasing our capacity to adapt and tolerate broader conditions? As Andris Auliciems notes in his 1997 paper: *'we need to be mindful of the general principle that, within a changing environment, survivability is greater among the adaptable than the adapted and ask which trend is technological development favouring[...]'*[209] Thus, a broader application of passive cooling strategies can play an important role in improving resilience in a warming world. By providing an alternative to conditioned buildings (or reducing demand to such a degree that the cooling required is minimal) it can avoiding further penetration of high-power air conditioning equipment, particularly in temperate areas where it historically has not been needed. Avoiding 'locking in' air-conditioning systems will reduce energy and capacity demand on the grid, and protect housing affordability.

If the market is to embrace passive design more broadly, whether through growth in demand or through regulation, some safety nets will need to be put in place to mitigate the risk of overheating. This can be done prescriptively by setting maximal ratios of southern windows to treated floor, adding requirements for shading, ensuring operability of windows, requiring cool roofs, etc. Some of these measures are addressed by the Passive House standard, some have been laid out in various design guides (albeit not in code language)[xxxvi] and some have already been integrated into energy codes.[xxxvii] A performance-based compliance path could also be considered, using energy modelling to show that a proposed design meets the comfort criteria defined in standards such as ASHRAE 55, BS EN 15231, and ISO 7730.

The equipment and systems typically used in new construction may not be appropriate for these lower heating and cooling demands, and alternative solutions are not always familiar to HVAC installers/designers, or readily available on the market.[210] Further training for the HVAC industry, as well as development of North American heating/cooling equipment for small loads, will also be required as passive approaches are mainstreamed (see Sections 1 and 12).

Box 10. Resources on passive cooling

CHMC, *Tap the Sun: Passive Solar Techniques and Home Designs* (1998).

Zero carbon Hub, *Solutions to Overheating in Homes, Evidence Review* (2016). http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview.pdf

[xxxvi] For example, PHI certification checks for overheating.

[xxxvii] For example, the requirement for cool roofs in California; see previous footnote.

7. Part 1: Conclusion

The previous five sections discussed the stock of passive buildings, their energy performance, their incremental cost, and strategies to minimize moisture and overheating risks. From these, certain observations can be drawn pertinent to the acceleration of market transformation.

Which building types to prioritize, and how

- Strictly from a 'proof-by-number' perspective, there is a strong case for the technical and financial feasibility of a larger adoption of passive house practices for ground-oriented, low-rise, and mid-rise residential buildings in North America. These market segments are rapidly growing; passive mid-rise buildings, in particular, are already competitive in the open market without strong incentives or policy drivers. We believe that with proper policy support and investment in training, passive approaches could be common practice in the ground-oriented and mid-rise residential sector in less than a decade.
- Residential high-rise passive buildings like Cornell Tech's 26-storey residence in New York are just emerging in North America, and more demonstration projects should be encouraged.
- Offices and school buildings are a relatively mature segment in Europe with over 180 PHI certified projects of each registered on the iPHA database. These segments are still emerging in North America (we could find 22 projects documented), and would gain to be supported. European experience show a passive approach can be adapted relatively easily to these building types, and provide an expertise base which can be called upon to support projects in North American if needed.
    - A large section of Class A offices already undergo green building certification; demonstration projects showing how a passive approach could achieve energy credits at a lower cost would help leverage these markets to build more demand for high-performance components and expertise. The cost of high-performance curtain wall systems remains a barrier, which will need to be addressed either through technological innovation or by encouraging a shift away from floor-to ceiling glazing.

- Class B and C offices generally have compact simple building form with punched windows, making passive design an ideal solution to provide improved energy performance and indoor air quality at an affordable cost. While improved air quality and lower fees might provide some competitive advantage to secure and retain tenants, split incentive is often a deterrent to additional capital investment. Public sector procurement policies can help drive demand, but deep penetration in this market might require regulation.
- For schools, if the initial barrier of 'lowest cost' procurement policies could be addressed, a passive approach would return long-term savings in operation and maintenance for school districts while providing a healthy environment and a great educational opportunity for students and their parents.

- For more complex building types, additional demonstration projects are needed to understand technical and market constraints. Because attempting to meet strict energy budgets can become onerous when function or architectural design of the building already place a lot of requirements on HVAC systems, a flexible approach aiming for the integration of passive design principles (irrespective of whether certification targets are met) might be most productive. Recognizing this, certification processes already allow for a certain amount of flexibility. There is work underway to create passive house design guidelines for unique building types, such as supermarkets and swimming pools, but there is still much to be learned on a site-by-site basis and these projects therefore require a significant tolerance for innovation risk. Again, public sector participation and leadership will be important (see Sections 9.1 and 11.2). Projects with high visibility that allow some access for the public are ideal candidates as they can increase awareness of passive design amongst the public and key market stakeholders.

Energy case for passive house

- Modelling shows passive design can reduce heating demand by 40 to 90% compared to typical current building practice. Monitoring of energy consumption shows that actual heating load is within ~10 kWh/m^2/year for most projects studied. As the systems involved are simple, the greatest source of variation generally comes from occupant behaviour (higher thermostat set points, misunderstanding of HRV ventilation options leading to windows being opened more often, etc.)

- As the climate warms, passive strategies can be used to reduce cooling loads in conditioned buildings and reduce the risk of overheating in free-running buildings. These solutions can play a role in avoiding the lock-in of air-conditioning systems in regions where they historically had not been needed. They can also increase social resilience: adaptive theory of thermal comfort has shown that occupants of free-running buildings can be comfortable in a wider range of conditions, particularly if they have direct means to control their indoor environment (opening windows, closing blinds, etc.)

Business case

- Detailed costing studies and anecdotal evidence from builders show that it is possible to build residential passive buildings within typical construction budgets; incremental cost estimates vary, but most are below 10%, and within normal budget variability.
- Given the low cost of energy in North America and continued failure to internalize the social cost of carbon, it can be difficult to make the business case for passive construction solely on the basis of energy cost savings. To complete the picture, we need costing studies that quantify potential maintenance cost savings associated with the higher quality components as well as the decrease replacement costs resulting from simpler mechanical systems. Sensitivity analysis showing how future energy and carbon cost increases might affect the business case would also be useful.
- While there is growing evidence that higher energy efficiency can increase sale values (see Section 11), better documentation of sales costs and time on market would help make the case for builders. Universal energy labelling would also help provide validated information to compare the performance of different homes. This would also help communicate the relationship between quality construction, energy efficiency, and non-energy benefits: comfort, air quality, durability and resilience.

Quality control

As discussed in the sections on moisture management and cooling, the passive house approach raises the stakes: it provide great benefits if basic precautions are taken, but can also lead to underperformance if poorly executed. As passive buildings move from niche to broad adoption, certain quality controls will need to be integrated into building practices to mitigate moisture and overheating risks:

- Air barrier testing, with strict airtightness requirements
- Proper accounting of thermal bridges and whole wall R-value calculations
- Involvement of a certified professional in the review of the enclosure design, or use of climate-appropriate pre-approved designs

- Design guidelines for passive cooling strategies including the sizing of south-facing windows, shading devices, cool roofs, etc.

These guidelines can be codified and incorporated into prescriptive codes, or provided as support to meet performance requirements for cooling systems and/or thermal comfort. Methodologies to predict thermal comfort in conditioned and free-running buildings have been defined in ASHRAE 55, and could be adapted for integration in energy codes or adopted by reference.

Capacity building

Mainstreaming passive design will require training and retraining some key roles in the construction industry. Not all trades and professions need to be involved, but general contractors, architects, envelope engineers and mechanical engineers will need to be engaged. PHI and PHIUS provide a structure for training and networking of passive house practitioners in many areas of Canada and the U.S.; there are over 1,600 Passive House trained trades and professionals in North America, and this trend is growing rapidly (see Section 2.3). In addition, passive house strategies are already being integrated into the curriculum of some trade, engineering, and architecture schools.

These changes are underway, but the effort would be better coordinated if there was a long-term target for energy codes, as well as clarity on the expected performance increment in the next code revisions. This long- and mid-term clarity is necessary for governments, institutions, and individuals to plan their investments in training programs. This scale-up can also be supported by the creation of innovation excellence centres (such as that proposed by the City of Vancouver), which would act as clearinghouses for the dissemination of research results and hubs for ongoing education. Various examples exists; some are discussed in Section 00, along with other strategies to accelerate capacity building.

PART 2: MARKET BARRIERS AND POLICY BEST PRACTICES

8. Using public policy to address barriers

The second part of this report focuses on understanding barriers to market transformation for high-performance enclosures, and capturing lessons learned from policy efforts in Europe and North America to address these barriers.

Our capacity to reduce emissions from the building sector fundamentally depends on the socio-economic system in which the construction industry operates: history of building practice, ownership and management models, contracting and liability, procurement rules, market conditions, availability of components, jurisdictional constraints on regulations, land use planning, social expectations on building look, feel and comfort, etc. The most challenging barriers to reducing energy are non-technical: alignment of value chain in contracting relations, innovation risks, split incentives, occupant behavior, ensuring ongoing maintenance, enforcement of regulations, monitoring and disclosure of energy use, etc.

The goal of the next six chapters is not to articulate these barriers—which have been amply discussed elsewhere[211, 212, 213, 214, 215]— but to explore how public policy can be used to address them. Based on the findings of the PassREg project in Europe[216] and on a series of interviews with North American practitioners and policymakers (Appendix A), we categorize barriers to market transformation in six areas:

1. Political vision and regulation
2. Industry capacity
3. Business case and financing
4. Supply chain
5. Public and industry awareness of passive design and benefits
6. Quality assurance

These are explored further in the following chapters. For each category, we first present a table summary of the barriers and solutions identified in the literature and in interviews; these give a high-level overview of the issues at play, and can act as a useful checklist when designing programs or market interventions. We then highlight some of the best practices from North America and Europe that have contributed to addressing these barriers.

Before diving into the details, however, we find it useful to review mental models of transitions in complex systems, providing a broader context to understand barriers and where we currently stand in a market transformation process.

8.1 Models of transition

Much research has been done to describe how complex socio-economic systems can be purposefully transformed.[217,218] Of particular relevance to our topic is the question of how niche practices either evolve to become norms, or fade out as temporary hype. How can we ensure the practical know-how, tools, and mindset of passive house practitioners become integrated into general practice, rather than remain the purview of a few converts? This question, of course, can be seen as a subset of a larger conversation on the dissemination of green building practices in general, or even more fundamentally, on the capacity of construction industry to innovate.[219] Irrespective of the scope considered, market transformation theory and complex system theory can yield some insights on strategies to support the transition.

Market transformation theory reminds us that transitions are non-linear, and follow a general pattern (Figure 26): a predevelopment phase, in which a lot of experimenting takes place with little visible societal change, is followed by a take-off phase, in which the structure of the system starts to shift, and an acceleration phase, where multiple system levels are affected, synergies emerge, and changes are scaled up. For the transition to be successful, the change must be embedded into a new normal, an anchoring period called the stabilization phase. Failing that, the innovation will remain confined to a niche, or fade out.

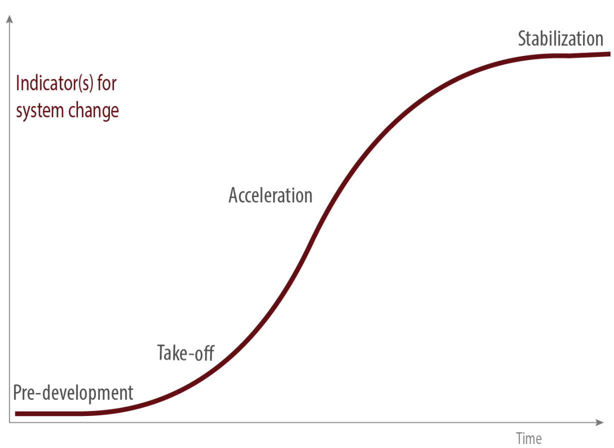


Figure 26. Market transformation phases

Source: Rogers[220]

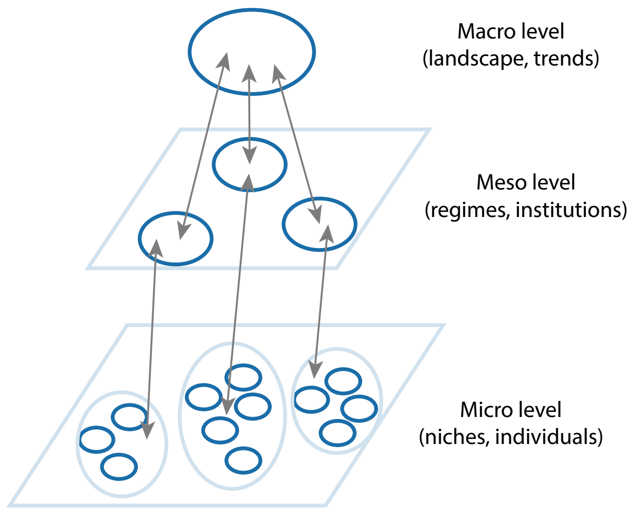
According to the Dutch association DNA in de Bouw: "*Each transition phase requires a different approach to further stimulate progress of the transition. Roughly stated: during the predevelopment* *phase the emphasis is on search and experiment, during take-off it is on selecting and facilitating, during acceleration it is on scaling up and facilitating and during the stabilization phase it is on bedding in and anchoring. (…) A region already in the acceleration phase might focus more on networking and collaboration activities and on market penetration."*[221]

Evidence suggests that the passive house movement might well be moving from a take-off phase to an acceleration phase. The growth and institutionalization of the passive house movement in North America, as evidenced by the formalization of practitioner networks (Table 3, Table 4), the number, distribution, and variety of PH buildings (Figure 11, Figure 12), the growing number of trained professional and trades (Figure 13), increased availability of components,[xxxviii,222] and the growing reference to passive design in public policies (Appendix C), are some indication of this acceleration.

Complex system theory reminds us that scaling up during this acceleration phase will require shifts in structure (institutions, economical and physical organization of a system), culture (mindset, values, paradigms), and practices (routines, rules and behaviour). These changes will need to influence interactions between different levels of the system (Figure 27). In most of North America, the passive house movement is still a niche, trying to transform the existing regime of traditional builders and institutions — though this transformation is well underway in some leading jurisdictions such as New York and Vancouver (Section 1). This takes place in a macro-level context of increased urbanization, globalization, economic uncertainty, and a possible profound transformation of the energy supply spurred by technological innovation and climate change.

Of particular importance to successful transformation is not only the alignment of macro-level drivers, but also the strengthening of interaction between the micro and meso level, i.e. between the niche and the established regime. Connecting champions in leadership positions within the regime with niche practitioners, collaborations between niche-market subject matter experts and large companies, introduction into the scope of corporate social responsibility, and early adoption by public sector agencies with sufficient buying power to impact the market are some of the common ways by which niche strategies start to permeate and change the established paradigm.[223]

[xxxviii] While this is not tracked explicitly, a few anecdotal evidence illustrates the point: in the early part of 2016, six window manufacturers in B.C. have signaled their interest to produce PH-certified windows); in 2015, the U.S.-based high-performance building supply retailer 475 started offering components and training in Canada.



Macro level examples

Carbon pricing and energy costs

Climate policy (e.g. EU Directive on Energy Performance of Buildings)

Meso level examples

Contracting, tendering, permitting and inspection practices

Public building procurement policies

Corporate policies

Micro level examples

Networks of PH practitioners

Advocacy organizations

Figure 27. Levels of change in transition dynamics

The following sections of this chapter review some of the strategies taken by public agencies, private institutions, and practitioners to encourage such connections between the micro and meso levels of the built environment sector. We summarize barriers to the broad adoption of high-performance building enclosures (many of which are common to green building practices in general), and present some of the best practices to address them. This is by no mean an exhaustive list, and we encourage the reader to attract our attention to other successful initiatives the community would gain to learn from.

As this is not meant to be a strategic plan for the transformation of the building sector, we do not rank or prioritize these interventions. All of these barriers will need to be resolved for the transformation to occur, though not all might necessitate public policy intervention.

9. Political vision and regulation

Buy-in at a political level is necessary to provide a mandate for public sector involvement in market transformation. Table 12 summarizes key barriers related to political vision and regulations and high level solutions highlighted in the literature. The sections below highlight some examples of how public procurement policies and building regulations have been used to encourage high-performance enclosures. Public policies to support capacity building and to improve the business case for passive design are discussed in following sections.

Table 12. Barriers and solutions to political vision and regulation

Barriers	Solutions
Structure	
Procurement policies prevent public sector to lead in innovation Existing regulations misaligned with PH design approaches (see extended list below) Energy efficiency standards not aligned with desired outcomes	Stable and continuing policy on energy efficiency at national and regional levels Regional roadmap, involving all relevant regional stakeholders Incentives or funds supporting a high standard of energy efficiency Examples of PH in government and public buildings, including PH procurement policies Clear definition on NZEB and its measurement instrument(s)
Culture	
Lack of political will, motivation for transition Lack of clear direction, vision, targets & insight in progress towards vision and target Lack of stakeholder consensus Lack of knowledge with policymakers and public servants (particularly permitting and inspection staff)	Regular study tours to educate and inspire policymakers and public servants through examples of successful projects and happy inhabitants Work practices Regulations demanding a high standard of energy performance and delivered quality of the systems Rezoning and rental/sale of public land used to negotiate higher efficiency in private developments Ongoing education for permitting and inspection staff; PH training

9.1 Public buildings procurement policies

More than 38 cities or states in Europe require public buildings, or buildings on publicly owned land, to meet Passive House standards (Table 13). Their joint population comes to a total of over 30 million people.

Table 13. Jurisdictions requiring passive house performance for civic buildings[224]

Jurisdiction	Population	Required since
State of Bavaria (DE)	12,500,000	2011
State of Hesse (DE)	6,000,000	2010
Hamburg (DE) - for all municipally funded projects	1,700,000	2012
Lower Austria (AT)	1,600,000	2008
Brussels (BE)	1,100,000	2015
Cologne (DE)	1,000,000	2010
State of Saarland (DE)	1,000,000	2011
Frankfurt (DE)	690,000	2007
Oslo (NW)	620,000	2014
Bremen (DE)	550,000	2010
Luxembourg	540,000	2017
Leipzig (DE)	520,000	2008
Nuremberg (DE)	500,000	2009
Antwerp (BE)	500,000	2013
District of Lippe (DE)	350,000	N/A
Freiburg (DE)	230,000	2011
Leverkusen (DE)	160,000	2009
Heidelberg (DE)	150,000	2010
Walldorf* (DE)	145,000	2010
Offenbach Harbour – Mainviertel (DE)	120,000	2009
Aschaffenburg (DE)	69,000	2008
Kempten (DE)	62,000	2011
Wels (AT)	59,000	2008
Dornbirn (AT)	45,000	2007
Bregenz (AT)	28,000	2007
Rankweil (AT)	12,000	2007

Götzis (AT)	11,000	2007
Wolfurt (AT)	8,000	2007
Villamediana de Iregua (SP)	7,500	2013
Hörbranz (AT)	6,500	2007)
Altach (AT)	6,000	2007
Frastanz (AT)	6,000	2007
Mäder (AT)	3,500	2007
Zwischenwasser (AT)	3,000	2007
Thüringen (AT)	2,000	2007
Krumbach (AT)	1000	2007
Langenegg (AT)	1,000	2007
School District of Darmstadt-Dieburg (DE)	N/A	2010
TOTAL population	**30,305,500**	

While not as common in North America, Passive House procurement policies are being explored and adopted by jurisdictions in the United States and Canada. Below are some examples:

- **Vancouver Passive House procurement policy (2016):** states that Passive House certification will be required for all new city owned buildings, unless it is deemed unviable. The Vancouver Affordable Housing Agency has also incorporated a requirement to assess projects against the Passive House standards as part of its RFP process.[225]
- **New York City** Local Law LL31/2016[226]: passed in March 2016, this new law requires that new capital projects for city-owned property (new construction, additions and substantial reconstruction) be designed to use no more than 50% of energy used today (called "low energy intensity buildings"). All projects must also consider the feasibility of providing at least 10% of energy from onsite renewables, and projects three stories or less must consider the feasibility of net zero energy use.[xxxix, 227]

[xxxix] A previous version of the bill proposed that City capital projects greater than two million dollars be built to Passive House standards (either PHIUS or iPHA). On the topic of Passive House, the working group summary report comments: *"[The Passive House] absolute targets provide more certainty to energy performance outcomes, but are not commonly used in the New York City building industry today. In addition, a metric for New York City must account for the varying space uses and differences in building occupancy in the city to avoid penalizing industries that have high energy use profiles, such as trading floors and television studios. Collaboration with other jurisdictions and leaders on this effort is also key to ensuring market alignment of any new standards."*

- **Affordable housing policies U.S. (various locations):** In many U.S. jurisdictions, affordable housing development is funded through tax credits. This is a very competitive process, in which various developers compete for limited funds. Some housing agencies have started to award additional points for Passive House projects, which has spurred increased interest from developers. As an example, in the first year of the PHFA Passive House policy, 39 of the 85 projects submitted (35%) were Passive. The agency funded eight PH projects, totaling 422 units. This is the largest concentration of PH in the U.S.[228]
    - **The Pennsylvania Housing Finance Agency (PHFA) (2014):** PHFA grants 10 points (out of 130) for development that meet Passive House certification requirements under iPHA or PHIUS.[229]
    - **The New York State Homes & Community Renewal (HCR) (2015):** awards five points (out of 100) for projects seeking Passive House certification or other green standard (Enterprise Green Communities, LEED, National Green Building Standard)[230]
    - **Other states agencies likely to include PH criteria in 2016:** Idaho, Illinois, Delaware, New Jersey, Rhode Island[231]
    - **Other states considering including PH criteria**: Alaska, California, Colorado, Connecticut, DC, Iowa, Maine, Maryland, Massachusetts, Michigan, Montana, Nevada, North Dakota, Ohio, Oklahoma, Oregon, South Dakota, Utah, Vermont[232]
- **BC Housing procurement policy (2016):** Passive House is now included as an option along with LEED for provincially funded projects. BC Housing has included targeting Passive House certification as a requirement in two recent RFPs one in Merritt (climate zone 5) and one in Smithers (climate zone 7). Decisions as to whether these projects will apply for precertification is expected in the coming months.

Public procurement rules, however, can create significant barriers to effectively using public buildings to foster innovations. Lack of client knowledge, lack of fairness and inequitable allocation of risk, failure to recognize a value-based approach to market and the importance of design have been highlighted as barriers to innovation in public sector buildings.[233] Even when a mandate for leadership is given, these barriers and the ‘lowest bid’ culture can impede investment in solutions returning long-term value. Public agencies, like many clients of the construction industry, do not always know how to include and assess sustainability objectives in their RFP process, reinforcing the ‘lowest bid wins’ effect. Providing procurement guidelines can be a first step to address this barrier. A more thorough procurement policy review, such as the one conducted in Scotland in 2013,[234] can also enable more fundamental changes to align with a a “quality-first” objective where life cycle costs and the value of design are recognized.

9.2 Land use changes and rezoning

A developer's interest in maximizing profit through zoning changes or rezoning is an ideal time to require high-performance enclosures in exchange. This can be done by making a passive approach a condition for rezoning, or by relaxing certain zoning constraints in order to encourage passive buildings.

The passive house standard has been used in some high visibility redevelopment in Europe (see below). North America has not seen extensive passive house developments yet, but zoning policies are used by some jurisdictions to incent passive design, and large projects are beginning to emerge. The City of North Vancouver is using Passive House as a compliance path for the pre-zoning of a new neighborhood. The City of Vancouver has used Passive House certification as a compliance path for rezoning, and is increasingly requiring passive design elements and stringent performance targets.

Bahnstadt, Germany

Bahnstadt, a new city district in Heidelberg, Germany, is being built on a former railway and train yard. It will be the first district consisting entirely of buildings constructed to the Passive House standard, and will also be carbon neutral. A woodchip biomass cogeneration plant supplies the district with heat and electricity.[235] The redevelopment is a joint initiative between the City of Heidelberg and a private developer. At 116 hectares, it is one of the largest urban development projects in Germany and the largest area of Passive House buildings in the world. More than 100,000 square metres of floor space are planned, consisting of residential buildings, offices, university-related services (e.g. laboratories), kindergarten, retail (food and non-food), and hotels, with the aim to accommodate 12,000 residents and 7000 workplaces. The official opening of the district was in April 2014.

Nieuw-Ziud, Belgium

Under Antwerp's 2011 climate plan, the city committed to become carbon neutral by 2050, and incentivizing the Passive House standard is one of the mechanisms they are using to achieve that goal. Nieuw-Zuid, a private mixed-use residential development, is a model for the city. Under a cooperation agreement, this is a joint project between the city of Antwerp and a private developer. Nieuw-Zuid has 2000 residences, two schools, two daycares, a sport hall, offices, shops, hotels, and restaurants. Energy requirements of all buildings in Nieuw-Zuid must not exceed 15 kWh/m^2 per year. Nieuw-Zuid is part of the European Passive House Regions with Renewable Energies (PassREg-project). As part of the project, the Flemish government is funding the city to conduct consultation, outreach and education with residents and occupants at Nieuw-Zuid on energy efficient behavior. The goal is to create a joint commitment to use energy sparingly by all those who live/work at Nieuw-Zuid. The Flemish government subsidy of this program also allows the city to share its experience with other future projects.[236]

ZERO:E park, Germany

The ZERO:E park in the Wettbergen district of Hanover, Germany, will be the biggest zero-emissions district in Europe. The new neighborhood will consist of 330 single-family Passive House homes. This new residential area being developed is an important milestone in meeting Hanover's climate and environmental protection goals. All buildings will be built to Passive House standard (including German's first Passive House certified supermarket) and energy efficient appliances will be installed. (Any additional CO_2 emissions will be offset through hydropower generation.) ProKlima, a climate protection fund, financed by the City of Hanover and several nearby towns, is supporting the construction of Passive House buildings in this development. The city sees these projects as means to model energy efficiency and ecological development and to generate public enthusiasm for climate change issues for those living in the district.[237,238]

Moodyville, North Vancouver

The City of North Vancouver is pursuing a unique sustainability approach in the Moodyville area. Moodyville comprises about 1 million square feet of buildable area. As a result of the City's pre-zoning initiative of these lands, it is expected that most of Moodyville will be built out within the next five years as a new family-oriented development node. The redevelopment will be built around a frequent transit corridor and connected to a major park and greenway system.

In order for new buildings to receive additional density beyond single-family or duplex development, the City's sustainability strategy requires that they be designed to achieve one of the following:

- Passive House Certification
- The highest tier of the Stretch Code (similar to Passive House) currently under development by the province
- LEED-NC Gold with 15% better than ASHRAE 90.1 2010 energy performance or LEED For Homes Gold Certification with EnerGuide 86 Certification, as well as a commitment to a noise mitigation strategy.

A performance bond of 1% of construction costs is collected for verification of energy or green building standards. If performance is not achieved, the funds are transferred into the city's Climate Action Reserve Fund. Only developments designed to achieve Passive House certification will be exempt from a district energy connection for district heating. This acts as a indirect financial incentive for choosing the Passive House option at rezoning.[239]

City of Vancouver Green Rezoning Policy

Under this policy, rezoning for large commercial and multi-unit residential projects must meet Passive House certification, or demonstrate compliance with stringent thermal energy demand and greenhouse gas intensity targets, among other conditions. This policy impacts 60% of square footage developed in the City of Vancouver (an estimated 2.6 million square feet of new development each year).[240] As of 2020, all new low-rise residential buildings applying for rezoning will need to meet the passive house thermal load intensity target of 15 kWh/m^2/year. This requirement will be extended to all new low-rise MURBs and be adopted in the Vancouver Building Bylaw by 2025.

9.3 Zoning relaxations for thick walls

Practitioners from localities with high land prices have indicated that the loss of usable floor space was the most significant barrier to the adoption of super-insulated walls (see Appendix A for a list of other regulatory barriers). To address this constraint, some jurisdictions have allowed for some exemptions or relaxations for buildings meeting certain performance criteria. Where space is at a premium, these can make a material difference in the business case for a project and act as strong incentives. These zoning relaxations should be a policy priority for jurisdictions with high land value.

Examples of such policies in North America:

- **City of New York Zone Green thick wall exclusion (2012):** Zone Green allows for up to 8 inches of wall thickness to be exempted from the calculation of floor area to encourage high-performance buildings without decreasing the amount of usable space in the building. This exemption applies where above-grade exterior walls exceed the thermal enclosure requirement of the New York City Energy Conservation Code by a prescribed percentage.[241]
- **City of Vancouver thick wall exclusion** (2010, 2015, 2016): Allows all building types to exclude the area used for insulation exceeding minimum code requirements in floor space ratio calculation. Maximum limit on exclusion was explicitly based on the amount of insulation deemed required to achieve Passive House. In 2016, Council granted the director of planning discretion to relax height and setback requirements to make use of the square footage gained from the wall thickness exclusion.[242]

9.4 Streamlining permitting and inspection

Some jurisdictions encourage higher performance by facilitating permitting processes, or removing existing regulatory barriers.

- **San Francisco priority permitting (2014, updated 2015):** the planning department offers accelerated permit processing to multi-unit residential (or large commercial) building that are Passive House Certified (PHIPHI, PHIUS, or EnerPHit), LEED Platinum, or Net Zero Energy (as defined by Living Building Challenge).[243]
- **City of Vancouver building officials training (2015):** To ensure there is no delay in processing applications for Passive Houses, the City of Vancouver will provide training on passive design and construction to city staff. This will primarily engage staff in Housing Review and Inspections, but also in Development Review, Development Planning, and Building Review. Staff have created a draft specialized application process for Certified Passive House projects for one or two family homes.[244]
- **City of Vancouver Passive House equivalency (2015):** City made some allowance for PH certified HRV windows and door components, that might not have equivalent NAFS certification.[245]

9.5 Passive House requirements in building regulations

Several jurisdictions require Passive House equivalent performance for a range of buildings beyond the public sector. Some make it a condition for sale or lease of municipal land (Hiedelberg and Waldorf, in Germany), some require it for residential buildings only (Luxembourg, Freiburg (DE)), and others require it for most new buildings: Leverkusen, Cologne, and Nuremburg (Germany), Dún Laoghaire (Ireland) and the capital-region of Brussels (Belgium) (Table 14). Together, these jurisdictions have a population of over 4 million people.

These requirements generally include some opt-out mechanisms, or alternative compliance path, for buildings for which passive performance is not possible, or not appropriate. For example, the Dún Laoghaire council policy states that *"all new buildings will be required to meet the passive house standard or equivalent, where reasonably practicable. By equivalent we mean approaches supported by robust evidence (such as monitoring studies) to demonstrate their efficacy, with particular regard to indoor air quality, energy performance, comfort, and the prevention of surface/interstitial condensation."*[246] Brussels is another example, offering an alternate compliance path for buildings that cannot meet the energy targets – see Box 11.

Similarly to Passive House, Denmark's energy code sets a maximum energy budget for thermal load intensity. Despite the fact that the targets are not quite as strict as those set by the Passive House standard, we have included it in this table given its similar approach.

Table 14. European jurisdictions requiring passive house performance beyond civic buildings

Jurisdiction	Pop.	Requirement
Denmark	5,600,000	yearly space heat demand ≈ 40 kWh/m^2 (2010) yearly space heat demand ≈ 28 kWh/m^2 (2015)[247]
Brussels (BE)	1,100,000	For new residential buildings, homes, schools, and office buildings (since 2015)
Cologne (DE)	1,000,000	For new buildings (2019)[248]
Luxembourg	540,000	For new residential buildings (2017)[249]
Nuremberg (DE)	500,000	For new buildings (since 2009)[250]
Freiburg (DE)	230,000	Low energy standard for new residential buildings (since 2009); with plans to require passive house by 2011 (implementation unconfirmed)[251]
Dún Laoghaire, Rathdown (IE)	210,000	For new buildings (since 2016)[252]
Leverkusen (DE)	160,000	For new buildings (since 2009)[253]
Heidelberg (DE)	150,000	For new buildings on purchased city land (since 2010)
Walldorf (DE)	145,000	For new buildings on purchased city land (since 2010)
Total Population (NOT including Denmark)	4,035,000	

Box 11. Performance targets adopted in Brussels in 2015

As of January 1, 2015, the Brussels region requires housing, offices and schools to meet these performance criteria:

- A net heating requirement of less than 15/kWh/m^2/yr
- A net cooling requirement less than 15/kWh/m^2/yr (only for offices and schools)
- An airtightness of 0.6 ACH at 50 Pascal
- An overheating over 25C limited to 5%
- A primary energy consumption limited to:
    - for housing (heating, hot water, ventilation, pumps and fans):
      45 kWh/m^2/yr + max(0, 30-7.5 * compacity) +15*max(0, 192/volume total-1)
    - for offices and schools: 95 – (2.5 * compacity) kWh/m^2/yr

Where compacity is the ratio of the habitable surface (measured from inside the walls) divided by the total insulated area surface (including floors and ceilings).[xl,254]

Compacity increases the closer the building form is to a square; its inclusion in these formula (with a negative coefficient) allows the threshold to be somewhat relaxed for building projects which by functional constraints have a poor compacity (i.e. up to 75 kWh/m^2/yr for housing, and to 95 kWh/m^2/yr for offices and schools). Note that compacity value is capped at 4 (i.e. no additional constraint is added to buildings with a compacity greater than 4, to avoid penalizing compact forms).[255] The regulation is under review for the overheating maximum (for building uses related to education and offices) and cooling requirements, enforcement of which has been postponed until January 1, 2017.[256]

Major renovations

Units for which mechanical systems and 75% or more of insulated wall area are being renovated must meet these standards as set out above, with a 20% relaxation on the maximal heating, cooling, and primary energy values.[257] For other renovation projects, minimum insulation and ventilation values must be met based on tables set in annexes.[258]

[xl] Compacity is also sometimes defined as the ratio of the habitable surface over the building volume to its insulated enclosure area (C = V/A); in this case, compacity increases the closer the form is to a sphere, and increases with larger buildings. The definition given in the main text is argued to be more appropriate to architecture and high-performance building, and has the advantage of being a dimensionless number.

Other compliance paths

The regulation was reviewed at the end of 2012 to allow some leniency for older buildings with insufficient solar gains, too much solar shadow, bad compacity, etc. In that case, a second compliance path ('Piste B') allows for a heating requirement target that is higher than 15/kWh/m^2/yr. The actual target is obtained via a government software program; the actual methodology used to set this alternative standard is not clear to us at this point, but it seems to be based on a reference-building approach using a standardized set of assumptions for average effective insulation, ventilation, thermal bridging, and airtightness.[259]

City of Vancouver Zero Emissions Building Plan

The City of Vancouver approved in July 2016 its Zero Emissions Building Plan[260], which calls for a 90% reduction (compared to 2007) in emissions from new buildings by 2025, and achieving zero emissions for all new buildings by 2030. While it does not explicitly require Passive House design or certification, this policy makes Vancouver the first jurisdiction in North America with a detailed roadmap and policy direction to encourage zero emissions buildings, the design of which will draw heavily on passive house principles and high-performance enclosures. By 2025, all new low-rise residential projects will be expected to meet the passive house thermal load intensity target of 15 kWh/m^2/year. The target for single family home will be slightly higher (30 kWh/m^2/year), as the passive house target was considered to be potentially too challenging to meet while maintaining the complex building shapes required to maintain some areas' early 20th century housing character.[261]

10. Industry capacity

As discussed in the conclusion of the first part of this report, industry capacity is fundamental to meeting the potential of the passive approach to deliver highly energy efficient, affordable, durable, and comfortable buildings. To meet these objectives, architects, engineers, general contractors, certain key trades, building inspectors, and permitting staff must be familiar with passive design best practices. While the number of trained professionals and trades is growing (Table 2), this is still only a dent in the effort needed to mainstream passive design.

Table 15 summarizes key barriers and solution to providing this knowledge broadly. We discuss below some strategies and resources developed to accelerate training. We then dive into more details into policies for airtightness measurement, as we see this as a key catalyst to educate and transform construction practices.

Table 15. Barriers and solutions to industry capacity

Barriers	Solutions
Structure	
Difficulty in finding trained trades and subcontractors Insufficient knowledge base Difficulty to access/availability of knowledge	Presence of training facilities
Culture	
Lack of interest, motivation to embrace PH/NZEB Lack of familiarity of suppliers with PH/NZEB Resistance of suppliers/builders to change the local building tradition Lack of awareness and familiarity for design professionals	Presence of a dissemination strategy for PH knowledge, including a strategy for change management of local building traditions where necessary Presence of supported professional networks and trade alliances for information sharing
Work practices	
Design-build projects lack integration; integrated design still niche, not the	Availability of education material for designers

norm	Availability of material (or on-site training) for contractors Availability of education material for private investors, public building owners, manufacturing industry, political decision-makers and public servants Best practice examples of PH/NZEB Accessible regional source of information about adaptation to climate, to traditional architectural values and to other local conditions Accessible source of information on PH solutions for building services, planning and design Integrated approach to designing and building

10.1 Networks and technical support

Knowledge-sharing hubs have been created in many leading jurisdictions to accelerate capacity building amongst professionals and trades. These organizations act as what innovation researcher Everett Rogers refers to as ‘change agents.’ Their function is to guide adopters — potential clients and innovating companies — through the various innovation-decision stages (initial knowledge of the concept, formation of an attitude towards it, decision to adopt or reject, decision to implement, and confirmation of this decision).[262] Having a third party, distinct from the builders, certifying projects and monitoring their performance also helps consumers build awareness and trust in passive buildings, necessary conditions to stimulate demand.[263] Below are a few examples of such hubs.

CarbonBuzz, U.K.

CarbonBuzz is an online platform for benchmarking and tracking energy use in projects from design to operation and is a collaboration between Royal Institute of British Architects and the Chartered Institution of Building Services Engineers. The platform allows users to compare design energy use with actual energy use side by side to help them close the design and operational energy performance gap in buildings, and encourage performance over and above regulation.[264]

The Building Energy Exchange, NY

BEEx provides support for the building industry through energy and lighting efficiency education, technical exhibits, critical research and networking opportunities. The Exchange runs classes, events and exhibits to help create partnerships and broker relationships among design, construction, and real estate professionals within the Greater New York City Region.[265]

The Integrated Design Lab (IDL), University of Washington

IDL brings together interdisciplinary UW research, faculty, staff, and students to support the development of high-performance commercial and institutional building design including lighting, daylighting and energy infrastructure. The IDL provides technical assistance, design guidance and building energy efficiency research, and has developed relationships with the design and construction industry as a result. The IDL's goals are to assist in decisions that support 50% reductions in a building's loads and 50% increases in its system efficiencies, utilizing state-of-the art simulation and verification techniques.[266]

Plateforme Maison Passive (PMP) and Passiefhuis-Platform (PHP), Belgium

PMP and PHP were created to encourage the uptake of Passive House in Belgium's two official languages, French and Flemish. The organizations provide clients and companies with education and outreach, training, and technical research and guidance, and Passive House certification. More specifically, they offer or facilitate[267]

- Individual advice explaining passive house concepts
- An annual Passive House Fair, facilitating networking and connection of suppliers, builders, and clients
- Referrals of clients to companies offering specific technological solutions
- Organization of site visits to establish peer-to-peer contacts with other clients
- Knowledge exchange through symposia and information sessions
- Scientific evaluation of demonstration projects and data collection
- Quality assurance and passive house certification
- A website providing information on technologies, case studies, and events

The Zero Emissions Building Centre of Excellence, Vancouver, B.C. (upcoming)

As part of the 2016 Zero Emissions Building plan, the City of Vancouver intends to establish a Centre of Excellence, which will exist to compile and disseminate information and skills related to the design, permitting, construction and operation of zero emission buildings in Vancouver and B.C.[268]

10.2 Informal networks of practitioners

Informal networks of practitioners have emerged in regions of rapid passive house development. Some were initiated or supported by training hubs, others were independently created. For example, several of the developers who successfully pitched Passive House projects for the Pennsylvania Housing Finance Authority's affordable housing call in 2014 have formed an informal peer-learning network to exchange lessons learned.[269] The architect Michael Ingui, in New York, regularly organizes mandatory cross-project meetings between contractors working on his various sites, where the different teams exchange successes and failures.[270] Designers and contractors participating in the BatEx incentive program in Brussels created ArchiBatEx, a similar independent experience-sharing group.

These opportunities for peer learning provide great synergy at low cost, and should be encouraged by hub organizations. In the U.K., for example, Constructing Excellence supports a network of over 30 Best Practice Clubs, allowing local construction industry leaders to "learn about the principles of Best Practice, while creating a culture and local support network of continuous improvement."[271]

However, as innovation moves beyond early adopters operating within niche market, and reaches larger companies operating at the meso-level, concerns for protection of competitive advantage become a deterrent to the open sharing of solutions. Innovation hubs or excellence centres as mentioned above then become a more crucial tool to accelerate transformation, providing value to companies by pooling R&D resources, learning from failure, and disseminating innovative practices.[272]

10.3 Online resources

Publications and internet-based resources provide another platform to share information; the Solutions Open Source (SOS) database and Passipedia are two on-line resources for Passive House professionals and policy makers.

The **Solutions Open Source database,**[273] initially supported by Intelligent Energy Europe, is mostly aimed at policy makers, and provides a wiki platform to document regional-scale strategies to accelerate uptake of passive house techniques and onsite renewables in new builds and retrofits. It was built as part of the passREg project,[274] and documents many of its case studies. It is, however, unclear whether the website is still actively maintained.[275]

Passipedia[276] is an online information platform maintained by the Passive House Institute. It is a repository for peer-reviewed and non-peer reviewed scientific research on Passive House, providing study summaries and links to the original research papers (often in German). Some general articles are available for free, but full access requires a membership to the Passive House Institute or to a local PHI-supported organization.

BePassive[277] was a quarterly magazine published by PHP/PMP which targeted architects, government agencies, builders, developers, engineers, manufacturers, real estate agents and others involved in construction. It was an important vehicle for knowledge dissemination in

Brussels during the initial stages of the Passive House transition in the region. The quarterly magazine provided clear and visually compelling information on Passive House projects and initiatives. The magazine was coupled with national and regional events promoting the standards. The last issue was published in September 2014, and all issues are now only available online.

10.4 Airtightness testing requirements

Improving airtightness of the enclosure is an effective and low-cost way to improve building performance; it adds minimal material costs, depending mostly on attention to detailing at the design stage and on proper execution during construction, and significantly reduces energy losses. Under Passive House requirements, a building must achieve an airtightness test score of no more than 0.6 air changes per hour.

Airtightness testing of a building enclosure identifies breaches in a building's air barrier, and determines the overall leakage of the enclosure. By providing direct visual evidence of the location of leaks, and an easy-to-understand metric against which to measure continuous improvement, airtightness testing closes a missing feedback loop necessary to improve air barriers. Study shows that measuring and report airtightness can rapidly improve construction outcomes.[278]

Below are examples of policies implemented to require air-barrier testing:

Washington State and City of Seattle airtightness requirements (2009, revised 2012)

The 2012 Washington State Energy Code and the 2015 Seattle Energy Code requires air leakage not greater than 2 L/s•m^2 (0.40 cfm/ft^2) at 75 Pa and airtightness testing for all new houses and additions[279] and for new commercial buildings.[280]

Meeting the airtightness target is a requirement for new residential homes to obtain their occupancy permit. Commercial buildings can still get their certificates of occupancy if they fail the test, but builders must first seal leaks "to the extent practicable," and send in a report of what they corrected. Tests must be done in accordance to ASTM E779 or an approved equivalent standard.

Key learnings from the first few years of implementing airtightness testing showed that although testing was a significant burden for the first one or two projects, by the third project most contractors were able to work with subcontractors to reduce leaks without too many issues.[281] Coordinating trades and contractor schedules with testing was a big concern. Advance planning or testing the building in sections alleviated the issue. Rigid adherence to airtightness requirements created a potential risk that results would be falsified, and third-party testing was recommended to mitigate this risk.[282]

The Seattle building industry has been for the most part successful in meeting the challenge of building relatively airtight buildings. A review of 31 projects conducted during the first two years of the policy as shown all but four buildings (85% of those tested) met or exceeded the proposed air leakage target.[283] Those buildings that did not meet the target have well-documented explanations for the excessive leakage.

City of Vancouver airtightness requirement for one- and two-family dwellings (2009, revised 2014)

Since 2009, the Vancouver Building Bylaw (VBBL) requires airtightness testing for one- and two-family dwellings. The testing must be conducted by a Certified Energy Advisor using EnerGuide Rating System procedures.[284]

The 2014 VBBL added minimum airtightness requirements (leakage no greater than 3.5 air changes per hour), and new testing requirements: a pre-assessment based on plan (to be submitted for building permit), and a pre-drywall blower-door test and a thermal bypass checklist (to be completed by a certified energy advisor before the City's insulation inspection). A copy of the final EnerGuide Report must be submitted at the time of final inspection, and remediation might be required if the home does not meet the 3.5 ACH target.[285,286] This addition of a pre-construction assessment and pre-drywall site visit by a CEA has provided significant opportunity to engage with builders and increase awareness of energy efficient building practices.

Airtightness requirement in B.C. stretch code (in development)

The province of B.C. is currently in the process of developing a tiered ‘stretch code’ articulating a set of beyond-code energy performance and administrative requirements that local governments could adopt as baseline code or as condition for rezoning or access to incentives. The current proposal includes a requirement for airtightness testing. No specific airtightness target is suggested, but an overall thermal energy demand target would be set for the upper tiers of the standard. The first tier of the standard would only include the administrative requirements, without additional energy performance requirement beyond those of the building code. The exact protocol to be used for testing has not been identified at this stage.

Box 12. Passive house training for trades and professionals in B.C.

The pool of trades and professionals with experience in high-performance buildings is growing rapidly in B.C. Training is offered by Passive House Canada, the British Columbia Institute of Technology (BCIT) and the University of British Columbia School of Architecture and Landscape Architecture (UBC-SALA).

The Passive House Canada chapter counts over 215 members, and offers Passive House trade and professional certifications. More than 70 people attended the Passive House Certified Designer/Consultant examination offered this past fall in Vancouver — numbers never seen outside of Germany. Registration or projected registration in Passive House Canada courses through mid-2017 currently exceeds 1000 participants, a massive leap forward in capacity building for the country.

BCIT recently launched a High-performance Building Hands-On Laboratory. The laboratory was established in response to a needs assessment conclusion that trades training for Passive House and all high-performance building standards and techniques was necessary. Building mock-ups, as well as practice walls, HVAC integration and an airtight house are current and envisioned components of the learning lab.

UBC-SALA also provides professional training in high-performance construction, and is about to launch a one-year master’s focused on this domain.

For the last several years, BuildEx, an annual conference targeting tradespeople and professionals in the building sector, has dedicated one of four streams to Passive House. A section of the trade show floor was also dedicated to Passive House builders and suppliers.

11. Business case and financing

The incremental cost of building to the Passive House standard is a common concern. Some builders and policy-makers consider the level of effort put into improving the enclosure, and the associated cost burden, to be disproportionate to the benefit. Even if cost effective on a life cycle basis, the business case for builders is not always easy to make because of a lack of knowledge of energy efficiency, uncertainty about future cost and savings, competing demands for limited capital, split incentive, and the tendency to discount and underestimate operating costs, amongst other factors (Table 16). Environmental protection and energy costs are not the only benefits of passive construction, however, and other values such as comfort, health, and prestige are often used to market higher performance.

There are many avenues to improve the business case for energy efficiency and address some of the barriers. The following sections summarize some of the most common ones.

Table 16. Barriers and solutions to business case and financing

Barriers	Solutions
Structure	
Risks and benefits accrue to different parties (split incentive) Existing incentives programs misaligned with PH, adding redundant requirements Tax disincentives as improved energy efficiency increases property taxes Cost of energy/carbon too low Incremental cost due primarily to (in order of most commonly mentioned): 1. Materials: windows, additional insulation/framing, HRV 2. Innovation: additional design cost for first 2-3 projects (decreases after that); cost of energy modelling 3. Labour: contactors that have not built yet to PH standard may factor in a safety buffer	Presence of energy labelling schemes to enable valuation of energy performance in real estate transactions Presence of stable financial mechanisms supporting market development for PH/NZEB Presence of tax remissions for certified NZEB buildings One-stop shop models for incentive distribution

Culture	
Improved energy performance and non-energy benefits not recognized in appraisal process	Habit of evaluating and calculating issues from a long-term perspective instead of short-term (e.g. life cycle costing instead of initial investment costing)
Work practices	
Time required to keep abreast of and apply for incentive programs; delay in receiving payment	Presence of integrated and functional tendering, like tendering based upon the design-build-finance-maintain (DBFM) method, leading to a high standard energy performance Rental and leasing contracts include heating & cooling costs Presence of a higher valuation of property with NZEB standard (requires comparable data and price signal) Use of investment and decision models supporting sustainable NZEB design and investment (e.g. LCC and/or DBFM-methods) Use of financial arrangements and contracts based on guaranteed performance

11.1 Energy labelling and benchmarking

The fact that prospective buyers or renters cannot readily 'see' the energy efficiency of a building makes it more unlikely to influence sales and purchase decision and pricing. Energy labelling provides a reliable mean for buyers to measure and compare energy efficiency of different buildings, thus providing the necessary information to allow its valuation by markets.[287] Once buildings are occupied, tracking, benchmarking, and disclosure of energy performance using platforms such as Energy Star Portfolio Manager[xli] provides a source of data for markets and a feedback mechanism to ensure continued performance of buildings.[288] Studies done in Europe, as well as Asia, Australia, and the U.S., have shown that buildings with higher energy efficiency, and labelled as such, can fetch price premiums on sales and rentals.[289]

In the absence of universal labelling/benchmarking schemes, the energy benefits of high-performance homes (and associated co-benefits) are still generally not taken into consideration

[xli] EnergyStar Portfolio Manager provides building owners with a platform to track the energy performance of their buildings over time, and compare them to buildings with similar function, size and climate. This provides building owners a unique tool to identify underperforming buildings; the simple act of tracking energy performance on a regular basis has been shown to reduce energy use on average 2.4% per year.

in the valuation/appraisal process in North America. The appraisal process, being evidence-based, requires comparable (similar type, similar market) buildings to have shown increased sales price before a value can be assigned to a feature. The paucity of such data in North America, and the absence of universal energy labelling schemes to provide a baseline, makes valuation of energy efficiency features in assessments more difficult.

There is, however, some research starting to emerge which could inform appraisal processes. A 2016 peer-reviewed study analyzed the sale of 800 homes that had undergone energy retrofits through Renovate America's PACE program in California. The study concluded that home sellers recovered their full investment cost at resale, if not more. This is remarkable considering that sale price lift from most other home improvements is generally about ~60% of their original cost.[290]

Studies in other jurisdictions show that universal energy labelling can help integrate the value of energy efficiency into sale and rental prices. An analysis of listing data for buildings for sale or rent in areas of Austria, Belgium, France and the United Kingdom has shown that, in general, a higher energy rating on the energy performance certificate (EPC) led to a higher sales and rental price (Figure 28). The sales premium for a one-letter improvement in energy efficiency ranged from a high of 11% in Austria to a low of 2.8% in Ireland.[291] Premiums on rental prices range from 1.4% in Ireland to 4.4% in Vienna.

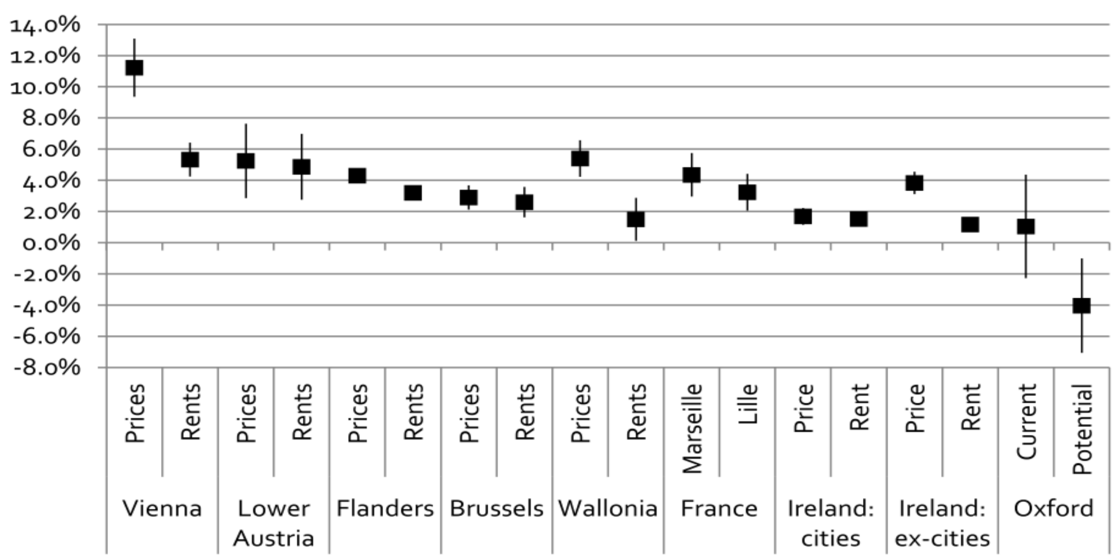


Figure 28. Effect of energy efficiency on European home sale prices and rental markets

Data shows impacts of a one-letter or equivalent improvement in the Energy Performance Certificate rating across European sales and rental markets. Bars indicate the 95% confidence interval.

Source: Mudgal et al[292]

This same study reviewed 25 studies analyzing the impacts on property values of various energy labelling schemes. The studies covered voluntary or mandatory labelling programs in the EU (EPC), Japan (Tokyo Green Building Programme), United States (Energy Star, Green Point and/or LEED), Singapore (Green Mark), Switzerland (Minergie) and Australia (ACT House Energy Rating Scheme). Most of the papers studied the impact of labelling on sales prices; a few also covered rental rates. Of the 22 studies considered, 19 showed higher energy performance ratings to have a positive impact on either rental or sales values, or both.[293]

Thus, introduction of mandatory energy labelling scheme and promotion of voluntary certification programs can help improve the business case for energy efficient buildings, while also accelerating uptake of high-performance enclosures. By stimulating investment in energy efficiency, labelling and benchmarking policies also drive economic development.[xlii,294]

11.2 Design competitions to increase demand and visibility

Between 2007 and 2013, through a design competition called Bâtiments Exemplaires (exemplary buildings, or 'BatEx'), the number of passive buildings in the Brussels–Capital Region increased from zero to 136, totaling over 350,000 square metres.[295]

The goals of the BatEx program were:

1. to stimulate demand for sustainable buildings through voluntary mechanisms;
2. to demonstrate the financial and technical feasibility of high energy efficiency performance buildings; and
3. to test capacity for a regulated minimum energy efficiency performance requirement.

The program offered three forms of incentives: cash incentives, technical support and recognition. The incentives were allocated through a design competition to new construction projects (61% of projects) and renovations (39% of projects). Six rounds of competition were held (2007, 2008, 2009, 2011, 2012, and 2013) resulting in:[296]

- 33 million euros granted (~C$8.25 million[xliii] per round), equivalent to less than 5% of total construction cost (815 million euros)

[xlii] A study by the Market Transformation Institute estimated that implementing a U.S.-wide reporting and disclosure requirement could reduce energy use in the U.S. by over 50,000 GWh per year, reduce energy costs by $3.8 billion per year and create 59,000 jobs by 2020.

[xliii] All $ values here are in Canadian dollars, based on a $1.50 per Euro conversation rate. Historically, Euro-USD coversion trends around USD$1.3 per Euro.

- 361 project proposals (~60 per round)
- 243 projects selected (~40 per round); 56% of these were passive buildings, the rest qualified as 'very low' or 'low' energy (i.e. with heating loads less than 15, 30 and 60 kWh/m^2, respectively)
- 621,000 m^2 built (~103,000 m^2 per round); 350,000 m^2 of which was passive, and
- 762 new or renovated social housing units; 505 of which were passive.

Cash incentives

Approved projects were awarded a subsidy of 100 euros/m^2 (~$14 per square foot), which is divided between the contracting authority (90 euros/m^2) and the developer (10 euros/m^2). With a maximum subsidy of 500,000 euros ($750,000) for the contracting authority and 100,000 ($150,000) for the developer, only the first ~5,500 m^2 (~60,000 square feet) of a project are subsidized.[297]

Capping subsidies in this way, where the average grant received per square metre decreased as the size of the project grew, allowed more projects to access cash incentives.[298] Juries also considered distribution of the funds across project types, location and project teams when selecting winning projects. Table 17 below shows the average grant and total area built for different building types over six rounds of competition. As a result of the cap, the per-metre square incentive for larger commercial projects can be quite low, averaging ~38 euros/m^2 (~$5 per square foot) over the 38 projects selected.

Table 17. BatEx average grant, total floor space, and number of projects per building type, 2007 – 2014

	Average grant (euros/m^2)	Total floor space (m^2)	Number of projects
Individual housing	97	15,313	67
Collective housing	53	199,161	74
Offices and businesses	38	242,609	38
Facilities	73	164,421	64

Data source: Bruxelles Environment[299]

Technical support

Advisors offered free technical assistance throughout the BatEx project tender process to designers and contractors.[300] The advisor involvement in BatEx projects played an important role in developing and disseminating good construction practices.

Recognition

Project visibility and the value of being recognized as an 'exemplary' building were key drivers of program uptake. High-profile opportunities included organization of visits and presentation of projects at seminars and to the media, building site tarpaulins, publications and brochures, a website dedicated to the call for project tenders and the winners (www.sustainablecity.be), and the presence of the environment minister at the opening ceremony of each BatEx building.

11.3 Direct and indirect subsidies

Subsidies for specific energy conservation measures, funded by public agencies or utilities, are a common way to improve the business case for high efficiency buildings.

Alongside the BatEx program, the Brussels capital region had an extensive energy subsidy program accessible to new and existing building. A suite of subsidies was made available for insulation, green roofing, glazed windows, and other materials, mechanical components and appliances for individual homes, collective housing, and tertiary sector buildings (Table 21). Subsidies are also available for energy audits and feasibility studies. A Green Social Loan was established to encourage low-income families to access zero interest loans, valued at 500 to 20,000 euros, to be used for insulation and effective heating. This helps the energy efficient building program as a whole reach as wide an audience as possible.[301,302] Between 2004 and 2009, 65 million euros (~$16 million / year) were allocated over 110,000 subsidies.[303]

Many other jurisdictions provide subsidies for energy efficiency measures. One of the oldest is the proKlima Fund, created in the 1998 through a partnership with the Municipality of Hanover (Germany) and the local energy supplier. Over 15 years, it has provided over 53 million euros to support the renovation of buildings and to establish the 'passive house' standard. For each euro of financial assistance provided by proKlima, an additional 12.7 euros has been leveraged from other investments.[304]

In Baltimore County, Maryland, the county provides a tax incentive for Passive House construction. Up to 100% of property taxes for three years (to a maximum of five for a carbon neutral building) is refunded for single and multi-unit residential buildings achieving energy savings greater than 30% based on a Passive House Certified Consultant's assessment.[305]

11.4 Financing

Financing programs aim to address barriers related to lack of awareness, competition for limited capital (i.e. when energy efficiency investment compete with other priorities), and split incentives (the benefit of greater comfort and energy efficiency not accruing to the party doing the initial capital investment).

Split incentives for the new market occur in any situation where the energy efficiency investment might be greater than the expected value lift from the improved performance and comfort. This is particularly true for short-term residential real estate tenures, as an owner planning to sell after a few years might not value longer-term investment on efficiency and durability. Split incentives also occur in commercial buildings with triple net lease arrangement, where tenants are responsible for real estate taxes, insurance, and maintenance, including utilities costs. Split incentives can occur even when the original developer/client is the long-term occupant of the space because budgets for capital expenditure and operation and maintenance are often managed separately. This is the case for most public building projects.

Financing mechanisms that can redistribute some of the initial capital cost over time and/or transfer some of the initial costs to the party who will benefit from the savings can alleviate split incentive barriers. Ideally, long-term amortization reduces payments such that they are offset by energy savings. Some of the most promising approaches are discussed below.

Property assessed clean energy (PACE)

PACE allows property owners to finance energy efficiency and renewable energy projects through an assessment on their property tax bills for up to 20 years. This structure, in theory, allows transfer of repayment obligation to the new property owner upon sale, thus eliminating the risk that an owner is unable to recoup the investment at the time the property is sold. Since the first states adopted enabling legislation in 2008, PACE has been authorized in 31 states and the District of Columbia.[306] However, an ongoing dispute on who should be repaid first in case of default (the PACE lender or the mortgage lender), [xliv] has significantly slowed program

[xliv] In 2010, Fannie Mae and Freddie Mac, the U.S.'s two government-sponsored mortgage backing enterprises, stated they would no longer purchase mortgage loans secured by properties with outstanding PACE loans. The Federal Housing Finance Agency (FHFA) was concerned that residential PACE assessments had a lien status superior to that of existing mortgages underwritten by Fannie Mae and Freddie Mac. This meant that, in the event of a default, any outstanding PACE assessments (though not the entire amount financed) would be paid off before other liens such as first deeds of trust. Since 2010, a number of developments have facilitated a resurgence of residential PACE programs, particularly in California. This included the passage of state legislation (SB 555), the implementation of legal instruments to address FHFA concerns and disclose the consequence a PACE lien can have on an existing mortgage, and the establishment of a PACE loss reserve program. Despite those, in 2014 the FHFA maintained their

development.[307,308] California is one notable exception, having over 44,000 PACE assessments valued at over $900 millions, nearly 90% of which are through Renovate America's HERO (Home Energy Renovation Opportunity) program.[309] many cities and counties in the U.S. now have PACE programs for residential, commercial and municipal sectors.[310]

Local improvement charges (LICs)

In Canada, enabling legislation in Ontario and Nova Scotia allows local governments to use LICs to provide energy efficiency financing programs for homeowners. LICs are a pre-existing mechanism used by municipalities to recover the costs of local capital improvements (such as improved sidewalks, sewers) by imposing charges on properties that benefit from the work. LIC-based retrofit pilot programs for detached and multifamily homes are currently underway in Toronto, and Halifax is launching a long-term LIC-based residential solar energy installation program after a successful two-year pilot involving 400 homes.[311] The City of Yellowknife in the Northwest Territories is also considering launching a LIC program.[312]

On-bill financing

Mostly used in the residential sectors, these are loan programs administered by utility companies and attached to the meter (so potentially transferable at time of sale, though the details vary). Repayments are made on the utility bills. As of 2012, 14 states in the U.S. had on-bill financing programs, with another six running pilots or having programs in the works.[313] Two of the longest running on-bill financing schemes in North America are located in Manitoba and Tennessee. Table 18 summarizes outcomes from these programs between 2001 and 2013. In both cases, contractors and suppliers played a central role in publicizing the program and in completing much of the paperwork for the homeowner.[314]

position on PACE, and still does not allow purchase or refinancing of properties with Fannie or Freddie mortgages if the property has a first-lien PACE loan attached to it. In August 2015, the White House and the Federal Housing Administration (FHA) announced they were working with the Department of Energy to develop lender guidance that would see PACE loans be subordinate to a first lien mortgage – thus siding with FHFA on this issue. While this might increase the risks (and therefore potential costs) of PACE loans, resolution of this pending uncertainty should facilitate the development of PACE program and enable the transfer of loans at time of sale.

Table 18: Program results for two on-bill financing programs, 2001-2013

Jurisdiction	Market penetration	Loan volume ($ millions)	Interest rate	Rejection rate	Default rate	Average energy saved per household (kWh/yr)
Manitoba	15%	$290	4.8-6%	5%	0.5%	825
Tennessee	2%	$500	6-8%	25%	3%	1,200-2,000

Source: Efe et al[315]

Public revolving funds

Revolving funds generally combine state-backed low-interest loans with grants and/or loan repayment bonuses to encourage investment in energy efficiency in new and existing buildings. The best example is the German KfW development bank's "energy efficiency renovation" program.[xlv] It is a very successful example of a public–private partnership, with KfW providing low-interest capital and grants, and local retail bank providing the client-interface for owners/builders.[316] The funds are generated through capital markets via bonds guaranteed by the government. The level of grants provided, and the maximal size of the loan, increases with the depth of the energy efficiency measures. KfW-approved loans can reach up to €75,000 per property at a preferential interest rate in the range of 1% to 3%.[317] This program is accessible to public sector, residential and commercial projects.

A 2011 study compared the costs of the program to the public revenues it generated through taxes concluded that the program returned nearly four times more to the public coffers than it costs; more than five times if reduction in unemployment benefits are included (Table 19).

[xlv] Note that the program, despite the name, covers both new and existing energy efficiency, as well as on-site renewables.

Table 19: Public budget implication of Germany's KfW energy efficiency grant and loan program, 2010

Item	Amount € M	% of program cost
KtW program costs	1,366	100%
REVENUES		
Taxes and levies on materials	2,682	196%
Income tax from increased labour	2,282	167%
Corporate tax	388	28%
TOTAL A (excluding impact of additional employment)	**5,352**	**392%**
Net increase in public funds after deducting program costs	3,986	292%
Reduced unemployment etc. benefits	1,823	133%
TOTAL B (including impact of additional employment)	**7,175**	**525%**
Net increase in public funds after deducting program costs	5,809	425%

Source: KfW[318]

Notes:

Costs include interest rates reductions and grants (covering 10% to 17.5% of the loan per household).

Total A represents the impact assuming all the additional labor is taken up by increased overtime, i.e. with no additional jobs, whereas Total B assumes all additional labor is down to new employment. The true figure would lie somewhere in between the two.

The table represents direct and induced investments (i.e. including grant value and contributions by owner). In new construction, only the additional investments related to energy efficiency is included (not the total cost of the project).

The value of the environmental benefits of reduced CO_2 emissions or increased energy security have not been quantified.

Transfers to condominium corporations

Another approach to dealing with split incentives in the condominium market could be to finance the incremental costs of efficiency separately from the rest of the development costs and have this loan transferred to condominium boards/strata. Condo owners would then repay the loan through an additional line on their fees, which, ideally, would be more than offset by reduced utility and maintenance costs. In the case of passive design approach, the increase could also be balanced by decreases in reserve fund payments, as the capital replacement costs of these simpler systems can lead to significant savings.[319]

One of the barriers to this approach is the fact that the condominium board does not itself own any assets to use as collateral to the loan, which increases risk for the financing agency. This is despite the fact that a strata is otherwise, an ideal lendee: it never changes address, has no key-person risk, and has a stable source of income.

12. Supply chain

A mature supply chain for high-performance components will help reduce the incremental costs of high-performance enclosures by providing a range of solutions and ensuring a competitive marketplace. Having a range of options to choose from will also help designers meet requirements of heritage districts, and avoid the need to compromise aesthetics for performance. Many practitioners have flagged the lack of options for high-performance windows and small-scale HRV units as a challenge in the current market.

The best way to stimulate supply chains is to create a predictable demand for the products. Thus, one of the most effective strategies to advance the market is to provide early signals of the intent to regulate, and ensure initial demand through incentives for early adopters and public procurement policies (Table 20). These topics have been discussed in previous sections. In this section, we delve into more details on the product incentives that supported the rapid growth of the passive market in Brussels, as well the opportunity for policy-makers to partner more closely with industry to maximize local economic development opportunities generated by the increased demand for passive buildings.

Table 20. Barriers and solutions in the supply chain

Barriers	Solutions
Structure	
Lack of suitable variety and competitive market for high-performance products (whether manufactured in North America or imported) Imported products do not have North American certification required by codes Testing procedures for locally manufactured products not trusted for PH	Predictability of demand; clarity of targets for codes and programs Presence of incentives for the industry to increase the local availability of high-performance products Recognition of equivalencies between North American and European certification standards
Work practices	
Difficulty in adapting passive design to match ‘look and feel’ of local buildings (e.g. historical districts, floor-to-ceiling glass towers, etc.)	Local development and availability of products suitable for PH Manufacturers/suppliers certify European products based on North America standards

12.1 Predictability of demand and component incentives

During the initial years of Brussels' BatEx program, the local supply chain faced stiff competition from imported Passive House-compliant components. Within a few years, however, local businesses including a number of small to medium enterprises were able to develop Passive House-certified products and compete effectively in the market.

Key to innovation was certainty that a market for higher quality products exists, as provided by the BatEx program, which was expected at the onset to be funded until 2014, the announcement in 2009 that all publicly owned buildings in the region would be built to passive standard starting the following year, and the announcement in 2011 that a passive house requirement would be put in place for new construction in 2015.

Further to this long-term secured demand, initial demand was stimulated through subsidies for energy efficient upgrades to appliances and components. Table 21 provides examples of the types of subsidies that were available in the early days of Passive House and energy efficient construction in Brussels.

Table 21. Energy subsidies available for Brussels residential sector in 2007

Component eligible for subsidy	Amount*	Maximum subsidy per project
Roof insulation	$18/m^2$ ($1.7/sq ft) of insulated area	$1,500
Insulation of external walls and/or floor	$37.5/m^2$ ($3.5/sq ft) of insulated area	$3,750
High efficiency double glazing	$75/m^2$ ($7/sq ft) of glazed area	$3,750
Mechanical ventilation with heat recovery	50% of cost	$4,500
External solar protection	20% of cost	$600
Condensing gas boiler	50% of cost	$750
On-demand gas water heater	50% of cost	$300
Heat pump for domestic hot water	50% of cost	$7,500 if used for heating $3,750 if DHW only
Thermal controls	50% of cost	$7,500
PV system	50% of cost	$4,500

Category A++ refrigerator or freezer	$300 per unit	N/A
Category A dryer	$300 per unit (for electric) $600 per unit (for gas)	N/A
Collective housing (2+ dwellings) and public/non-profit sector — in addition to above subsidies		
Energy audit	50% of cost	N/A
Feasibility study	50% of cost	N/A
Energy design study (pre-construction)	50% of cost	N/A
Energy monitoring system	50% of cost	N/A
Lighting retrofit	30% of cost	N/A
Speed regulator on ventilation compressors, pumps	20% of cost	$7,500
Pipe insulation	20% of cost	$7,500

* Where a percentage of the cost is covered, this includes both equipment and installation. Conversion: 1 euro = CAD$1.50.

Data source: EnEffect[320]

12.2 Industry partnerships

To engage more closely with industry partners that support and stand to benefit from the growth of a high-performance component market, the Brussels Capital Region created the Employment-Environment Alliance (AEE). The AEE is comprised of professional organizations, unions and other organizations working in the area of environmental protection. It uses a participatory approach, and focuses on job creation, economic development, and improvement of sustainability practices in the private sector. The members draft open collaboration proposals and share information and best practices.[321] This engagement with industry partners not only helps build political support for policies, but also allows adjustments to public policy to react to the reality of supply chains, and to facilitate the dissemination of market information needed to encourage its development.

13. Public and industry awareness of passive design and benefits

Implementing bold public policies to advance energy efficiency in the building sector requires some political capital, as budgetary constraints require a judicious balance of incentives and regulations (carrots and sticks) to drive change. This political capital relies on public and industry awareness of the social problems we are trying to solve, and of the solutions that are advanced. Public and industry awareness is also the first step to providing market demand and offer, to building capacity, and to ensuring proper operation and maintenance of high-performance buildings. Table 22 summarizes some of the barriers and solutions to increasing awareness of passive design. Below, we review research results on the role of universal labelling in creating awareness of energy efficiency, and give a short synopsis of a few successful marketing campaigns.

Table 22. Barriers and solutions to public and industry awareness

Barriers	Solutions
Culture	
Misconceptions around, and lack of awareness of, benefits of PH by policy makers, civil servants, consumers and suppliers Passive House perceived as a brand; brand issues	Marketing and communication strategy to create demand for PH/NZEB, taking into account different consumer segments and their specific characteristics Marketing and communication strategy to create political will and motivation to facilitate the transition towards PH/NZEB
Work practices	
Costs and lack of appropriate manpower to execute strategies on marketing and communication Lack of demonstration projects showcasing range of building types in various regions	Availability of resources needed to implement marketing and communication strategy Measurement of progress in actual implementation of marketing and communication strategy

13.1 Energy labelling

Studies have shown that energy labelling has a direct impact on increasing the awareness of energy efficiency.[322] In Ireland, for example, where energy performance certificates were phased in between 2007 and 2011, awareness of energy labelling on homes and buildings increased from 21% in 2008 to 69% in 2011.[323] Labelling and benchmarking would be important tools to increase public awareness about the significant energy efficiency offered by high-performance enclosures.[324]

13.2 Awareness campaigns

Passive House Days

In 2015, Passive House Days events were held in over 30 countries, including countries in Eastern and Western Europe, North America, and Asia-Pacific. Over 700 Passive House buildings were open for tours to the public. This was the twelfth annual Passive House Days. In addition to tours, there were also conferences, seminars, workshops offered by Passive House members around the world.[325]

Be Normal campaign

Promotion of the Passive House standard in the Brussels–Capital Region was done through highly visible outreach and advertising. In addition to the launch of the magazine Be.Passive to showcase Passive House standards and new projects, fun public events, Passive House Fairs and symposia were organized in the region. Creative outreach and advertising using tactics like flash mobs and an ad campaign[326] were used to draw attention to, de-mystify and normalize Passive House, and make it understandable for all residents.

Ice challenge

The Ice Challenge[327] was a successful public outreach and education interactive art installation/event organized by Passiefhuis Platform (PHP) in Brussels and Antwerp, with the aim to illustrate the benefits good building insulation. Two 1,300 kilogram blocks of ice were placed into two shacks — one very well insulated, the other one — not. During the summer months, the two shacks were placed side by side in Antwerp and Brussels city centres for everyone to see. Visitors guessed how much ice would be left in each shack after 40 days. During the 2007 Ice Challenge, more than 450 kilograms of ice still remained in the well-insulated cabin; the ice in the non-insulated one had completely melted after 11 days.[328]

Figure 29. The Ice Challenge

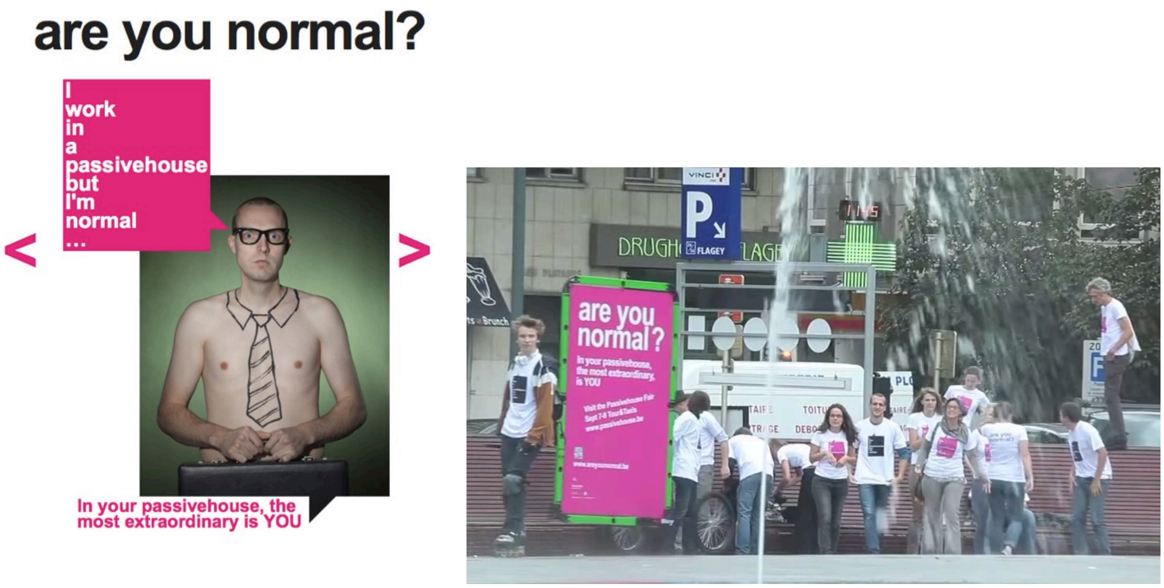


Figure 30. (a) Poster and (b) guerilla marketing from Brussels' education and outreach campaign

14. Quality assurance

As discussed in the conclusion of Part 1 (Section 7), by increasing the expectation we have of buildings, passive design simultaneously increases the risk of failures. As we transition from a voluntary standard implemented by keen early adopters to a broader adoption of passive design principles, we will need to set in place robust quality assurance processes. Not only do these help prevent possible failures, but they also provide a feedback mechanism for builders and policy makers to enable continuous improvement.

Table 23. Barriers and solutions to quality assurance

Barriers	Solutions
Work practices	
Insufficient delivered quality Lack of experts capable of doing quality assurance Lack of infrastructure to perform quality assurance Improper use and maintenance of PH/NZEB Value of certification beyond the first 2-3 projects does not justify the cost / time investment	Presence of a well-functioning regional infrastructure for quality assurance (tests, specifications and/or other specific methods) Availability of sufficient PH/NZEB solutions for quality assurance in region (quality performance criteria sets, descriptions and procedures) Presence of a sufficient number of experts to perform quality assurance on PH Monitoring of PH projects in terms of indoor climate, costs, energy performance etc. Requirements of quality performance in contracts for PH Training provided for maintenance teams, tenancy managers and homeowners

14.1 Passive House certification

Certification agencies play an important role in the current passive house ecosystem by providing builders and buyers a third-party quality assurance process. By providing support during the design process and by reviewing energy models, wall assemblies, and component selection, they help ensure the construction follows sound building science. This increases the likelihood that the building will actually meet its energy targets once operated, and mitigates the risk of failures: moisture problems, overheating, or insufficient ventilation leading to sick building syndrome, etc.

Interviews with practitioners revealed that many of them certified their first few buildings in order to access to this support and quality assurance; once they gained confidence in their preferred building approaches and solutions, many opted out of certifying their building to gain more flexibility in design and/or avoid certification costs.

14.2 Performance bonds

In some jurisdictions such as Washington, D.C., a performance bond is retained at time of building permit to create some accountability for the energy outcomes. The value of the performance bonds is returned to the project proponent only once the building is proven to have met, in practice, the performance requirement agreed upon at the permitting stage. This approach is being considered for the Moodyville development in North Vancouver (section 9.2)

14.3 Monitoring studies and monitoring of market through benchmarking

Locally conducted monitoring studies of demonstration projects are an important step in building confidence in the effectiveness and safety of high-performance enclosure and in assessing their cost-effectiveness from a consumer and/or builder perspective.[329, 330] In many leading jurisdictions, this research is conducted, or at least compiled, by a central agency: the Passivhaus Institute in Germany, PHIUS in the U.S., IGpassivhaus in Austria, PHP/PMP in Belgium, to name only a few. The International Passive House Association (iPHA) provides a global network to connect these regional organizations.

The use of energy benchmarking platform such as Energy Star Portfolio Manager also offers the capacity to track the performance of complex buildings over time, and compare them to their peers. The development of benchmarking, reporting, and policy disclosure such as those in place in New York, Chicago, and Seattle will systematize this data collection and make the data sets widely available for research and analysis.[331,332] This will in turn provide crucial feedback to inform the development of energy codes.[333]

15. Part 2: Conclusion

High-performance enclosures rely on relatively simple products and practices, most of which are already familiar to builders. Nevertheless, assembling these components to get maximal performance while ensuring durability and comfort represents a shift for the industry. Energy modelling will need to become an integrated part of the design process, to optimize shape, solar heat gains and shading, and to account for internal heat sources. Increased air tightness brings the need for mechanical ventilation, which will need to be mindfully designed to supply fresh air where needed, balance humidity, and redistribute heat. Interfaces and penetrations in the enclosure need to be detailed to ensure continuity of insulation and air barrier and avoid rain infiltration. Protection of the air barrier, new procedures for the installation of high-performance windows, and installation and balancing of HRVs will require additional care during construction. Practitioners in the field would certainly add a few items to this list, but it would not fill a page. These are significant changes, but nothing insurmountable. This is the next step in a continuously evolving industry: an evolution, not a revolution.

What makes this situation different from 'natural evolution' of the field, however, is the sense of urgency. Countries, states, provinces, and cities across North America have committed to taking action to avoid the worst impacts of global warming, and adopted targets informed by climate science. When looking at emissions from the building sector, they face a unique challenge: buildings last a long time. And because retrofitting buildings to increase their energy efficiency is costly and slow given the multitude of dispersed owners who need to care, understand, and invest, it is crucial that new buildings are built to the best standard as soon as possible. Each building that we allow to be built to current standards is a 50+ year liability in a world that needs to be almost fully decarbonized within the next 30 years. More than the nature of the transformation, it is its necessary pace that calls for public and private mobilization.

The last six chapters gave an overview of the barriers we face and presented some solutions to these obstacles. The barriers vary by location, ownership structure, and market segment. Fortunately, not all of these barriers require direct intervention to be resolved; properly stimulated, the market will fill the gaps. Many barriers will be resolved once some basic market failures are addressed through energy labelling, financing, and carbon pricing. Other barriers will be best addressed through programs and policies that create a predictable demand for passive buildings. This will prime the supply chains and provide a critical mass such that everyone will know, within a few year, someone who has experienced first-hand the thermal comfort and air quality of passive buildings.

Building from the European and North American experience, Table 24 provides recommended next steps.

Table 24. Early strategic actions for market transformation

Goal	Strategy	First steps / key consideration	Examples
Get more passive buildings on the ground	Public procurement policy	Political direction Procurement best practice guides Procurement policy review	NYC-owned building policy LL31/2016 Scotland procurement review
	Rezoning incentives and removal of barriers	Thick wall exclusions Density bonusing Code variances to enable passive solutions	NYC Green Zoning Vancouver Zero Emissions Building Plan
	Incentive for low-cost, high-performance 'exemplary' buildings	Tailor incentives (visibility, cash, density) and selection process (design competition vs. program) to different market segments	BatEx, Brussels
Ensure markets and policy-makers have energy data	Benchmarking, reporting and disclosure Universal home energy labelling	Start with reporting requirements and setting up information management systems. Announce disclosure requirements at least two years in advance.	NYC, Chicago benchmarking policies European energy performance certificates
Facilitate access to capital	PACE	Enabling legislation and clarity on liens to enable transfer at sale	California PACE programs
	Government backed green development funds	Political vision and creation of fund	Germany's KfW Bank
Facilitate training and flow of information	Centres of excellence Regional practitioner hubs	Gap analysis considering existing training networks and institutions. Consider one-stop shop model for training services and data gathering/analysis	BEEx Scotland construction hubs. NAPHA and NAPHN
Clarity on code evolution	Code roadmap Stretch code Mobilize the voice of the 'green economy'	Provide long term target for new building performance and target for next code revision Align beyond-code programs and incentives with long term vision and use to clear path for code revision	Washington State code roadmap California 2020/2030 NZE goals Massachusetts reach code

Internalize full cost of energy	Carbon pricing	Carbon tax increasing over time in rate and scope or join cap and trade system	BC Carbon tax WCI carbon market
	Utility rates	Conservation stepped-rate and time of use rates	Various

1. **Get more passive buildings on the ground.** Support the market segments that are already well underway (detached to mid-rise residential) or emerging (office, schools). Prioritize simple solutions that can be broadly applied, but also encourage projects that provide high visibility or break new grounds: high-rise MURBs, high-rise office, city halls, libraries. Collect basic data on the project economics and design strategy and work with research institutions to conduct detailed monitoring of energy use and indoor conditions.

2. **Ensure markets and decision makers have access to energy information.** If you can't measure it, you can't manage it. Require benchmarking and reporting based on square footage, starting with larger buildings first and including smaller ones over time. Put in place home energy labelling requirements for new construction and at point of sale/renovation. These will provide the feedback mechanisms needed to guide code evolution, facilitate valuation of energy efficiency, and drive the retrofit market.

3. **Free up additional capital to cover incremental costs.** Create legislative structure to enable private industry to provide services combining lending and technical support (e.g. PACE model). Use government bonds to provide low-cost capital for loans and incentives and assess the potential for increased public revenues; the increased revenue and economic activity triggered will return more funds to public coffers (e.g. KfW model).

4. **Create information sharing hubs offering training for industry and providing public education and outreach**. There is also need for a body to compile and analyze energy and costing data, to monitor the state of the market for high-performance components, and provide support for code development and design of demand-side management programs. These two functions can be joined, or assumed by different bodies, but in both cases they will likely play primarily a coordination role between various organizations providing the services.

5. **Prepare the ground for regulation.** Set mid- and long-term targets to allow time for industry to prepare and for policy development. Use information gathered from early projects to test economic and technical feasibility. Use benchmarking data to monitor impact of energy code changes and market evolution.

The pace of change that is called for will be faster than is natural, and will require government intervention and mandates. This transformation will also offer significant economic opportunities; unfortunately, the parties that stand to benefit are distributed and historically have not had a strong political voice. This is also changing, as the 'green economy' movement grows. The construction industry stands to gain in this transformation; as money moves from operational budgets to capital budgets, it also flows from the energy sector into the construction sector.

Change creates risk, and risk has a cost. But the risk can be mitigated if the change is well planned and implemented in collaboration with stakeholders across the building sector. The end result will see a stronger, more innovative, and rejuvenated construction industry; and as the construction sector across North America struggles with recruiting millennials and faces a demographic labour cliff, a shift towards a more innovative, technologically empowered industry will contribute to bringing in new blood. This shift is already well underway and accelerating, with leading jurisdictions in North America paving the way for widespread adoption of high-performance enclosures.

Appendix A. Interviewees

Table 25. List of interviewees

#	Name	Title
01	Ken Levenson	CFO / Sales Director, 475 High Performance Building Supply (NY)
02	Tad Everhart	Energy Advisor LLC (OR)
03	Dylan Lamarr	Architect & Energy Consultant, Green Hammer (OR)
04	Timothy McDonald	Associate Professor, Temple University (PA)
05	David Salamon	Certified Passive House Designer, WRT (PA)
06	Sean Pander	Green building manager, City of Vancouver (BC)
07	Rob Nicely	President, Carmel Building & Design (CA)
08	Tomàs O'Leary	Co-Founder & Managing Director, Passive House Academy (EU)
09	Katy Hollbacher	Principal and founder, Beyond Efficiency (CA)
10	Allen Gilliland	Founder, One Sky Homes (CA)
11	Richard C. Yancey	Executive Director, Building Energy Exchange (NY)
12	Rob Bernhardt	President, Passive House Canada & Bernhardt Developments Ltd (BC)
13	Rob Hawthorne	Owner, architect, PDX Living (OR)
14	Helen Goodland	Principal, Brantwood Consulting Partnership (BC)
15	Rich Chien	GreenFinanceSF Program Manager, City of San Francisco (CA)
16	Gregory McCall	Energy Policy Specialist, Building Review Branch, Planning and Development Services, City of Vancouver (BC)
17	Katrin Klingenberg	Executive Director, PHIUS (IL)
18	Elizabeth Hanson	Senior Policy Advisor, NYC Mayor's Office of Sustainability (NY)
19	John Lee	Deputy Director for Green Buildings and Energy Efficiency, NYC Mayor's Office of Sustainability (NY)
20	Brandon Nicholson	Founding Principal, NK Architecture (WA)
21	Amina Lang	International Communications, Passive House Institute (EU)
22	Bill Uhrich	Principal, SIMCIC + UHRICH ARCHITECTS
22	Monte Paulsen	Managing Director, Red Door Energy Design Ltd. (BC)

Appendix B. Passive House Standards criteria

B.1 Passive House Institute

Three levels of Passive House certification for new construction can be achieved: Classic, Plus and Premium. The three certifications recognized are based on demand and generation of renewable energy.

Table 26. PHI Passive House Criteria

			Criteria[1]			Alternative Criteria[2]
Heating						
Heating demand	[kWh/(m^2a)]	≤	15			-
Heating load[3]	[W/m^2]	≤	-			10
Cooling						
Cooling + dehumidification demand	[kWh/(m^2a)]	≤	15 + dehumidification contribution[4]			variable limit value[5]
Cooling load[6]	[W/m^2]	≤	-			10
Airtightness						
Pressurization test result n_{50}	[1/h]	≤	0.6			
Renewable Primary Energy (PER)[7]			Classic	Plus	Premium	
PER demand[8]	[kWh/(m^2a)]	≤	60	45	30	±15 kWh/(m^2a) deviation from criteria...
Renewable energy generation[9] (with reference to projected building footprint)	[kWh/(m^2a)]	≥	-	60	120	...with compensation of the above deviation by different amount of generation

Data source: Passive House Institute[334]

Notes:

1 The criteria and alternative criteria apply for all climates worldwide. The reference area for all limit values is the treated floor area (TFA) calculated according to the latest version of the PHPP Manual (exceptions: generation of renewable energy with reference to projected building footprint and airtightness with reference to the net air volume).

2 Two alternative criteria which are enclosed by a double line together may replace both of the adjacent criteria on the left which are also enclosed by a double line.

3 The steady-state heating load calculated in the PHPP is applicable. Loads for heating up after temperature setbacks are not taken into account.

4 Variable limit value for the dehumidification fraction subject to climate data, necessary air change rate and internal moisture loads (calculation in the PHPP).

5 Variable limit value for cooling and dehumidification demand subject to climate data, necessary air change rate and internal heat and moisture loads (calculation in the PHPP).

6 The steady-state cooling load calculated in the PHPP is applicable. In the case of internal heat gains greater than 2.1 W/m^2 the limit value will increase by the difference between the actual internal heat gains and 2.1 W/m^2.

7 The requirements for the PER demand and generation of renewable energy were first introduced in 2015. As an alternative to these two criteria, evidence for the Passive House Classic Standard can continue to be provided in a transitional phase by proving compliance with the previous requirement for the non-renewable primary energy demand (PE) of QP ≤ 120 kWh/(m^2a).

The desired verification method can be selected in the PHPP worksheet "Verification". The primary energy factor profile 1 in the PHPP should be used by default unless PHI has specified other national values.

8 Energy for heating, cooling, dehumidification, DHW, lighting, auxiliary electricity and electrical appliances is included. The limit value applies for residential buildings and typical educational and administrative buildings. In case of uses deviating from these, if an extremely high electricity demand occurs then the limit value can also be exceeded after consultation with the Passive House Institute. Evidence of efficient use of electrical energy for all significant devices and systems is necessary for this with the exception of existing devices which have already been owned by the user previously and for which an improvement of the electrical efficiency by means of upgrading or renewal would prove uneconomical over the lifecycle.

9 Renewable energy generation plants which are not spatially connected to the building may also be taken into account (except for biomass use, waste-to-energy plants, and geothermal energy): only new systems may be included (i.e. systems which did not start operation before the beginning of construction of the building) which are owned by the building owner or the (long-term) users (first-time acquisition).

B.1.1 Certification levels

The heating demand of a Passive House may not exceed 15 kWh/(m^{2}a). This will continue to apply, but with the introduction of the new categories,[335] the overall demand for renewable primary energy (PER / Primary Energy Renewable) will be used instead of the primary energy demand, which was previously used. In the case of the Passive House Classic category, this value will be 60 kWh/(m^{2}a) at the most. A building built to Passive House Plus is more efficient as it may not consume more than 45 kWh/(m^{2}a) of renewable primary energy. It must also generate at least 60 kWh/(m^{2}a) of energy in relation to the area covered by the building. In the case of Passive House Premium, the energy demand is limited to just 30 kWh/(m^{2}a), with at least 120 kWh/(m^{2}a) of energy being generated.

B.1.2 PER factors

The sun and wind provide primary electricity. Some of this electricity can be used directly. However, storage capacities are necessary for transferring surplus energy to time periods with lower energy gains. These supply secondary electricity as required, and this is associated with losses. Depending on the type of energy application, the proportion of primary and secondary electricity varies, as do the losses for providing energy. These specific energy losses of an energy application are described as the respective PER factor. The demand for domestic energy is quite constant throughout the year, which is why the share of direct electricity is high and the PER factor is low. In contrast with this, heating is necessary only in winter. In order to provide enough energy in winter, electricity must in part be produced in summer and stored with very high losses for the winter, which results in a high PER factor.[336]

B.1.3 Other low energy standards

The PHI Low Energy Building standard is used for buildings that cannot meet Passive House criteria for various reasons.

The EnerPHIT standard is applied to existing buildings undergoing retrofit and refurbishing of components. Compliance with EnerPHIT is demonstrated either through components used (windows, insulation, exterior colour, ventilation) or through energy demand (energy required for heating, cooling and dehumidification) of the building. Requirements vary depending on which climate zone (arctic, cold, cool-temperate, warm-temperate, warm, hot, and very hot) the building is located. EnerPHIT Classic, Plus, and Premium certification can be achieved, depending on the demand and generation of renewable energy.

Table 27. Additional criteria applicable to all PHI Passive House levels

Topic	Criteria
Frequency of overheating	Percentage of hours in a given year with indoor temperatures above 25 °C: • without active cooling: ≤ 10 % • with active cooling: cooling system must be adequately dimensioned
Frequency of excessively high humidity	Percentage of hours in a given year with absolute indoor air humidity levels above 12 g/kg • without active cooling: ≤ 20 % • with active cooling: ≤ 10 %
Minimum thermal protection	Maximal thermal transfer coefficients for slab insulation, walls, windows, roof. • Vary based on climate and enclosure component, see Section 2.4 Table 6
Occupant satisfaction	All rooms with prolonged occupancy must have at least one operable window. It must be possible for the user to operate the lighting and temporary shading elements. Priority must be given to user-operated control over any automatic regulation. In case of active heating and/or cooling, it must be possible for users to regulate the interior temperature for each utilisation unit. The heating or air-conditioning technology must be suitably dimensioned in order to ensure the specified temperatures for heating or cooling under all expected conditions
Ventilation system	The ventilation volume flow rate must be adjustable for the actual demand. All rooms within the thermal building enclosure must be directly or indirectly (transferred air) ventilated with a sufficient volume flow rate. If a relative indoor air humidity lower than 30% is shown in the PHPP for one or several months, effective countermeasures should be undertaken The ventilation system must not cause uncomfortable draughts. Ventilation noise: • ≤ 25 db(A): supply air rooms in residential buildings, and bedrooms

	and recreational rooms in non-residential buildings • ≤ 30 db(A): rooms in non-residential buildings (except for bedrooms and relaxation rooms) and extract air rooms in residential buildings

Data source: Passive House Institute[337]

B.2 Passive House US

Another major proponent of passive house design in North America is the Passive House Institute US (PHIUS.org), founded in 2007. Once a certifier for PHI, PHIUS now has a separate building performance standard, dubbed PHIUS+2015.[338] The targets for new new standard were developed in cooperation with Building Science Corporation under a U.S. DOE Building America Grant.[339] The study yielded a formula that has been used to generate cost-optimized performance targets for more than 1,000 locations. The PHIUS Technical Committee aim to update the formula every three to five-year to reflect changing economic, climate, and other variables.

Certification criteria and targets for a sample of cities in Canada and the U.S. are presented in Table 28 and Table 29.

Table 28. PHIUS + 2015 Certification criteria

Annual heating demand[a]	< A kWh/m^2
Annual cooling demand (sensible + latent) [a]	< B kWh/m^2
Peak heating load[a]	< C W/m^2
Peak cooling load[a]	< D W/m^2
Airtightness[b]	≤ 0.05 cfm/sf enclosure @50Pa[d]
Primary energy demand[d]	≤ 6200kWh/yr/person

Data source: PHIUS[340]

Notes

a. See Table 29 for a sample of target values for major cities across North America
The heating and cooling criteria are determined from formulas based mainly on local climate factors including degree-days, outdoor design temperatures and design humidity, and annual solar radiation. The formulas were developed from life cycle cost optimization studies. As a result the heating criteria also depend secondarily on energy prices (on a state-by-state average basis), because higher electricity prices justified more investment in heat-saving upgrades. The energy price effect was not statistically significant for cooling, thus the cooling criteria depend only on climate factors. For now, there is the option to calculate the project peak loads in WUFI Passive/PHPP, or Manual J. Targets vary depending on the calculation method.

b. A whole-building test for air tightness must be performed. If testing at 75 Pa, report the flow coefficient and exponent from the blower door tests. The requirement is as follows:

For buildings of five stories and above that are also of noncombustible construction: q50 <= 0.080 CFM_{50}/ft^2 or q75<= 0.100 CFM_{75}/ft^2 of gross enclosure area

For all other buildings: q50 <= 0.050 CFM_{50}/ft^2 or q75<= 0.080 CFM_{75}/ft^2 of gross enclosure area

c. Conversion to ACH will depend on volume of the house, but is roughly equivalent to 1.3 ACH for a ~1,200 sqft home. See PHIUS+2015 single family home calculator http://www.phius.org/Tools-Resources/Protocols-Calculators/PHIUS+2015_Calculator_Single_Family.xlsx

d. Occupancy is determined by the # of bedrooms + 1, per unit

Table 29. PHIUS + 2015 Certification targets for a sample of Canadian and U.S. cities

Zone	City	State	Imperial				S.I.			
			Annual heating demand	Annual cooling demand	Peak heating load	Peak cooling load	Annual heating demand	Annual cooling demand	Peak heating load	Peak cooling load
			$kBtu/ sf_{iCFA}$		$Btu/ sf_{iCFA}\cdot h$		kWh/ m^2_{iCFA}		$W/m^2_{iCFA}\cdot h$	
Canada										
7	Calgary	AB	7.8	1.0	5.7	3.3	24.7	3.2	18.1	10.4
7	Edmonton	AB	8.4	1	5.8	3.3	26.5	3.2	18.2	10.4
6	Montreal	QC	7.6	1.8	5.6	3.7	23.9	5.7	17.7	11.7
6	Saint Johns	NL	8.3	1	4.4	3	26.1	3.2	13.9	9.4
5	Toronto	ON	6.4	2.1	4.8	4	20.1	6.5	15.1	12.5
4C	Vancouver	BC	5.5	1	3.8	2.9	17.4	3.2	11.9	9.2
U.S.										
8	Barrow	AK	16.7	1.0	5.8	1.5	52.6	3.2	17.2	11.1
7	Adirondack	NY	8.1	1	5.5	3.5	25.4	3.2	17.6	13.5
6	Minneapolis	MN	6.9	3.1	5.6	4.3	21.9	9.8	16.0	13.8
5	Chicago	IL	6	3.6	5.1	4.4	19	11.4	13.2	12.0
4A	New York	NY	5.2	2.1	4.2	3.8	16.3	6.6	8.5	10.1
3C	San Fran.	CA	2.5	1.0	2.7	3.2	7.9	3.2	9.6	16.5
2A	Pensacola	FL	1.7	12.3	3	5.2	5.2	38.9	4.2	17.3
1A	Miami	FL	1	19.6	1.3	5.5	3.2	61.8	18.1	10.4

Source: PHIUS[341]

Notes:

iCFA= Interior Conditioned Floor Area

Appendix C. Programs or policies to encourage high-performance enclosures in North America

C.1 Enabling policies and political vision

- **City of Vancouver Zero Emissions Building Plan (2016):** Vancouver is the first major North American city to establish a detailed roadmap of targets and actions to achieve zero emissions in all new construction by 2030. The city plans a phased approach with interim targets of 70% emissions reduction in newly permitted buildings by 2020 and 90% by 2025.[342]This plan would make passive house thermal performance a requirement for all low-rise residential development in Vancouver by 2025 (and for all low-rise rezonings by 2020).
- **President Obama energy efficiency and renewable energy in residential sector announcement (2015):** press releases cites the inclusion of Passive House track in New York State's Home and Community Renewal 2015 RFP.[343]
- **New York City's low-carbon building strategy, NY (2014):** Mayor Bill de Blasio office's released *One City: Built to Last* in 2014, articulating a vision for dramatically reduced greenhouse gas emissions from buildings. It states that New York City will look to ''Passive House, carbon neutral, or 'zero net energy' strategies to inform the standards.''[344]
- **Marin County (CA) building code** (2013): Marin County code encourages ''green building'' by authorizing the establishment of incentives for ''green building compliance'', citing Passive House Institute as one of three eligible standard-setting bodies (along with Build It Green and the U.S. Green Building Council.)''[345]

C.2 Procurement policies

- **Affordable housing policies (various locations):** Developers applying for tax-credit funding for multi-unit affordable housing projects must compete to access this funding. Qualified Allocation Plans (QAPs) establish scoring criteria to assess projects; some grant additional points for Passive House projects.

  - **The Pennsylvania Housing Finance Agency (PHFA) (2014):** PHFA is granting 10 points (out of 130) for development that meet Passive House certification requirements under iPHA or PHIUS.[346] As a result, in first year of the policy 39 of the 85 projects submitted (35%) were PH. The agency funded eight PH projects, totaling 422 units. This is the largest concentration of PH in the U.S.[347]
  - **The New York State Homes & Community Renewal (HCR) (2015):** awards five points (out of 100) for projects seeking Passive House certification or other green standard (Enterprise Green Communities, LEED, National Green Building Standard)[348]
  - **Other states agencies having indicated intent to include PH criteria:** Idaho (IHFA: 2015), Illinois (IHDA: 2015), Delaware (DSHA: 2016), New Jersey (SNJHMFA: 2016), Rhode Island (RHI: 2016)[349]
- **New York City** Local Law LL31/2016[350]: passed in March 2016, this new law requires that new capital projects for city-owned property (new construction, additions and substantial reconstruction) be designed to use no more than 50% of energy used today (called "low energy intensity buildings"). All projects must also consider the feasibility of providing at least 10% of energy from onsite renewables, and projects three stories or less must consider the feasibility of net zero energy use.[351, 352]
- **City of Vancouver Passive House procurement policy (in development):** The 2016 Zero Emissions Buildings plan states that Passive House certification will be required for all new city owned buildings, unless it is deemed unviable. A new fire hall is already being planned to achieve Passive House certification.[353] The Vancouver Affordable Housing Agency has also incorporated a requirement to assess projects against the Passive House standards as part of its RFP process. A new social housing unit is being planned as a passive house project.[354]

C.3 Changes in land use for additional density and floor space

- **City of Vancouver Green Rezoning Policy (2010, 2014, 2016):** requires rezoning for large commercial and multi-unit residential projects to meet stringent thermal energy demand and greenhouse gas intensity targets, or else to achieve Passive House certification. This policy impacts 60% of square footage developed in the City of Vancouver (an estimated 2.6 million square feet of new development each year), and essentially mandates a level of performance approaching the Passive House standard for rezonings.[355] The 2016 Zero Emissions Building Plan stipulates that low-rise MURBs rezoning will be required to meet the passive house thermal load intensity target of 15 $kWh/m^2/year$ by 2020, with the requirement being extended to all new low-rise MURBs by adoption in the Vancouver Building Bylaw by 2025.
- **City of Vancouver thick wall exclusion (2010, 2015, 2016):** allows all building types to exclude the area used for insulation exceeding minimum code requirements in floor space ratio calculation. Maximum limit on exclusion was explicitly based on the amount of insulation deemed required to achieve PH. In 2016, Council granted the director of planning discretion to relax height and setback requirements to make use of the square footage gained from the wall thickness exclusion.[356]
- **City of New York Zone Green thick wall exclusion (2012):** Zone Green allows for up to 8 inches of wall thickness to be exempted from the calculation of floor area to encourage high-performance buildings without decreasing the amount of usable space in the building. This exemption applies where above-grade exterior walls exceed the thermal enclosure requirement of the New York City Energy Conservation Code by a prescribed percentage.[357]

C.4 Streamlining permitting and inspection

- **San Francisco priority permitting (2014, updated 2015):** the planning department offers accelerated permit processing to multi-unit residential (or large commercial) building that are Passive House Certified (PHIPHI, PHIUS, or EnerPHit), LEED Platinum, or Net Zero Energy (as defined by Living Building Challenge).[358]
- **City of Vancouver building officials training (2015):** To ensure there is no delay in processing applications for Passive Houses, the City of Vancouver will provide training on passive design and construction to city staff. This will primarily engage staff in Housing Review and Inspections, but also in Development Review, Development

Planning, and Building Review. Staff have created a draft specialized application process for Certified Passive House projects for one or two family homes.[359]

- **City of Vancouver Passive House equivalency (2015):** City made some allowance for PH certified HRV windows and door components, that might not have equivalent NAFS certification.[360]

C.5 cash incentives, tax credits, fee rebates

- **Baltimore County High Performance Home tax credit:** up to 100% refund of property taxes for three year (or five for a carbon neutral building) for single and multi-unit residential building achieving energy savings greater than 30% as attested by a PH Certified Consultant.[361]

Appendix D. Regulatory barriers to high-performance enclosures in North America

Based on interviews with practitioners and two workshops at the 15th North American Passive House Network Conference (Vancouver), this section summarizes ways in which current regulations are creating barriers for passive design. Of these, the loss of useable floor space because of thicker walls was flagged as the most important issue to resolve in areas with high land value.

Land use policies

- Floor space ratio, setbacks, height restrictions: thicker walls lead to loss of useable area
- Setbacks prevent addition of external insulation for retrofit of existing buildings
- Rezoning: incentives for Green buildings commonly based on LEED
- Historical districts: Lack of local component matching historical preservation requirements
- Cantilevered balconies not counted as site coverage but balconies supported by posts are (posts needed to avoid thermal bridging)
- District energy connectivity requirements: standing charge even if not connected
- Design panel pushback on energy efficient design and insistence on copious use of glazing

Codes, permitting and inspection

- Permit reviewers and inspectors not used to new types of wall assemblies (particularly for commercial buildings) and ventilation systems

Specific elements / systems causing issues

Ventilation

- Code requirement based on exhaust by kitchen/bathroom; conflicts with continuous ventilation from HRV, synced through-wall heat exchangers, etc.
- Code limits proximity of intake and exhaust to each other and to openings or windows; incompatible with installation of wall-mounted HRVs in smaller units

- Code does not accept recirculating kitchen hoods, or combining of kitchen and bathroom exhaust
- Fire code does not accept plastic flex-ducts
- Venting requirements for elevator mechanical rooms, stairwells, and others vertical shafts
- Indoor air quality code requirements for outdoor air inlets in windows (e.g. Washington State Ventilation and Indoor Section 303.4.1.5)

Glazing: Windows and doors

- Imported components do not have required North American certifications (NAFS, UL).

Structural wood

- Most fire districts in NYC don't allow wood frame construction

Incentive programs

- Incentive programs require verification through energy model platforms that were not designed for high-performance buildings
- Misalignment between Energy Star and Passive House: Energy Star requires blower door test of the individual units, Passive House requires test of the entire building. Energy model requirements are different (for Energy Star performance path) and prescriptive path may not be available in future.

Appendix E. RCES-2009 data and climate zone definition

Table 30. Median energy intensities from RCES-2009

Building type	Very Cold / Cold	Hot-Dry / Mixed-Dry	Hot-Humid	Mixed-Humid	Marine
Average Heating EUI (kBTU/sqft)[a]					
Single-Family Detached	32	11	4	19	16
Single-Family Attached	37	9	5	23	17
Apartment in Building with 2 - 4 Units	52	16	5	29	19
Apartment in Building with 5+ Units	36	11	6	19	13
Average Cooling EUI (kBTU/sqft)[b]					
Single-Family Detached	0	3	9	3	0
Single-Family Attached	1	1	8	2	0
Apartment in Building with 2 - 4 Units	0	1	8	2	0
Apartment in Building with 5+ Units	1	2	8	3	0
Total EUI [(kBTU/sqft)[c]					
Single-Family Detached	60	50	41	51	48
Single-Family Attached	67	41	37	57	48
Apartment in Building with 2 - 4 Units	91	61	39	70	49
Apartment in Building with 5+ Units	68	47	38	55	42
Sample size (number of dwellings)					
Single-Family Detached	2631	990	1337	2276	378
Single-Family Attached	306	91	114	272	68
Apartment in Building with 2 - 4 Units	352	108	111	223	49

Apartment in Building with 5+ Units	500	209	253	529	118
Median heated square footage					
Single-Family Detached	2025	1509	1702	1877	1630
Single-Family Attached	1298	1140	1207	1489	1233
Apartment in Building with 2 - 4 Units	950	665	816	900	678
Apartment in Building with 5+ Units	787	636	833	863	666

Data source: IEA[362]

Notes:

a. TOTALBTUSPH (Total usage for space heating, in thousand BTU, 2009) / TOTHSQFT (Total heated square footage)

b. TOTALBTUCOL (Total usage for air conditioning, in thousand BTU, 2009) / TOTHSQFT (Total heated square footage)

c. TOTALBTU (Total usage, in thousand BTU, 2009) / TOTHSQFT (Total heated square footage)

Table 31. Definition of ASHRAE climate zones

Thermal Zone	Name	I-P Units	SI Units
0	Extremely Hot – Humid (0A), Dry (0B)	10,800 < CDD50ºF	6000 < CDD10ºC
1	Very Hot – Humid (1A), Dry (1B)	9000 < CDD50ºF ≤ 10,800	5000 < CDD10ºC ≤ 6000
2	Hot – Humid (2A), Dry (2B)	6300 < CDD50ºF ≤ 9000	3500 < CDD10ºC ≤ 5000
3A and 3B	Warm – Humid (3A), Dry (3B)	4500 < CDD50ºF ≤ 6300 AND HDD65ºF ≤ 3600	2500 < CDD10ºC < 3500 AND HDD18ºC ≤ 2000
3C	Warm – Marine (3C)	CDD50ºF ≤ 4500 AND HDD65ºF ≤ 3600	CDD10ºC ≤ 2500 AND HDD18ºC ≤ 2000
4A and 4B	Mixed – Humid (4A), Dry (4B)	2700 < CDD50ºF ≤ 6300 AND 3600 < HDD65ºF ≤ 5400	1500 < CDD10ºC < 3500 AND 2000 < HDD18ºC ≤ 3000
4C	Mixed – Marine	CDD50ºF ≤ 2700 AND 3600 < HDD65ºF ≤ 5400	CDD10ºC ≤ 1500 AND 2000 < HDD18ºC ≤ 3000
5A and 5B	Cool– Humid (5A), Dry (5B)	1800 < CDD50ºF ≤ 6300 AND 5400 < HDD65ºF ≤ 7200	1000 < CDD10ºC ≤ 3500 AND 3000 < HDD18ºC ≤ 4000
5C	Cool – Marine (5C)	CDD50ºF ≤ 1800 AND 5400 < HDD65ºF ≤ 7200	CDD10ºC ≤ 1000 AND 3000 < HDD18ºC ≤ 4000
6A and 6B	Cold – Humid (6A), Dry (6B)	7200 < HDD65ºF ≤ 9000	4000 < HDD18ºC ≤ 5000
7	Very Cold (7)	9000 < HDD65ºF ≤ 12600	5000 < HDD18ºC ≤ 7000
8	Subarctic/Arctic (8)	12600 < HDD65ºF	7000 < HDD18ºC

Marine (C) definition – Locations meeting all four of the following criteria:

1. Mean temperature of coldest month between 27°F (-3°C) and 65°F (18°C)
2. Warmest month mean < 72°F (22°C)
3. At least four months with mean temperatures over 50°F (10°C)
4. Dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

Dry (B) definition – Locations meeting the following criteria:
Not marine and

$P < 0.44 \times (T - 19.5)$ [I-P units]

$P < 2.0 \times (T + 7)$ [SI units]

Where:

P = annual precipitation in inches (cm) and

T = annual mean temperature in °F (°C).

Moist (A) definition – Locations that are not marine and not dry.

Source: Building and Safety Standards Branch[363]

Endnotes

[1] U.S.: EPA, "Sources of Greenhouse Gas Emissions" https://www3.epa.gov/climatechange/ghgemissions/sources/electricity.html

Canada: Canadian Electricity Association, *Canada's Electricity Industry.* http://www.electricity.ca/media/Electricity101/Electricity101.pdf; Environment Canada, "Greenhouse Gas Emissions by Economic Sector." https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=F60DB708-1

[2] Diana Urge-Vorsatz, Ksenia Petrichenko, Maja Staniec, and Jiyong Eom, "Energy Use in Buildings in a Long-Term Perspective," *Current Opinion in Environmental Sustainability* 5 (2013), 141. http://dx.doi.org/10.1016/j.cosust.2013.05.004

[3] Architecture 2030, *Roadmap to zero emissions* (2014). http://architecture2030.org/files/roadmap_web.pdf

[4] Passive House Institute, "Passive House requirements." http://www.passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm

[5] The number of PHIUS certified designers and trades was estimated from records of course registration and the historical pass rate on the PHIUS exam.

[6] U.S.: EPA, "Sources of Greenhouse Gas Emissions" https://www3.epa.gov/climatechange/ghgemissions/sources/electricity.html

Canada: 12% of direct emission from commercial, institutional and residential buildings (87 $MtCO_2e$ in 2014). Buildings account for more than half of electricity use (Canadian Electricity Association, *Canada's Electricity Industry.* http://www.electricity.ca/media/Electricity101/Electricity101.pdf), and electricity generation accounts for 11% of national emissions (Environment Canada, "Greenhouse Gas Emissions by Economic Sector." https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=F60DB708-1).

[7] Diana Urge-Vorsatz, Ksenia Petrichenko, Maja Staniec, and Jiyong Eom, "Energy Use in Buildings in a Long-Term Perspective," *Current Opinion in Environmental Sustainability* 5 (2013), 141. doi:http://dx.doi.org/10.1016/j.cosust.2013.05.004

[8] Architecture 2030, *Roadmap to zero emissions* (2014), 3. http://architecture2030.org/files/roadmap_web.pdf

[9] China: 38%, U.S./Canada: 15%, India: 9%, Latin America: 9%, Middle East / Africa: 9%, Other emerging: 12%, Western Europe: 4% , Other developed: 4%; from Richard Dobbs, Jaana Remes, James Manyika, Charles Roxburgh, Sven Smit, and Fabian Schaer, *Urban World: Cities and the Rise of the Consuming Class* (McKinsey & Company, 2012). 8. http://www.mckinsey.com/global-themes/urbanization/urban-world-cities-and-the-rise-of-the-consuming-class

[10] Diana Urge-Vorsatz, Ksenia Petrichenko, Miklos Antal, Maja Staniec, Eren Ozden, and Elena Labzina, *Best Practice Policies for Low Carbon & Energy Buildings Based on Scenario Analysis* (Global Buildings Performance Network, 2012), 69. http://www.gbpn.org/reports/best-practice-policies-low-carbon-energy-buildings-based-scenario-analysis

[11] *Urban World: Cities and the Rise of the Consuming Class*, 8.

[12] Passive House Institute, *Active for more comfort: Passive House* (2014), 8. http://www.passivehouse-international.org/upload/download_complete_PH_Brochure.pdf

[13] Passive House Institute, *Review of the 19th International Passive House Conference 2015 in Leipzig* (2015), 5. http://www.passivhaustagung.de/en/review-19th-international-passive-house-conference

[14] H. Orr, J. Wang, D. Fetsch, and R. Dumont, "Technical Note: Airtightness of Older-Generation Energy-Efficient Houses in Saskatoon" *Journal of Building Physics* 36 (2012): 304, 305. doi:10.1177/1744259112460748

[15] Passive House Institute, "Passive House requirements." http://www.passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm

[16] See Passive House Institute US, "PHIUS and passive building in the United States" http://www.phius.org/about-phius/phius-and-passive-building-in-the-united-states for a history of the relationship between PHI and PHIUS. Also see Building Energy Exchange, *Passive NYC: A Snapshot of Low Energy Building Opportunities, Barriers, & Resources* (2015), 25 for a comparison of the two rating systems.

[17] See PHIUS+2015 single family home calculator http://www.phius.org/Tools-Resources/Protocols-Calculators/PHIUS+2015_Calculator_Single_Family.xlsx

[18] "Minergie." http://www.minergie.ch/minergie_fr.html

[19] Canadian Home Builders' Association, "What is R-2000?" http://www.chba.ca/r-2000/what-is.aspx; Natural Resources Canada, "More information on the R-2000 Standard." http://www.nrcan.gc.ca/energy/efficiency/housing/new-homes/5089

[20] Mark Frankel and Jim Edelson, *Washington State Energy Code Roadmap* (New Buildings Institute, 2015). http://newbuildings.org/sites/default/files/WashingtonEnergyCodeRoadmap201509.pdf

[21] Ibid. 11.

[22] North American Passive House Network, *Net Zero Energy Buildings: Passive House + Renewables.* (2015). http://naphnetwork.org/NAPHN_NZEB_2015_V2/Flipbook.pdf

[23] PHIUS Multifamily Resource Centre, "Multifamily Passive Building Projects." http://multifamily.phius.org/service-group/multifamily-passive-building-projects

[24] Sustainable Energy Authority of Ireland, *Non-Domestic Passive House Projects.* http://www.seai.ie/Renewables/Renewable_Energy_Library/Non-Domestic_Passive_House_Guidelines.pdf

[25] Wikipedia.de, "Hochhaus Bugginger Straße 50." https://de.wikipedia.org/wiki/Hochhaus_Bugginger_Stra%C3%9Fe_50

[26] René Toth, *RHW.2 – World' S First Passive House Office Tower* (2015). http://www.innovativegebaeude.at/fileadmin/media/best_practice_objekte/RHW2_Handout.pdf

[27] Cornell Tech, "Cornell Tech Announces Construction of First Passive House High-Rise in the World," media release, June 12, 2015. http://tech.cornell.edu/news/cornell-tech-announces-construction-of-first-passive-house-residential-high

[28] Passipedia, "Passive Houses in different climates." http://passipedia.org/basics/passive_houses_in_different_climates

[29] "Passivhaus-Datenbank." http://www.passivhausprojekte.de

[30] Sustainable Energy Authority of Ireland, *Non-Domestic Passive House Projects.* http://www.seai.ie/Renewables/Renewable_Energy_Library/Non-Domestic_Passive_House_Guidelines.pdf

[31] Passipedia, "Baseline study - implementing the Passive House concept in hospitals."

http://passipedia.org/planning/non-residential_passive_house_buildings/ph_hospitals/baseline_study_-_implementing_the_passive_house_concept_in_hospitals ; see also http://ukpassivhausconference.org.uk/sites/default/files/Roland%20Matzig.pdf

[32] ScienceLife, "University of Chicago opens first Passive House-certified laboratory in North America," July 25, 2014. https://sciencelife.uchospitals.edu/2014/07/25/university-of-chicago-opens-first-passive-house-certified-laboratory-in-north-america/

[33] *Non-Domestic Passive House Projects*, 35.

[34] Ibid, 47. See also "Monitoring of the Passive House Indoor Swimming Pool in Lünen", Passipedia 2016. http://passipedia.org/examples/non-residential_buildings/passive_house_swimming_pools

[35] Retail stores, for example have a particular set of design issues which have been addressed in a report by the Passive House Institute specifically on the topic. The report is currently available only in German. Passivhaus Institut, *Passivhaus-Verkaufsstätten*, Protokollband Nr. 40 (2012). http://passiv.de/de/05_service/01_literaturverkauf/00_literaturhinweise/40_pb40.htm

[36] *Non-Domestic Passive House Projects.*

[37] Passive House Canada Course Registration, April 2016 to March 2017 (actuals and projections), provided by Passive House Canada, August 2016.

[38] See http://www.passivhausplaner.eu/index.php?page_id=323&level1_id=277 and http://www.phius.org/get-professional-training for more information on PHI and PHIUS professional certification programs.

[39] PHI data from: http://www.passivhausplaner.eu/mitgliederdatenbank.php and http://www.passivehouse-trades.org/mitgliederdatenbank.php

[40] City of Vancouver, *Zero Emissions Building Plan* (2016). http://council.vancouver.ca/20160712/documents/rr2.pdf

[41] City of Vancouver, *Green Buildings Policy for Rezoning: Process and Requirements* http://former.vancouver.ca/commsvcs/bylaws/BULLETIN/G002.pdf

[42] *Zero Emissions Building Plan*, 24

[43] Ibid., 25

[44] Ibid., 42 see also City of Vancouver, *Floor Space Exclusion to Accommodate Improved Building Performance (Envelope and Thermal Insulation)* (2016). http://former.vancouver.ca/commsvcs/BYLAWS/bulletin/F008.pdf

[45] Emilie Adin, personal communication, 15 March 2016.

[46] Government of New York City, *Low energy intensity building requirements for certain capital projects, 2016/0312*. http://legistar.council.nyc.gov/LegislationDetail.aspx?ID=2240482&GUID=0A9A548C-E3D9-4057-AEAC-426CA033FBBF

[47] Laurie Kerr, "Next Gen Lean and Green NYC-Owned Buildings," *Urban Green*, March 9, 2016. http://urbangreencouncil.org/content/news/next-gen-lean-and-green-nyc-owned-buildings

[48] Government of New York, *Multifamily New Construction Program (MF NCP) Guidelines* (2016) http://www.passivehouseacademy.com/images/library/NYSERDA-Multifamily-New-Construction-Program-Guidelines.pdf

[49] NYC PLanning, *Zone Green Text Amendment,* April 30, 2012. http://www1.nyc.gov/assets/planning/download/pdf/plans/zone-green/zone_green.pdf

[50] Tim McDonald, personal communication, 14 August 2015.

[51] RDH Building Engineering, *Energy Consumption and Conservation in Mid-and High-Rise Residental Buildings in British Columbia* (2012), 233. http://www.hpo.bc.ca/sites/www.hpo.bc.ca/files/download/Report/MURB-EnergyStudy-Report.pdf

[52] The City of Vancouver adopted ASHRAE 90.1-1989 in 1991, and ASHRAE 90.1-2001 in 2005. See Tom-Pierre Frappé-Sénéclauze , and Josha MacNab, *Evolution of Energy Efficiency Requirements in the B.C. Building Code* (Pembina Institute, 2015), 7. http://www.pembina.org/pub/evolution-of-energy-efficiency-requirements-in-the-bc-building-code

[53] Katie Spataro, Marin Bjork, and Mark Masteller, *Comparative Analysis of Prescriptive, Performance-Based, and Outcome-Based Energy Code Systems* (Alaska Housing Finance Corporation, 2011), 10. https://www.ahfc.us/files/9013/5754/5384/cascadia_code_analysis_071911.pdf

[54] In fact, the design elements that are kept identical between the reference building and the proposed design vary slightly across standards (e.g. ASHREA 90.1 ECB, 90.1-PRM (appendix G), Title 24, NECB, ESPM, etc.). Building design parameter can be either characterized as assets, neutral dependent, or neutral independent, depending on how closely the reference building matches the rated building. 'Neutral independent' design parameters are identical in the baseline and in the proposed building (neutral), and the values are pre-defined in the standard (independent). In Title 24, for example, schedule of operations are set independently from those of the proposed building. 'Neutral dependent' parameters, on the other hand, are identical between the baseline and rated building but the parameters are set to match the value of the proposed building. In ASHRAE 90.1, schedule of operations are kept constant between baseline and proposed model, but follow the schedule for the proposed building. An 'asset' design parameter, finally, may differ between baseline and proposed building models. Because its value (or design) is set for the baseline, the energy impacts of choosing a different value (or design) for the design will be captured in the comparison. The HVAC system type could be considered an asset, for example, thus presuming a predefined type for the baseline and allowing the design to innovate beyond that. Alternatively, the HVAC design could be seen as a neutral dependent variable, requiring both baseline and rated buildings to assume the same technology is used, while the performance of the equipment is seen as an asset, whereby the baseline performance would be set according to minimum standard requirement and rated building be allowed to go beyond that value. Both of these approaches exist in ASHRAE 90.1: the Energy Cost Budget (ECB) method in Standard 90.1 is used as an optional performance-based path to establish compliance with the standard, while the Performance Rating Method (PRM, commonly referred to as Appendix G), is used for beyond-code certifications such as LEED. In the PRM approach, more variables to be considered assets: for example, the HVAC system type, window-to-wall ratio, and orientation are set in the baseline (assets), while the shape and size of the building match the proposed design (neutral dependent). For more details, see Table 3 in David B. Goldstein and Charles Eley, "A Classification of Building Energy Performance Indices," *Energy Efficiency* 7 (2014). doi:10.1007/s12053-013-9248-0

[55] "A Classification of Building Energy Performance Indices," 356.

[56] Meghan Pinch, Scott Cooper, Brendan O'Donnell, and Duane Jonlin, *Driving Innovation, Rewarding Performance: Seattle's Next Generation Energy Codes and Utility Incentives* (2014) 6-239. http://aceee.org/files/proceedings/2014/data/papers/6-496.pdf

[57] U.S. Green Building Council, *Better Buildings, Better Policy* (2014) 2. http://www.usgbc.org/sites/default/files/STATE_WINS_REPORT_2014-3.pdf

[58] Government of British Columbia, *Climate Action for the 21st Century* (2010). http://www2.gov.bc.ca/gov/DownloadAsset?assetId=A330ECA3E0FE44AFA4ED6F7EF5B591E3&filename=climate_action_21st_century.pdf

[59] U.S. Department of Energy, "New York City - Green Building Requirements for Municipal Buildings." http://energy.gov/savings/new-york-city-green-building-requirements-municipal-buildings

[60] U.S. Green Building Council, *LEED in the Public Sector* (2014). http://www.usgbc.org/sites/default/files/LEED Public Buildings Brief.pdf

[61] City of Vancouver, *Green Buildings Policy for Rezonings* (2014). http://former.vancouver.ca/commsvcs/guidelines/G015.pdf

[62] Cathy Turner and Mark Frankel, *Energy Performance of LEED for New Construction Buildings* (2008), prepared for U.S. Green Building Council. www.usgbc.org/ShowFile.aspx?DocumentID=3930

[63] Guy R. Newsham, Sandra Mancini, and Benjamin J Birt, "Do LEED-Certified Buildings Save Energy? Yes, But..." *Energy and Buildings* 41 (2009), 1. doi:10.1016/j.enbuild.2009.03.014

[64] *Energy Performance of LEED for New Construction Buildings,* Figure 9 and Figure 19.

[65] U.S. Green Buildings Council, *LEED v4 for Building Design and Construction*. http://www.usgbc.org/sites/default/files/LEED%20v4%20ballot%20version%20(BDC)%20-%2013%2011%2013.pdf

[66] Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2014), i. https://www.bchydro.com/powersmart/business/programs/new-construction.html#thermal

[67] Curt Hepting, *Summary Review Assessment of Energy Performance Codes ASHRAE 90.1-2004, 90.1-2010 and NECB for British Columbia* (2011), 4. http://www.enersys.ca/reports/ASHRAE vs NECB Summary-FINAL.pdf

[68] Light House Sustainable Building Centre, *British Columbia Building Performance Study* (2014). http://www.sustainablebuildingcentre.com/wp-content/uploads/2014/02/BC-BUILDING-PERFORMANCE-STUDY_Feb-2014.pdf

[69] In B.C., for example, electricity costs (~8 cents/kWh) are nearly three times as high as natural gas costs (~3 cents/kWh), while the indirect GHG emission from electricity generation (~11 gCO_2e/kWh in 2014*) are about 94% lower than the direct GHG emissions from natural gas (180 gCO_2e/kWh); even less if we include upstream emission from production and transportation of natural gas (about 12% to 24% of direct emissions, depending on fugitive emissions assumptions: see www.pembina.org/pub/BCShaleTool). This means that per energy-dollar saved, a conservation measure targeting electricity will result in only one-fiftieth of the GHG reductions that would have been gained if a conservation measure targeting natural gas use had been selected instead. * from BC Hydro, *Greenhouse Gas Intensities 2004–2014*. https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/environmental-reports/ghg-intensities-2004-2014.pdf

[70] *Energy Performance of LEED for New Construction Buildings,* Figure 22.

[71] *Roadmap for the Future of Commercial Energy Codes*, 2.4.

[72] See Meghan Pinch, Scott Cooper, Brendan O'Donnell, and Duane Jonlin, *Driving Innovation, Rewarding Performance: Seattle's Next Generation Energy Codes and Utility Incentives* (2014). http://aceee.org/files/proceedings/2014/data/papers/6-496.pdf

[73] U.S. Energy Information Administration, "Residential Energy Consumption Survey: 2009 RECS Survey Data." https://www.eia.gov/consumption/residential/data/2009/index.cfm?view=microdata

[74] U.S. Energy Information Administration, "Residential Energy Consumption Survey: 2012 RECS Survey Data." https://www.eia.gov/consumption/commercial/data/2012/index.cfm?view=microdata

[75] Corey Saft and Eric Helton, "Hot, Humid and Still Cool," presentation at the 7th annual North American Passive House Conference, September 28-29, 2012. Denver CO.

[76] A. German, B. Weitzel, C. Backman, M. Hoeschele, B. Dakin, *Sonoma House: Monitoring of the First U.S. Passive House Retrofit* (U.S. Department of Energy, 2012). https://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/sonoma_house.pdf

[77] Shawn Oram, *16th & Nebraska Passive House First Year Billing Analysis*, prepared by Ecotope Consulting Research Design (2011). https://drive.google.com/file/d/0B1LBpmAm1oeAVktKbkZCUU03Vms/view

[78] David Hales, *Hood River Passive House* (U.S. Department of Energy, 2014), 13. http://www.nrel.gov/docs/fy14osti/60999.pdf

[79] Danny S. Parker, "Very Low Energy Homes in the United States: Perspectives on Performance from Measured Data," *Energy and Buildings* 41 (2009). doi:10.1016/j.enbuild.2008.11.017.

[80] Alpine Space European Territorial Cooperation, *User Habits, Impact on Energy Consumption in Passive Houses* (2012). http://www.enerbuild.eu/publications/2012-06_ENERBUILD-result_5-4.pdf

[81] Ibid.

[82] Ibid.

[83] Ibid.

[84] Ibid.

[85] Ibid.

[86] D. Stecher and K. Allison, *Long-Term Results: New Construction Occupied Test House, Urbana, Illinois* (U.S. Department of Energy, 2012). www.nrel.gov/docs/fy13osti/53707.pdf

[87] Leeds Metropolitan University, Centre for the Built Environment, *Denby Dale Passivhaus: Monitoring & Performance Report* (2012). www.denbydalepassivhaus.co.uk

[88] Ebel (2003) and Feist et al(2000) as referenced in Passipedia. "Passive House heating systems in practice - Results and experiences gained from field measurements." Sep. 2014.

[89] [Peper/Feist 2002] as referenced in Passipedia (2015), http://www.passipedia.org/operation/operation_and_experience/measurement_results/energy_use_measurement_results

[90] [Reiß/Erhorn 2003] as referenced in Passipedia, (2015).

[91] [Krellner 2015] as referenced in Passipedia, (2015).

[92] Andreas Molin, Patrik Rohdin, Bahram Moshfegh, "Investigation of energy performance of newly built low-energy buildings in Sweden," *Energy and Buildings* (2011). http://dx.doi.org/10.1016/j.enbuild.2011.06.041

[93] Passive House database, ID 0696. http://www.passivhausprojekte.de/index.php?lang=en#d_696

[94] Peper, Soeren. 2015. "Monitoring in the Passive House District of Bahnstadt , Heidelberg," no. July. http://www.passipedia.org/operation/operation_and_experience/monitoring_in_the_passive_house_district_of_bahnstadt_heidelberg

[95] Playing on the Passive House Hill – the new kindergarten in the Heidenau city park. Passipedia (2014). http://passipedia.org/examples/non-residential_buildings/passive_house_kindergartens/central_europe/new_kindergarten_in_the_heidenau_city_park_germany

[96] Reidberg Passive House school, Frankfurt, Germany. Passipedia (2014). http://passipedia.org/examples/non-residential_buildings/passive_house_schools/central_europe/riedberg_passive_house_school_frankfurt_germany

[97] North American Passive House Network, *Net Zero Energy Buildings: Passive House + Renewables.* (2015). http://naphnetwork.org/NAPHN_NZEB_2015_V2/Flipbook.pdf

[98] *Denby Dale Passive House: monitoring & performance report*.

[99] *Long-Term Results: New Construction Occupied Test House, Urbana, Illinois.*

[100] David Hales, *Hood River Passive House* (U.S. Department of Energy, 2014), 13. http://www.nrel.gov/docs/fy14osti/60999.pdf

[101] Shawn Oram, *16th & Nebraska Passive House First Year Billing Analysis*, prepared by Ecotope Consulting Research Design (2011). https://drive.google.com/file/d/0B1LBpmAm1oeAVktKbkZCUU03Vms/view

[102] A. German, B. Weitzel, C. Backman, M. Hoeschele, B. Dakin, *Sonoma House: Monitoring of the First U.S. Passive House Retrofit* (U.S. Department of Energy, 2012). https://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/sonoma_house.pdf

[103] Alison G. Kwok, *Annual Report: Stellar Apartments,* for St. Vincent de Paul Society of Lane County (2014). University of Oregon NetZED laboratory.

[104] Andreas Molin, Patrik Rohdin, Bahram Moshfegh, "Investigation of energy performance of newly built low-energy buildings in Sweden," *Energy and Buildings* (2011). http://dx.doi.org/10.1016/j.enbuild.2011.06.041

[105] *Net Zero Energy Buildings: Passive House + Renewables*.

[106] Synergy Sustainability Institute, *The Business Case for Passive House* (2015). http://www.ryanhamilton.ca/Client/0052-SSi/PH_BusinessCase_2015.pdf

[107] Passive House database, ID 0696. http://www.passivhausprojekte.de/index.php?lang=en#d_696

[108] *User Habits, Impact on Energy Consumption in Passive Houses.* 27 & 29.

[109] Leeds Metropolitan University, Centre for the Built Environment, *Denby Dale Passivhaus: Monitoring & Performance Report* (2012), 7. www.denbydalepassivhaus.co.uk

[110] Naomi Morishita and Thomas Bednar, "The Impact of Occupants ' Exterior Shading Use and Window Opening on Summer Comfort in a Lowest-Energy Apartment Building." In *Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference*, 2013. http://www.academia.edu/22840206/The_Impact_of_Occupants_Exterior_Shading_Use_and_Window_Opening_on_Summer_Comfort_in_a_Lowest-Energy_Apartment_Building

[111] Passive House Institute, *Certified Passive House Criteria for non-residential Passive House buildings* (2013), 1. http://passiv.de/downloads/03_certfication_criteria_nonresidential_en.pdf

[112] Michael Rosenberg and Charles Eley, "A Stable Whole Building Performance Method for Standard 90.1." *ASHRAE Journal* (2013). http://eley.com/sites/default/files/pdfs/033-045_Rosenberg_WEB.pdf

[113] For further discussion of the merit of a reference building approach over a fixed-budget approach, see M. Rosenberg, R Hart, J Zhang, and R Athalye, *Roadmap for the Future of Commercial Energy Codes* (Pacific Northwest National Laboratory, 2015), 3.2. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24009.pdf and David B. Goldstein and Charles Eley, "A Classification of Building Energy Performance Indices," *Energy Efficiency* 7 (2014), 372. doi:10.1007/s12053-013-9248-0

[114] "A Classification of Building Energy Performance Indices."

[115] Matt Horne and Adam Goehner, *Wellhead to Waterline: Opportunities to limit greenhouse gas emissions from B.C.'s proposed LNG industry* (Pembina Institute, 2014). https://www.pembina.org/pub/2524

[116] Passipedia, "The PER sustainability assessment." http://passipedia.org/certification/passive_house_categories/per

[117] See Passive House Institute, "Internal Heat Gains in Relation to Living Area." https://passipedia.org/planning/calculating_energy_efficiency/phpp_-_the_passive_house_planning_package/internal_heat_gains_in_relation_to_living_area

[118] North American Passive House Network, *Net Zero Energy Buildings: Passive House + Renewables.* (2015). http://naphnetwork.org/NAPHN_NZEB_2015_V2/Flipbook.pdf

[119] *The Business Case for Passive House*.

[120] Integral Group, *Advanced Energy Efficiency Requirements for Homes in B.C.*, prepared for Provincial Advisory Committee on Energy Efficiency (2015), 11. http://www.integralgroup.com/wp-content/uploads/2015/05/Advanced-Energy-Efficiency-Requirements-for-Buildings-in-BC.pdf

[121] W. Feist, "Is it profitable to build a Passive House?" *Passive House Institute*, May 6, 2007. http://www.passivhaustagung.de/Passive_House_E/economy_passivehouse.htm

[122] *Net Zero Energy Buildings: Passive House + Renewables*.

[123] A. Audenaert, S. H. De Cleyn, and B. Vankerckhove, "Economic Analysis of Passive Houses and Low-Energy Houses Compared with Standard Houses." *Energy Policy* 36 (2008), 54. doi:10.1016/j.enpol.2007.09.022

[124] Wolfgang Feist, Søren Peper, and Manfred Görg, *CEPHEUS: Final Technical Report*, (Passivhaus Institut, 2001), Table 10 and 19. http://www.phius.org/media/W1siZiIsIjIwMTEvMTIvMjIvMTBfMDFfNTBfOTk2X0NFUEhFVVNfZmluYWxfbG9uZy5wZGYiXV0?sha=a0c58caa

[125] *CEPHEUS: Final Technical Report*, Table 10 and 19.

[126] Ibid.

[127] Martin Ingham, *Wimbish Passivhaus Development: Performance Evaluation – Executive Summary* (2014). http://www.hastoe.com/page/760/Wimbish-passivhaus-performs--Hastoe-releases-results-of-two-year-study-.aspx

[128] *EPHEUS: Final Technical Report*, Table 10 and 19.

[129] http://www.passivehouse-international.org/upload/2010-08-12_PR_Lodenareal.pdf see also http://www.din-a4.at/en/dina4-projekte/passivhaus-wohnanlage-lodenareal-2/

[130] Ardeshir Mahdavi and Eva Maria Doppelbauer, "A Performance Comparison of Passive and Low-Energy Buildings." *Energy and Buildings* 42 (2010). doi:10.1016/j.enbuild.2010.02.025

[131] *CEPHEUS: Final Technical Report*, Table 10 and 19.

[132] Ibid.

[133] Ibid.

[134] Ibid.

[135] *Non-Domestic Passive House Projects*.

[136] Tim McDonald, "The PHFA Project," In *NY15 Conference Presentation* (2015). http://nypassivehouse.org/wp-content/uploads/2015/06/NY15PH-08a-Developer-Roundtable-Tim-McDonald.pdf

[137] Sonia Zouari, Arch., personal communication, 14 September 2016. Incremental costs amount to about $25-30/sqft; heating costs are estimated at $27/unit based on 5cents/kWh (gas), approximately 84% savings compared to the Ontario Building Code.

[138] Study being completed for NYSERDA at time of writing; results expected shortly. Ilana Judah, Director of Sustainability at FXFOWLE, personal communication March 2016.

[139] Data in this section from Sustainable Energy Authority of Ireland. *Non-Domestic Passive House Projects* (2011). http://www.seai.ie/Renewables/Renewable_Energy_Library/Non-Domestic_Passive_House_Guidelines.pdf

[140] RDH Building Engineering and Red Door Energy Design, *Costing Study on Passive House for Single Family Homes in Vancouver: Summary* (2016) http://vancouver.ca/files/cov/Dec_1_City_of_Vancouver_Passive_House_Study_V2.pdf

[141] See David Hales, *Hood River Passive House* (U.S. Department of Energy, 2014), 12. http://www.nrel.gov/docs/fy14osti/60999.pdf

[142] Synergy Sustainability Institute, *The Business Case for Passive House*.

[143] Paul Warwick, Performance Construction, Personal communication March 2016

[144] A. Pape-Salmon, "Passive House building case study," conference presentation, Buildex, February 25, 2016, 30.

[145] Ibid.

[146] *The Business Case for Passive House*, 33.

[147] Ilana Judah, Director of Sustainability at FXFOWLE, personal communication March 2016.

[148] D. Penner, "Leaky Condo Crisis Rears Its Head Again in B.C." *Vancouver Sun,* May 22, 2014. http://www.vancouversun.com/technology/Leaky+condo+crisis+rears+head+again/9871711/story.html

[149] K.L. Chouinard and M.D. Lawton, "Rotting wood framed apartments -- not just a Vancouver problem," Available at http://users.encs.concordia.ca/~raojw/crd/reference/reference000867.html

[150] e.g. E. Sorensen, "Condo owners' deluge of woe", *Seattle Times*, September 6 1998. http://users.encs.concordia.ca/~raojw/crd/reference/reference001153.html

[151] Dave Barrett, *The Renewal of Trust in Residential Construction: Commission of Inquiry into the Quality of Condominium Construction in British Columbia* (1998), Chapter One: The Problem. http://www.qp.gov.bc.ca/condo/

[152] Ibid. Chapter Two: The Framework of Residential Construction, II. Building Codes

[153] Morrison Hershfield Limited, *Survey of Building Envelope Failures in the Coastal Climate of British Columbia,* (1996), prepared for Canada Mortgage and Housing Corporation. https://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/98102.htm

[154] Don Hazleden, "The Vancouver Experience," presentation to the Claddings Institute of New Zealand: The Science of Building Weathertightness, March 2002. http://www.cinz.org.nz/images/The%20Vancouver%20Experience%20020311.pdf

[155] Graham Finch and John Straube, "Hygrothermal Performance and Drying Potential of Wood Frame Rainscreen Walls in Vancouver's Coastal Climate," presentation to the 11th Canadian Conference on Building Science and Technology. http://www.nbec.net/documents/THEDRYINGPOTENTIALOFBUILDINGENVELOPESINVANCOUVERCOASTALCLIMATE-GRAHAMFINCHJOHNSTRAUBE.pdf

[156] CMHC, *Wood Frame Envelopes: Best Practice Guide* (1999). Available at http://www.naturallywood.com/sites/default/files/CMHC-Best-Practice-Guide-Wood-Frame-Envelopes.pdf

[157] CMHC, *Wood-Frame Envelopes in the Coastal Climate of British Columbia* (2001). Available at http://design-engine.ca/Information/Guidelines/wood frame envelopes best practice guide.pdf

[158] Homeowner Protection Office, *Annual Report 1998/99*, 7. https://hpo.bc.ca/files/download/AnnualReports/AnnualReport1998.pdf

[159] Office of Housing and Construction Standards, *Depreciation Reports* (2013). http://www.housing.gov.bc.ca/pub/stratapdf/Guide12.pdf

[160] HPO, *Annual Report 1998/99*, 7.

[161] "The Vancouver Experience."

[162] J. Wang, J. Clark, P. Symons and P. Morris, *Time to Initiation of Decay in Plywood, OSB and Solid Wood Under Critical Moisture Conditions* (2010). Proceedings of International Conference of Building Envelope Systems and Technology (ICBEST).

[163] Jonathan Smegal and John Straube, *High-R Walls for the Pacific Northwest – A Hygrothermal Analysis of Various Exterior Wall Systems Hygrothermal Analysis of Various Exterior* (2010), 14. http://buildingscience.com/sites/default/files/migrate/pdf/RR-1014_High-R_Walls_Pacific_Northwest.pdf

City of Vancouver and the Homeowner Protection Office, *R22+ Effective Walls in Wood-Frame Construction in British Columbia.* https://hpo.bc.ca/r22-effective-walls-wood-frame-in-BC

[164] *High-R Walls for the Pacific Northwest*, 5 and 72.

[165] *High-R Walls for the Pacific Northwest*, 74.

[166] Michael Fox, *Hygrothermal Performance of Highly Insulated Wood Frame Walls with Air Leakage,* M.A.Sc. thesis, Ryerson University (2014), 69-74. Available at http://newbuildscanada.ca/wp-content/uploads/2013/06/Michael-Fox-M-A-Sc-Thesis-May7.pdf

[167] Ibid., 72, see wall N3 in figure 4-16.

[168] Ibid., see walls 5, 6, and 7 in figure 4-15 to 4-19.

[169] J. Wang and S. Mistretta, *Field monitoring of hygrothermal performance of a wood-frame house in the Lower Mainland of BC built to the passive house standard* (FPInnovations, 2014). https://fpinnovations.ca/Extranet/Pages/AssetDetails.aspx?item=/Extranet/Assets/ResearchReportsWP/3100.pdf#.Vxv3sZMrKHp

[170] H. Orr, J. Wang, D., Fetsch and R. Dumont, "Technical note: Airtightness of older-generation energy-efficient houses in Saskatoon," *Journal of Building Physics*, 36(2012). http://doi.org/10.1177/1744259112460748

[171] Beckman and Proskiw, 1989; Proskiw, 1992; UNIES Ltd, 1992 cited in "Technical note: Airtightness of older-generation energy-efficient houses in Saskatoon," 301.

[172] W.Feist, W. Ebel, S. Peper and W. Hasper, *Long-term experience and measurements from the first Passive House building in Darmstadt-Kranichstein* (2016), 6.

[173] For more information, see for example the following review papers:

FPInnovations, *Vapour condensation potential in insulated wood-frame building enclosure assemblies* (2011). https://fpinnovations.ca/Extranet/Pages/AssetDetails.aspx?item=/Extranet/Assets/ResearchReportsWP/2857.pdf#.V9C0YZMrIo8

McClanaghan et. al, *Assessment of Future Demand for the HPO Reconstruction Program* (2008). *http://www.worldcat.org/title/backgrounder-on-the-assessment-demand-for-hpo-reconstruction-program/oclc/503051086*

J. Wang, J. C., P. Symons, P. Morris, "Time to Initiation of Decay in Plywood, OSB and Solid Wood Under Critical Moisture Conditions," *Proceedings of International Conference of Building Envelope Systems and Technology* (2010). http://commons.bcit.ca/bsce/refInfo/?refId=2036

[174] Fitsum Tariku, Director of the Building Science Centre of Excellence, BCIT, personal communication 20 April 2016.

[175] Homeowner Protection Office, *HPO Research and Education - Summary of Projects* (2016), 2. https://hpo.bc.ca/sites/default/files/download/Report/RE_Projects_Bulletin_Spring_2016.pdf

[176] City of Vancouver and the Homeowner Protection Office, *R22+ Effective Walls in Wood-Frame Construction in British Columbia,* https://hpo.bc.ca/r22-effective-walls-wood-frame-in-BC

[177] RDH Building Engineering, *Study of High-Rise Envelope Performance in the Coastal Climate of British Columbia* (2001), 3. https://hpo.bc.ca/files/download/Report/SHREP.pdf

[178] Ibid.

[179] Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2014). https://www.bchydro.com/powersmart/business/programs/new-construction.html#thermal.

[180] Graham Finch, *Walls and Windows for Highly Insulated Buildings in the Pacific Northwest*, presentation to the Passive House Northwest 2013 Annual Conference. http://www.slideshare.net/RDHBuildings/walls-and-windows-for-highly-insulated-buildings-in-the-pacific-northwest

[181] Morrison Hershfield, *Accounting for Thermal Bridging at Interface Details: A Methodology for De-Rating Prescriptive Opaque Envelope Requirements in Energy Codes* (2015). https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/power-smart/builders-developers/base-building-u-values-03102015.pdf

[182] Helen Goodland, Chris Lindberg, and Paul Shorthouse, *Construction Innovation Project: Building B.C.'s Vision* (2015). https://www.bccassn.com/media/bcca-report-construction-innovation-2016.pdf

[183] U.S. Energy Information Administration, *Annual Energy Outlook 2015,* A9. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

[184] In 2013. Residential: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=ca&rn=1&page=0 and http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=ca&rn=2&page=0

Commercial: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=com&juris=ca&rn=4&page=0

[185] *Annual Energy Outlook 2015,* 14.

[186] See the illustrative modelling test discussed in "Improved thermal insulation: good or bad in the summer?" in http://passipedia.org/basics/summer?s[]=overheating

[187] For a more comprehensive list, see: Zero Carbon Hub, *Solutions to Overheating in Homes: Evidence Review* (2016). http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview.pdf

[188] Chris Mattock, personal communication, May 2016. HPO, *Pathways to High-Performance Housing in British Columbia* (2014), 7. http://hpo.bc.ca/PathwaysToHigh-PerformanceHousing

[189] Ibid., 7.

[190] Ibid., 32

[191] Ibid., 32. For a case study of a net-zero home successfully cooled solely through natural ventilations, see J. Ellis, J Schwartz, and R Mora, "Assessment of Natural Ventilation Effectiveness for an Active Net-Zero Energy House," *International Journal of Ventilation* (2015). http://dx.doi.org/10.1080/14733315.2016.1214387

[192] *Solutions to Overheating in Homes*, 24.

[193] Ibid., 29.

[194] See for example the Manitoba Hydro head office building in Winnipeg, Canada: https://www.hydro.mb.ca/corporate/mhplace/building.shtml

[195] *Solutions to Overheating in Homes*, 28.

[196] CIBSE, *The Limits of Thermal Comfort : Avoiding Overheating in European Buildings* (2013) 10. http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7f5AAC

[197] Richard DeDear and Gail Brager, "Developing an Adaptive Model of Thermal Comfort and Preference," *ASHRAE Transactions* 104 (1998). http://www.worldcat.org/oclc/246005746

[198] Michael Humphreys, J. Fergus Nicol and Iftikhar Raja, "Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach," *Advances in Building Energy Research* 1 (2007). doi:10.1080/17512549.2007.9687269

[199] *The Limits of Thermal Comfort,* 9.

[200] PHIUS. 2015. "PHIUS + 2015 Passive Building Standard – North America" https://www.phius.org/PHIUSplusdocs/PHIUSPHIUSplusdocsdropbox.com/s/oe3rb5vqiclmvm0/PHIUS+CertificationGuidebook_v1.03.pdf

[201] *The Limits of Thermal Comfort,* 11.

[202] Jürgen Schnieders and Andreas Hermelink, "CEPHEUS Results: Measurements and Occupants' Satisfaction Provide Evidence for Passive Houses Being an Option for Sustainable Building," *Energy Policy* 34 (2006), 162 & 167. doi:10.1016/j.enpol.2004.08.049

[203] "Assessment of Natural Ventilation Effectiveness for an Active Net-Zero Energy House."

[204] Patrik Rohdin, Andreas Molin, and Bahram Moshfegh, "Experiences from Nine Passive Houses in Sweden - Indoor Thermal Environment and Energy Use," *Building and Environment* (2014). doi:10.1016/j.buildenv.2013.09.017

[205] Alpine Space European Territorial Cooperation, *User Habits, Impact on Energy Consumption in Passive Houses* (2012). http://www.enerbuild.eu/publications/2012-06_ENERBUILD-result_5-4.pdf

[206] Morishita, Naomi, and Thomas Bednar. 2013. "The Impact of Occupants ' Exterior Shading Use and Window Opening on Summer Comfort in a Lowest-Energy Apartment Building." In *Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference*, 7. http://www.academia.edu/22840206/The_Impact_of_Occupants_Exterior_Shading_Use_and_Window_Opening_on_Summer_Comfort_in_a_Lowest-Energy_Apartment_Building

[207] "CEPHEUS Results: Measurements and Occupants' Satisfaction Provide Evidence for Passive Houses Being an Option for Sustainable Building."

[208] "The Impact of Occupants ' Exterior Shading Use and Window Opening on Summer Comfort in a Lowest-Energy Apartment Building."

[209] Andris Auliciems, "Comfort, clothing and health," in *Applied Climatology: Principles and Practice,* ed. Russell D. Thompson, Allen Howard Perry (1997), 155

[210] Martin Holladay, "Passivhaus Buildings Don't Heat Themselves," *Green Building Advisor,* May 10, 2013. http://www.greenbuildingadvisor.com/blogs/dept/musings/passivhaus-buildings-don-t-heat-themselves

[211] DNA in de bouw, *Map of Missing Links: An Analysis of Typical Barriers in European Regions Introducing Passive House Technology with Renewable Energy* (2014). http://www.passreg.eu/download.php?cms=1&file=D_4_5_Map_of_missing_links.pdf

[212] Helen Goodland, Chris Lindberg and Paul Shorthouse, *Construction Innovation Project: Building B.C.'s Vision* (2015) https://www.bccassn.com/media/bcca-report-construction-innovation-2016.pdf

[213] Mark Frankel and Jim Edelson, *Washington State Energy Code Roadmap* (2015). http://newbuildings.org/sites/default/files/WashingtonEnergyCodeRoadmap201509.pdf

[214] Tom-Pierre Frappé-Sénéclauze and Maximilian Kniewasser, *The Path to Net-Zero Energy Buildings in B.C.: The Case for Action and the Role of Public Policy* (Pembina Institute, 2015). http://www.pembina.org/pub/the-path-to-net-zero-energy-buildings-in-bc

[215] Tom-Pierre Frappé-Sénéclauze, Annie Russell and Karen Tam Wu, *Pathways to Net-Zero Buildings in B.C.: Getting new Part 3 buildings net-zero ready* (Pembina Institute, 2015). http://www.pembina.org/reports/pathways-to-net-zero-summary.pdf

[216] DNA in de bouw, *Advisory Report on Barriers and Solutions in European Regions Introducing Passive House Technology with Renewable Energy Supply (*2015). http://www.passreg.eu/download.php?cms=1&file=D4_6_PassREg_Advisory_report.pdf

[217] Modus, *Towards a Sustainable Built Environment for British Columbia: Synthesis of Findings* (2015), 21. http://www.refbc.com/sites/default/files/Towards a Sustainable Built Environment for BC - FINAL 2015-10-13.pdf

[218] *Advisory Report on Barriers and Solutions in European Regions*, 2-9.

[219] *Construction Innovation Project*.

[220] Everett M. Rogers, *Diffusion of Innovations* (New York Free Press, 1995).

[221] *Advisory Report on Barriers and Solutions in European Regions,* 5.

[222] Rob Bernhardt, personal communication.

[223] Erwin Mlecnik, *Innovation Development for Highly Energy-Efficient Housing Opportunities and Challenges* (2013). http://repository.tudelft.nl/view/ir/uuid%3A82884adb-e990-4b8a-accc-d9440e52253d/

[224] International Passive House Association, "Passive House Legislation." http://www.passivehouse-international.org/index.php?page_id=176 and sources cited therein. Population data from Wikipedia.

[225] City of Vancouver, *Zero Emissions Building Plan* (2016), 24. http://council.vancouver.ca/20160712/documents/rr2.pdf

[226] Government of New York City, *Low energy intensity building requirements for certain capital projects, 2016/0312*. http://legistar.council.nyc.gov/LegislationDetail.aspx?ID=2240482&GUID=0A9A548C-E3D9-4057-AEAC-426CA033FBBF

[227] Laurie Kerr, "Next Gen Lean and Green NYC-Owned Buildings," *Urban Green*, March 9, 2016. http://urbangreencouncil.org/content/news/next-gen-lean-and-green-nyc-owned-buildings

Low energy intensity building requirements for certain capital projects. Bill 701, subdivision l, paragraph 3(i).

City of New York, *One City, Built to Last: Transforming New York City Buildings for a Low-Carbon Future*, technical working group report (2014), 108. http://www.nyc.gov/html/gbee/downloads/pdf/TWGreport_04212016.pdf

[228] Tim McDonald, personal communication, 14 August 2015.

[229] Pennsylvania Housing Finance Agency, *Allocation Plan For Year 2015 Low Income Housing Tax Credit Program* (2014), 23. http://www.phfa.org/forms/multifamily_program_notices/qap/2015_qap_final.pdf

Pennsylvania Housing Finance Agency, 2015 Multifamily Housing Application Package and Guidelines, Tab 03, Self-Scoring Sheet, at 173, http://www.phfa.org/developers/developer/housingapplication.aspx . Note that the criteria for meeting Energy Efficiency Goals require developments to meet Passive House Certification requirements but do not require final certification.

[230] New York State Homes & Community Renewal, *Request for Proposals: Multi-Family Programs* (2015). http://www.nyshcr.org/Funding/UnifiedFundingMaterials/2015/2015-RFP-MulltiFamilyPrograms.pdf

[231] Tim McDonald, personal communication, 14 August 2015.

[232] Tim McDonald, personal communication, 14 August 2015.

[233] For a more detailed discussion on the role of procurement policies, see Helen Goodland, Chris Lindberg, and Paul Shorthouse, *Construction Innovation Project: Building B.C.'s Vision* (2015), 47. https://www.bccassn.com/media/bcca-report-construction-innovation-2016.pdf

[234] http://www.gov.scot/resource/0043/00436662.pdf

[235] PassREg-Solution Open Source, "Bahnstadt, Heidelberg." http://passregsos.passiv.de/wiki/Bahnstadt_Heidelberg

[236] PassREg-Solution Open Source, "Niew-Zuid." http://passregsos.passiv.de/wiki/Nieuw-Zuid

[237] PassREg-Solution Open Source, "Zero: e park, Hannover" http://passregsos.passiv.de/wiki/Zero:e_park,_Hannover

[238] "Hannover-Wettbergen zero: e park, Hannover" webpage. http://www.zero-e-park.de/en/baugebiet/

[239] Emilie Adin, personal communication, 15 March 2016.

[240] City of Vancouver, *Green Buildings Policy for Rezoning: Process and Requirements* http://former.vancouver.ca/commsvcs/bylaws/BULLETIN/G002.pdf

[241] NYC PLanning, *Zone Green Text Amendment,* April 30, 2012. http://www1.nyc.gov/assets/planning/download/pdf/plans/zone-green/zone_green.pdf

[242] City of Vancouver, *Zero Emissions Building Plan* (2016), 42 see also City of Vancouver, *Floor Space Exclusion to Accommodate Improved Building Performance (Envelope and Thermal Insulation)* (2016). http://former.vancouver.ca/commsvcs/BYLAWS/bulletin/F008.pdf

[243] SF Environment, “Priority Permitting.” http://sfenvironment.org/article/larger-projects-commercial-amp-multifamily/priority-permitting; and City and County of San Francisco, *Priority Permit Processing Guidelines,* Administrative Bulletin, April 27, 2015. http://sfdbi.org/sites/sfdbi.org/files/AB-004_0.pdf

[244] Sean Pander, personal communication, 17August 2015.

[245] City of Vancouver, Letter to Passive House Institute on temporary allowances for building bylaw compliance, March 17, 2014. Available at http://canphi.ca/wp-content/uploads/2015/03/CMO-SUS-Passive-House-Equivlencies-Letter.pdf

[246] http://www.dlrcoco.ie/files/devplan2016_2022/media/pdf/Written_Statement/section5.pdf p138

[247] Marcel Elswijk and Henk Kaan, *European Embedding of Passive Houses* (2008), 18. http://www.aee-intec.at/0uploads/dateien578.pdf

[248] Grüne Köln, "Klimaschutz - Jetzt auch bei der Stadt Köln Passivhaus–Bauweise," media release, May 4, 2010. http://www.gruenekoeln.de/ratsfraktion/pressemitteilung-klimaschutz-jetzt-auch-bei-der-stadt-koeln-passivhaus-bauweise.html

[249] http://www.passivhaus-austria.org/sites/passivhaus-austria.org/files/Downloads/PH%20Regionen/Nationaler_Plan_Luxemburgs_zur_Erh__hung_der_Zahl_der_Niedrigstenergiege.pdf p 39

[250] Stadt Nürnberg, *Leitlinien zum energieeffizienten, wirtschaftlichen und nachhaltigen Bauen und Sanieren bei Hochbaumaßnahmen der Stadt Nürnberg* (2009),2. http://www.eneff-stadt.info/fileadmin/media/News/Dateien/Planungsvorgaben_Nuernberg_1109_Leitlinien_energieeffizientes_Bauen_und_Sanieren.pdf

[251] C40 Cities, “Cutting Home Energy Consumption by 80%: Freiburg, Germany,” 2011. http://www.c40.org/case_studies/cutting-home-energy-consumption-by-80

[252] http://www.dlrcoco.ie/files/devplan2016_2022/media/pdf/Written_Statement/section5.pdf p138

[253] Stadt Leverkusen, *Energiebericht 2008*, 76. http://www.ig-passivhaus.de/upload/Energiebericht2008_Stadt_Leverkusen_2009_11.pdf

[254] For more information, see PassivAct, “Compacité des bâtiments et conséquences,” September 11, 2013. http://www.passivact.com/Infos/InfosConcepts/files/CompaciteBatiment-Consequences.html

[255] Examples of compacity factors (the inverse ratio of compacity, i.e. external surface over habitable surface) are available at PassivAct, *Ordre de grandeur de facteurs de compacité Sp/Shab.* http://www.passivact.com/Documents/Compacite-OrdreGrandeur.pdf

[256] Ibid., 1.

[257] Bruxelles Environnement, *Les Exigences PEB à Partir de 2015* (2015), 4. http://documentation.bruxellesenvironnement.be/documents/IF_NRJ_ExigencesPeb2015FR.PDF

[258] See Annex XI http://www.environnement.brussels/uploadedfiles/Contenu_du_site/Professionnels/Themes/%C3%89nergie/01_PEB_et_climat_int%C3%A9rieur/01Travaux_PEB/07L%C3%A9gislation/ARRETE_210213_AnnexeXI_FR.pdf and Annex VI: http://www.environnement.brussels/sites/default/files/user_files/agbr_20071221_annexe_vi.pdf

[259] *Les Exigences PEB à Partir de 2015*, 5.

[260] City of Vancouver, *Zero Emissions Building Plan* (2016).

[261] Ibid., 15.

[262] Everett M. Rogers, *Diffusion of Innovations* (New York Free Press, 1995).

[263] Erwin Mlecnik, *Innovation Development for Highly Energy-Efficient Housing Opportunities and Challenges*, (2013), 76. http://repository.tudelft.nl/view/ir/uuid%3A82884adb-e990-4b8a-accc-d9440e52253d/.

[264] Carbonbuzz, "About CarbonBuzz." http://www.carbonbuzz.org/about.jsp

[265] Building Energy Exchange, "The Organization." http://be-exchange.org/about#theOrganization_scroll_to

[266] "Integrated Design Lab" webpage. http://www.integrateddesignlab.com/Seattle/Lab/lab.html

[267] *Innovation Development for Highly Energy-Efficient Housing Opportunities and Challenges*, 96.

PassREg-Solution Open Source, "Visibility and public support in Brussels." http://passregsos.passiv.de/wiki/Visibility_and_Public_Support_in_Brussels#PMP.2FPHP_Events

[268] City of Vancouver, *Zero Emissions Building Plan*.

[269] Tim MacDonald, presentation to 2015 NAPHN conference, Vancouver, 2015.

[270] Michael Ingui, personal communication, October 2015.

[271] Constructing Excellence, "Clubs." http://constructingexcellence.org.uk/clubs/

[272] Helen Goodland, Chris Lindberg, and Paul Shorthouse, *Construction Innovation Project: Building B.C.'s Vision* (2015), 63. https://www.bccassn.com/media/bcca-report-construction-innovation-2016.pdf

[273] PassREg-Solution Open Source. http://passregsos.passiv.de/wiki/PassREg-Solutions_Open_Source

[274] PassREg, "Passive House Regions with Renewable Energies." http://www.passreg.eu/index.php

[275] Last checked on March 18, 2016, the history logs dates the latest substantive changes to July 2015.

[276] Passepedia. http://passipedia.org/

[277] BePassive. http://www.bepassive.be/

[278] Denali Jones, Bailey Brown and Graham Finch, *Building Enclosure Airtightness Testing in Washington State: Lessons Learned about Air Barrier Systems and Large Building Testing Procedures* (2014). http://rdh.com/wp-content/uploads/2014/10/ASHRAE-2014-Annual-Conference-Building-Enclosure-Airtightness-in-WA-Final.pdf

[279] 2012 Washington State Energy Code, Residential Provisions, section R402.4.1.2 https://fortress.wa.gov/ga/apps/SBCC/File.ashx?cid=2842

[280] 2012 Washington State Energy Code, Commercial Provisions, section C402.4.1.2.2 https://fortress.wa.gov/ga/apps/SBCC/File.ashx?cid=2892

[281] *Building Enclosure Airtightness Testing in Washington State.*

[282] Duane Jonlin, personal communication, September 17, 2015.

[283] *Building Enclosure Airtightness Testing in Washington State.*

[284] City of Vancouver, *By-law No. 9691: A Bylaw to amend Building By-law No. 9419 regarding green building strategy for one family homes, one family homes with secondary suites, and two family homes* (2008), article 12.2.2.8. https://vancouver.ca/files/cov/green-homes-ammendments.PDF

[285] City of Vancouver, *By-law No. 10908: A By-law to regulate the construction of buildings and related matters and to adopt the British Columbia Building Code* (2014), article 10.2.2.12. http://former.vancouver.ca/blStorage/10908.PDF

[286] See also: City of Vancouver, *Vancouver Building By-law 9419*. http://vancouver.ca/your-government/vancouver-building-bylaw.aspx

[287] Tom-Pierre Frappé-Sénéclauze, Ellen Pond and Alison Cretney, *Home Energy Labelling: Strategic Plan for Labelling of Part 9 Residential Buildings in B.C.* (Pembina Institute, 2015). http://www.pembina.org/pub/home-energy-labelling

[288] United States Environmental Protection Agency, *Energy Star Portfolio Manager Data Trends: Benchmarking and Energy Savings* (2012). http://www.energystar.gov/buildings/sites/default/uploads/tools/DataTrends_Savings_20121002.pdf?646e-6ac1

[289] Tom-Pierre Frappé-Sénéclauze, Benjamin Thibault, and Ellen Pond, *Energy Labelling for New Homes - FAQs and Model Bylaw Amendments* (Pembina Institute, 2014), 14. http://www.pembina.org/pub/2523

[290] Laurie Goodman and Jun Zhu, "PACE Loans: Does Sale Value Reflect Improvements?" *Journal of Structured Finance* 21 (2016), 9. http://www.iijournals.com/doi/abs/10.3905/jsf.2016.21.4.006.

[291] Shailendra Mudgal, Lorcan Lyons and François Cohen. *Energy Performance Certificates in Buildings and Their Impact on Transaction Prices and Rents in Selected EU Countries* (2013), 115. https://ec.europa.eu/energy/sites/ener/files/documents/20130619-energy_performance_certificates_in_buildings.pdf

[292] Ibid. 117.

[293] Ibid. 115.

[294] Andrew C. Burr, Cli Majersik, Sarah Stellberg, Heidi Garrett-Peltier, *Analysis of Job Creation and Energy Cost Savings From Building Energy Rating and Disclosure Policy* (Institute for Market Transformation and Political Economy Research Institute, 2012), 3. http://www.peri.umass.edu/fileadmin/pdf/other_publication_types/PERI-IMT-2012-Analysis_Job_Creation.pdf

[295] Bruxelles Environment, *BatEx: Six Calls* (2014), 4.

[296] Bruxelles Environment, "S'inspirer des bâtiments exemplaires." http://www.environnement.brussels/thematiques/batiment/sinspirer-des-batiments-exemplaires

[297] EnEffect, *The Success Model of Brussels: Case Study* (2012), 21. http://nypassivehouse.org/wp-content/uploads/2014/12/Detailed-description-of-the-Success-Model-of-Brussels.pdf

[298] *BatEx: Six Calls*, 3.

[299] *BatEx: Six Calls*, 3, 8, 10, 11.

[300] *BatEx: Six Calls*, 3.

[301] Centre for the Built Environment, *Be.Passive: Lessons learnt from the Belgian Passivhaus experience* (2013). http://www.passivhaustrust.org.uk/UserFiles/File/BePassive%20Report.pdf

[302] *The Success Model of Brussels.*

[303] *From Eco-Building To Sustainable City*, 12.

[304] PassREg, *A Guide to Success* (2015), 49. phttp://www.passreg.eu/download.php?cms=1&file=D_2_6_PassREg_Success_Guide.pdf

[305] Baltimore County, "High Performance Homes Tax Credits." http://www.baltimorecountymd.gov/Agencies/budfin/customerservice/taxpayerservices/taxcredits/performancehomes.html

[306] "PACE Loans: Does Sale Value Reflect Improvements?", 3.

[307] U.S. Federal Housing Administration, *Guidance for Use of FHA Financing on Homes with Existing PACE Liens and Flexible Underwriting through Energy Department's Home Energy Score* (2015). http://portal.hud.gov/hudportal/documents/huddoc?id=FTDO.pdf

[308] Joe Kaatz and Scott J. Anders, *Residential and Commercial Property Assessed Clean Energy (PACE) Financing in California Rooftop Solar Challenge Areas* (2014). http://energycenter.org/sites/default/files/docs/nav/policy/research-and-reports/PACE in California.pdf

[309] "PACE Loans: Does Sale Value Reflect Improvements?", 3.

[310] For an updated list see PACENation, "Pace Programs Near You." http://www.pacenation.us/pace-programs/#map

[311] Robert Duffy and Charley Beresford, *This Green House II: Building Momentum on Green Jobs and Climate Action,* (Columbia Institute, 2016), 16. http://www.civicgovernance.ca/green-house-ii-2/

[312] Shauna Morgan, Nina Lothian and Ben Thibault, *Loans for Heat Towards a Yellowknife Energy Savings Program*, prepared for City of Yellowknife by the Pembina Institute, 2015. https://www.yellowknife.ca/en/resources/Green_Energy_Retrofit_ Program_-_March_31_2015_-_Pembina.PDF

[313] Mark Levine, Stephane De la Rue de Can, Christopher Williams Nina Zheng, Jennifer Amann, and Dan Staniaszek, *Building Energy-Efficiency Best Practice Policies and Policy Packages* (Lawrence Berkeley National Laboratory, 2012), 36. http://eaei.lbl.gov/sites/all/files/GBPN_Final.Oct_.2012.pdf

[314] Seref Efe, Inam ur Raheem, Tingting Wan & Carter Williamson, *Cheaper Power Bills, More Jobs, Less CO2: How On-Bill Financing Done Right can be a Quick Win for British Columbia* (Pacific Institute for Climate Solutions, 2015), 7-9. http://pics.uvic.ca/sites/default/files/uploads/publications/On-Bill Financing FINAL.pdf

[315] Ibid., 10.

[316] KFW, Energieeffizient Bauen und Sanieren. https://www.kfw.de/inlandsfoerderung/Privatpersonen/index-2.html

[317] *Building Energy-Efficiency Best Practice Policies and Policy Packages,* 188.

[318] KfW Bankengruppe, *Impact on Public Budgets of KfW Promotional Programmes in the Field of 'Energy-Efficient Building and Rehabilitation,'* (2011). 8. http://www.kfw.de/kfw/en/KfW_Group/Research/PDF-Files/STE_Research_Report.pdf

[319] Dharam Consulting, *Passivhaus Tall Residential Buildings: Indicative ECM & LCC Report* (2016). (DRAFT RESULTS)

[320] The Success Model of Brussels, 24-33.

[321] The Success Model of Brussels, 38.

[322] *Energy Performance Certificates in Buildings and Their Impact on Transaction Prices and Rents in Selected EU Countries*.

[323] Ibid. 89 and 118.

[324] Tom-Pierre Frappé-Sénéclauze, Ellen Pond and Alison Cretney, *Home Energy Labelling: Strategic Plan for Labelling of Part 9 Residential Buildings in B.C.* (Pembina Institute, 2015). http://www.pembina.org/pub/home-energy-labelling

[325] International Passive House Association, "International Passive House Days." http://www.passivehouse-international.org/index.php?page_id=262

[326] Are you normal?. http://areyounormal.be/en/

[327] Plate-forme Maison Passive, Action de sensibilisation - "Ice Challenge." http://www.maisonpassive.be/?-Action-de-sensibilisation-Ice-

[328] *The Success Model of Brussels.*

[329] Synergy Sustainability Institute, *The Business Case for Passive House* (2015). http://www.ryanhamilton.ca/Client/0052-SSi/PH_BusinessCase_2015.pdf

[330] Helen Goodland, Chris Lindberg, and Paul Shorthouse, *Construction Innovation Project: Building B.C.'s Vision* (2015), 56. https://www.bccassn.com/media/bcca-report-construction-innovation-2016.pdf

[331] Institute for Market Transformation. *U.S. Building Benchmarking and Disclosure Policies Map* (2014). http://www.buildingrating.org/sites/default/files/documents/US_Rating_Map (1).pdf

[332] NMR Group, *Statewide Benchmarking Process Evaluation* (2012). http://www.calmac.org/publications/Statewide_Benchmarking_Process_Evaluation_Report_CPU0055.pdf.

[333] Ryan Meres and Jayson Antonoff. *Linking Building Energy Codes With Benchmarking and Disclosure Policies* (2014). http://www.imt.org/uploads/resources/files/Linking_Codes_With_Benchmarking.pdf

[334] Passive House Institute, *Criteria for the Passive House , EnerPHit and PHI Low Energy Building Standard* (2015). http://www.passipedia.org/_media/picopen/phi_building_criteria_draft.pdf

[335] Passipedia, "The new Passive House Classes." http://www.passipedia.org/certification/passive_house_categories

[336] Passipedia, "The PER sustainability assessment." http://passipedia.org/certification/passive_house_categories/per

[337] Passive House Institute, *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard* (2015), Section 2.4, 13–17. http://www.passiv.de/downloads/03_building_criteria_en.pdf

[338] PHIUS, "PHIUS + 2015 Passive Building Standard – North America." http://www.phius.org/phius-2015-new-passive-building-standard-summary

[339] Graham Wright, Katrin Klingenberg, and Betsy Pettit, *Climate-Specific Passive Building Standards* (Building America, 2014). http://buildingscience.com/documents/bareports/ba-1405-draft-climate-specific-passive-building-standards/view

[340] PHIUS, *PHIUS + 2015 Passive Building Standard – North America: Protocol.* https://www.dropbox.com/s/oe3rb5vqiclmvm0/PHIUS%2B 2015 Packet v3.pdf?dl=0; "PHIUS+2015 Certification Packet." http://www.phius.org/PHIUSPlus2015docs/PHIUS+ Certification Packet 10.09.15 - PHIUS+ 2015.pdf

[341] "PHIUS + 2015 Passive Building Standard – North America."

[342] City of Vancouver, *Zero Emissions Building Plan* (2016). http://council.vancouver.ca/20160712/documents/rr2.pdf

[343] The White House, "President Obama Announces New Actions to Bring Renewable Energy and Energy Efficiency to Households across the Country," media release, August 24, 2015. https://www.whitehouse.gov/the-press-office/2015/08/24/fact-sheet-president-obama-announces-new-actions-bring-renewable-energy

[344] City of New York, *One City, Built to Last: Transforming New York City Buildings for a Low-Carbon Future*, technical working group report (2014), 108.

[345] Marin County, California., Ord. No. 3607 (November 12, 2013) (definitions are codified at Marin County Code 19.04.130), available at apps.marincounty.org/bos/ordinances/ord-3607.doc

[346] Pennsylvania Housing Finance Agency, *Allocation Plan For Year 2015 Low Income Housing Tax Credit Program* (2014), 23. http://www.phfa.org/forms/multifamily_program_notices/qap/2015_qap_final.pdf AND

Pennsylvania Housing Finance Agency, 2015 Multifamily Housing Application Package and Guidelines, Tab 03, Self-Scoring Sheet, at 173 (rev'd Dec. 15, 2014), http://www.phfa.org/developers/developer/housingapplication.aspx
Note that the criteria for meeting ''Energy Efficiency Goals'' require developments to meet Passive House Certification requirements but do not require final certification.

[347] Tim McDonald, Personal communication, 14 August 2015.

[348] New York State Homes & Community Renewal, *Request for Proposals: Multi-Family Programs* (2015). http://www.nyshcr.org/Funding/UnifiedFundingMaterials/2015/2015-RFP-MulltiFamilyPrograms.pdf

[349] Tim McDonald, Personal communication, 14 August 2015.

[350] Government of New York City, *Low energy intensity building requirements for certain capital projects, 2016/0312*. http://legistar.council.nyc.gov/LegislationDetail.aspx?ID=2240482&GUID=0A9A548C-E3D9-4057-AEAC-426CA033FBBF

[351] Laurie Kerr, "Next Gen Lean and Green NYC-Owned Buildings," *Urban Green*, March 9, 2016. http://urbangreencouncil.org/content/news/next-gen-lean-and-green-nyc-owned-buildings

[352] It is worth noting that a previous version of the bill proposed that City capital projects greater than two million dollars be built to Passive House standards (either PHIUS or iPHA). (Government of New York City, *Low energy intensity building requirements for certain capital projects, 2016/0312*. Bill 701, subdivision l, paragraph 3(i). http://legistar.council.nyc.gov/LegislationDetail.aspx?ID=2240482&GUID=0A9A548C-E3D9-4057-AEAC-426CA033FBBF). On the topic of Passive House, the working group summary report comments: *"[The Passive House] absolute targets provide more certainty to energy performance outcomes, but are not commonly used in the New York City building industry today. In addition, a metric for New York City must account for the varying space uses and differences in building occupancy in the city to avoid penalizing industries that have high energy use profiles, such as trading floors and television studios. Collaboration with other jurisdictions and leaders on this effort is also key to ensuring market alignment of any new standards." One City, Built to Last*, 108.

[353] City of Vancouver, *Zero Emissions Building Plan* (2016), 24.

[354] Ibid., 25

[355] http://former.vancouver.ca/commsvcs/bylaws/BULLETIN/G002.pdf

[356] City of Vancouver, *Zero Emissions Building Plan* (2016), 42. See also City of Vancouver, *Floor Space Exclusion to Accommodate Improved Building Performance (Envelope and Thermal Insulation)* (2016). http://former.vancouver.ca/commsvcs/BYLAWS/bulletin/F008.pdf

[357] NYC PLanning, *Zone Green Text Amendment,* April 30, 2012. http://www1.nyc.gov/assets/planning/download/pdf/plans/zone-green/zone_green.pdf

[358] SF Environment, "Priority Permitting." http://sfenvironment.org/article/larger-projects-commercial-amp-multifamily/priority-permitting; and City and County of San Francisco, *Priority Permit Processing Guidelines,* Administrative Bulletin, April 27, 2015. http://sfdbi.org/sites/sfdbi.org/files/AB-004_0.pdf

[359] Sean Pander, personal communication, 17August 2015.

[360] City of Vancouver, Letter to Passive House Institute on temporary allowances for building bylaw compliance, March 17, 2014. Available at http://canphi.ca/wp-content/uploads/2015/03/CMO-SUS-Passive-House-Equivlencies-Letter.pdf

[361] Baltimore County, "High Performance Homes Tax Credits." http://www.baltimorecountymd.gov/Agencies/budfin/customerservice/taxpayerservices/taxcredits/performancehomes.html

[362] U.S. Energy Information Administration, "Residential Energy Consumption Surve: 2009 RECS Survey Data." https://www.eia.gov/consumption/residential/data/2009/index.cfm?view=microdata

[363] B.C. Building and Safety Standards Branch, *Information Bulletin: Determining ASHRAE 90.1-2010 Climate Zones* (2014). http://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/construction-industry/building-codes-and-standards/bulletins/b14-01_determining_ashrae_901-2010_climate_zones.pdf