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HOUSING RESEARCH REPORT

Passive Approaches to Low-energy Affordable Housing Projects – Literature Review and Annotated Bibliography

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Passive Approaches to Low-energy Affordable Housing Projects – Literature Review and Annotated Bibliography

Prepared by:

Remi Charron, Ph.D., P.Eng, Certified Passive House Designer
Remi Charron Consulting Services
9318 Pemberton Meadows Road
Pemberton, BC V0N 2L2
Remi.Charron@mail.mcgill.ca

February 2017

Prepared for:

Thomas Green
Senior Researcher
Housing Needs Research Corporate Development, Policy & Research
Canada Mortgage and Housing Corporation (CMHC)
700 Montreal Road, C2-348
Ottawa, ON K1A 0P7
tgreen@cmhc-schl.gc.ca

Executive Summary

There is an increasing need for, and interest in, affordable housing models that can achieve improved levels of building performance in support of lower cost housing and to ensure the long term financial viability of affordable housing providers and projects. In affordable housing developments many occupants pay their own utility bills and this added cost can make even lower cost housing unaffordable. In cases where housing providers pay the utilities, high operations and maintenance costs can limit the funds available to be put towards immediate or long term repairs or improved client services.

One of the most promising and innovative responses to this challenge is through a "better building" approach using "passive" design and construction methods that can simply and effectively provide significant reductions in operating energy consumption while also providing a healthy living environment. Passive approaches to low-energy design focus on improving the design and performance of the building itself, with a big emphasis on a highly insulated and air-tight building envelope, eliminating thermal bridges, and providing efficient and effective heat recovery ventilation.

In support of affordable housing providers, there is a need for field experience and evidence-based data on the performance of low-energy sustainable multi-unit residential building (MURB) projects and the technologies and systems used to build them. In addition to technical issues, there is a need to assess how a passive low-energy MURB can be financially planned and developed through a better understanding of the dynamics between higher initial capital costs (e.g. construction, including design and installed equipment) and lower operating and maintenance costs, especially considered over a longer lifecycle period (say 30+ years) - particularly in comparison to a more conventional code built MURB. There is also a need to better understand how increased capital costs in some areas (e.g. a highly insulated building envelope) can lead to and be balanced by lower costs for other building components, such as reduced heating and cooling systems.

In support of this approach, this research project was initiated to investigate, document and identify the literature and case studies of passive approaches to energy reduction in affordable housing, with particular attention to multi-unit residential buildings. This report summarises the results from the literature review and associated key stakeholder interviews.

Case Studies

There are a number of Canadian projects that have been developed to achieve very high levels of energy performance utilising passive design concepts in the process. A series of 13 Canadian projects are presented. With tens of thousands of Passive House projects in Europe, and countless others around the world, there are many potential international projects to highlight. To provide some focus, international case studies were limited to affordable MURB projects built in Northern U.S. states as they would have more similar construction practices and challenges to Canada. A total of 14 U.S. projects are presented, three of which are retrofits.

Passive Design Approaches and Technologies

Incorporating passive design approaches to achieve ultra-high levels of performance does not limit the architect or designer to use particular construction practices or materials. Although construction

practices and materials can differ substantially between projects, there are typically five key design elements that need to be included:

1. An optimal level of thermal insulation.
2. Thermally insulated window frames with high quality glazing.
3. Careful design to limit thermal bridges to avoid unnecessary heat loss.
4. An airtight building envelope using an uninterrupted and continuous airtight layer.
5. Mechanical ventilation with heat recovery to ensure continuous supply of fresh air.

These passive low-energy design and construction strategies are the principle features of the Passive House (Passivhaus) standard, which is often considered to be the most rigorous voluntary energy-based standard in the design and construction industry today. Applicable to almost any building type or design, the Passive House high-performance building standard is an internationally recognized science-based energy standard in construction.

Technologies and design practices implemented in low to mid-rise wood-frame MURBs can be quite different than those found in high-rise MURBS, categorized as non-combustible construction (Part 3 of the National Building Code). For high-rise buildings, the key approach is often to use exterior insulation to reduce thermal bridging, coupled with high performance windows.

Cost-Benefit Studies

There is a wide range of reported incremental costs in the literature on building to Passive House levels of performance, ranging from 2% to over 40%, with many reported in the 5% to 10% range. One challenge in comparing incremental costs is that the base case for which to compare costs often varies between projects. Values also depend on a series of assumptions about what would be included in the base case. A number of projects reported a higher percentage of incremental costs for affordable housing projects, as they often start with a low-cost base case building.

Another approach is to simply look at the overall cost of building passive low-energy affordable housing projects to see if they are affordable relative to other projects. This type of information is available from a number of projects in Pennsylvania, for example. In October 2014, the state added 10 points (out of 130) for targeting Passive House performance to their affordable housing project proposal evaluation criteria. Subsequently, of the 85 multi-family affordable housing project proposals submitted in February 2015, 32 were aiming for Passive House. Out of 39 projects awarded funding, 7 were planned Passive House projects, involving a total of 422 units. The average cost of the 32 Passive House project proposals was \$169/ft^2, which compares quite favourably to the 53 non-Passive Houses that had an average cost of \$165/ft^2. A similar experience occurred at Housing Nova Scotia; their first Passive House duplex was built at around \$130/ft^2, whereas the second duplex had a contractor bid at just over \$100/ft^2, which is a comparable cost to their other housing projects.

Affordable housing providers can also achieve additional cost savings associated with building low-energy housing, beyond reduced utility costs. Past studies looking at the cost-benefits of weatherizing low income homes found that these savings can be comparable to the energy cost savings. These savings come through the avoidance of rate subsidies, lower bad-debt write-offs, fewer notices and

customer calls, fewer shut-offs and reconnections for bill payment delinquency, and increased property value, among other benefits.

Post Occupancy Evaluation

A number of studies looking at post-occupancy evaluations of passive low-energy buildings have found some incidences of overheating, which can be worse in upper floors of mid- to high-rise buildings. There is some concern that overheating of homes can become a likely health risk in the near future in the context of climate change, such that summer thermal comfort needs to be looked at in new construction. To more accurately model the risk of overheating, designers would need to use dynamic hourly simulation tools to better predict the potential for overheating.

A number of sources reported that energy saving projects that rely on more complex heating, ventilation and cooling systems have often underperformed in terms of energy savings, and have ended up costing substantially more in terms of ongoing operational and maintenance costs.

Stakeholder Interviews

In addition to reviewing existing literature resources, key affordable housing sector players were identified and interviewed to obtain qualitative information on their past experience and current intentions of building low-energy affordable housing. Stakeholder responses were then grouped and summarized by category of response.

<u>Drivers</u>

A number of reasons were given as to why they would pursue low-energy affordable housing projects:

- Meet requirements imposed on affordable housing providers.
- Aim for higher performance to help learn how to achieve increasing levels of performance that are anticipated in future code changes.
- Desire to lower the utility costs, either for tenants and/or affordable housing providers.
- Opted specifically for passive strategies to try to reduce maintenance and replacement costs.

<u>Technologies and Education</u>

Measures that are successfully implemented need to:

- Require little to no occupant controls,
- take into account that building operators are often untrained and have high turnover,
- be accommodating for occupants that open windows in winter, and
- be simple to design, commission and operate.

Following a project, tenant education is often required to help them learn how to interact with the building, such as:

- General guidance on how to reduce energy consumption.
- How to operate a HRV/ERV.
- How and when to open windows for passive-cooling (night flushing)

- How to adjust behaviour to accommodate for slower response time of ground-source heat pump heating systems.

Benefits and Barriers

Cited benefits include better indoor air quality, a more comfortable and quieter living environment, lower turnover, and lower utility costs.

Barriers that were identified by interviewees include:

- Lack of examples of larger passive low-energy MURBs that show lower utilities and O&M costs.
- Development requirements for LEED (Leadership in Energy and Environmental Design®) rating system performance, so it is difficult to change to other performance objectives such as Passive House.
- Lack of case studies overall, that report on construction costs, O&M costs and tenant feedback.
- Reluctance to try or approve new innovative concepts that they are not familiar with.
- The short turn-around time from when projects are awarded funding based on a conceptual design, to having to have a complete design (3-months) does not leave enough time to do more detailed design studies and performance modelling or to try new things.
- Developers reluctant to build to Passive House standard of performance if they need to sole-source windows and heat recovery ventilators (HRV's) due to limited market availability of high performance units.

Performance Metrics

Through the literature review and stakeholder interviews, the performance metrics that could help evaluate the sustainability of an affordable passive low-energy MURB project were examined. Based on feedback from interviews, the metrics that are interest to affordable housing providers the most are energy use intensity (kWh/m^2) and a number of metrics related to costs on a per floor area basis (Capital costs; Utility costs; Other operating and maintenance costs; and Anticipated repair and replacement costs).

Annotated Bibliography

The Annotated Bibliography provides the results of the literature review related to passive low-energy affordable housing research, performance, financial data and case studies, with particular attention paid to multi-unit residential buildings (MURBs). The annotated bibliography serves as the basis of the overall Final Report summarizing the existing literature on the topic.

Conclusion

Increasing interest in, and requirements for, managing housing costs and improving energy performance of affordable housing coupled with the anticipation of future increases to energy performance requirements in building codes has led to the rapid increase of ultra-low energy and Passive House projects in the past few years. Although reaching very high levels of performance requires the use of some mechanical equipment, such as heat (or energy) recovery ventilators, past experience has led towards passive approaches to reducing energy consumption, namely through super-insulated and

airtight building envelopes with high performance triple glazed windows. The goal is to achieve low energy consumption coupled with affordable capital costs and reduced maintenance costs.

The advantage of utilising the building envelope to achieve ultra-low energy performance is that it is not that complicated and it has been shown to work. In Pennsylvania, where many affordable housing Passive House projects are being constructed, the biggest change in construction practice is to add roughly 10 cm (4”) of exterior insulation to standard 38 x 140 mm (2”x6”) walls. This requires some learning on how to properly seal and flash windows, and how best to attach insulation, siding and other finishes. In addition, some learning needs to be done to build transitions that have limited thermal bridging, and on how to install a continuous air-barrier to achieve a very airtight building. Given that it is not such a large leap from where they are today, once the design and construction team has gone through one or two projects, they can learn how to effectively apply these new practices in future projects.

Résumé

Les modèles de logements abordables pouvant atteindre des niveaux améliorés de rendement et ainsi aider à abaisser le coût du logement et à assurer la viabilité financière à long terme des fournisseurs et des collectifs sont de plus en plus nécessaires et suscitent un intérêt grandissant. Dans les ensembles de logements abordables, de nombreux occupants payent leurs propres factures de services publics et ce coût additionnel peut rendre inabordables même les habitations à coût modique. Dans les cas où les fournisseurs de logements payent les services publics, les frais d'exploitation et d'entretien élevés peuvent limiter les sommes disponibles pour les réparations immédiates ou à long terme, ou pour l'amélioration des services aux clients.

Une des solutions les plus prometteuses et innovatrices pour relever ce défi est une approche fondée sur l'amélioration de la construction au moyen d'une conception et de méthodes de construction « passives » qui peuvent, simplement et efficacement, produire des réductions considérables de la consommation d'énergie des immeubles tout en offrant un milieu de vie sain. Les approches passives de la conception d'immeubles éconergétiques se concentrent sur l'amélioration de la conception et du rendement de l'immeuble lui-même, en accordant une grande importance à l'isolation et à l'étanchéisation maximale de l'enveloppe du bâtiment, à l'élimination des ponts thermiques et à l'efficience et l'efficacité de la ventilation à récupération de chaleur.

Pour soutenir les fournisseurs de logements abordables, il faut obtenir des informations tirées de l'expérience pratique et des données probantes concernant le rendement des immeubles collectifs éconergétiques durables et les technologies et systèmes utilisés pour les construire. En plus des questions techniques, il faut évaluer les moyens de planifier et d'aménager des immeubles collectifs éconergétiques passifs grâce à une meilleure compréhension de la dynamique entre les coûts d'immobilisation initiaux plus élevés (pour la construction ainsi que la conception et les équipements fixes) et les frais d'exploitation et d'entretien moins élevés, surtout pendant un cycle de vie plus long (disons 30 ans et plus) et notamment en comparaison aux immeubles collectifs plus traditionnels construits selon les exigences des codes du bâtiment. Il faut aussi mieux comprendre comment les coûts d'immobilisation plus élevés de certains composants (comme une enveloppe du bâtiment hautement isolée) peuvent être compensés par la réduction des coûts qu'ils entraînent pour d'autres composants de l'immeuble, comme les systèmes de chauffage et de climatisation.

Afin d'appuyer cette approche, ce projet de recherche a été entrepris pour chercher, répertorier et documenter la littérature et les études de cas sur les approches passives de la réduction de la consommation d'énergie des logements abordables, en accordant une attention particulière aux collectifs d'habitation. Ce rapport résume les résultats de la revue de la littérature et des entretiens connexes avec des intervenants clés.

Études de cas

Plusieurs ensembles de logements canadiens ont été aménagés de manière à atteindre de très hauts niveaux de rendement énergétique en utilisant des éléments de la conception passive. Treize ensembles canadiens sont présentés. Il y a des dizaines de milliers de collectifs construits selon les principes de la maison passive en Europe et d'innombrables autres partout dans le monde; les exemples internationaux ne manquent donc pas. Pour cibler la recherche, seules des études de cas de collectifs d'habitation

abordables construits dans les États du nord des États-Unis ont été retenues, puisque les pratiques de construction et les défis y ressemblent davantage à ceux du Canada. En tout, 14 ensembles américains sont présentés, dont trois qui ont fait l'objet de rénovations éconergétiques.

Méthodes et technologies de conception passive

L'intégration de méthodes de conception passive pour atteindre des niveaux extrêmement élevés de rendement n'oblige pas l'architecte ou le concepteur à utiliser des pratiques ou des matériaux de construction particuliers. Les pratiques et les matériaux peuvent différer considérablement d'un ensemble à l'autre, mais il faut habituellement intégrer cinq éléments de conception clés :

1. Un niveau optimal d'isolation thermique.
2. Des cadres de fenêtres à isolation thermique avec vitrage de grande qualité.
3. Une conception minutieuse pour limiter les ponts thermiques et éviter les pertes inutiles de chaleur.
4. Une enveloppe du bâtiment rendue étanche au moyen d'un matériau d'étanchéité ininterrompu et continu.
5. Une ventilation mécanique avec récupération de la chaleur pour assurer un approvisionnement continu en air frais.

Ces stratégies de conception et de construction éconergétiques passives sont les principales caractéristiques de la norme de la maison passive (Passivhaus), qui est souvent considérée comme la norme éconergétique volontaire la plus rigoureuse qui existe aujourd'hui dans le secteur de la conception et de la construction. La norme de construction à haut rendement de la maison passive, applicable à presque tous les types ou modèles d'immeubles, est une norme internationalement reconnue de construction éconergétique fondée sur la science.

Les technologies et pratiques de conception appliquées dans les immeubles collectifs à ossature de bois de faible à moyenne hauteur peuvent être très différentes de celles qu'on utilise dans les tours d'habitation classées comme constructions non combustibles (partie 3 du Code national du bâtiment). Pour les tours d'habitation, la principale approche consiste souvent à utiliser l'isolation extérieure pour réduire les ponts thermiques, alliée à des fenêtres à haut rendement.

Études coûts-avantages

Dans la littérature, les coûts additionnels de construction de logements atteignant les niveaux de rendement de la maison passive varient énormément, allant de 2 % à plus de 40 %, et bon nombre des coûts signalés se trouvent dans la fourchette de 5 % à 10 %. Une difficulté que présente la comparaison des coûts additionnels, c'est que le cas de référence servant à comparer les coûts varie souvent d'un ensemble à l'autre. Les valeurs dépendent aussi d'une série d'hypothèses concernant ce qui serait inclus dans le cas de référence. Le pourcentage indiqué des coûts additionnels pour certains ensembles de logements abordables était supérieur parce que, souvent, le cas de référence était un immeuble à coût modique.

Une autre approche consiste tout simplement à examiner le coût global de la construction d'ensembles de logements abordables éconergétiques passifs pour voir s'ils sont abordables comparativement à d'autres ensembles. Par exemple, on peut trouver ce type de renseignements pour un certain nombre d'ensembles en Pennsylvanie. En octobre 2014, l'État a ajouté 10 points (sur 130) pour les mesures

visant à atteindre le rendement d'une maison passive à ses critères d'évaluation des propositions de construction d'ensembles de logements abordables. Par la suite, parmi les 85 propositions d'ensembles de logements multiples abordables soumis en février 2015, 32 visaient l'atteinte de la norme de la maison passive. Parmi les 39 propositions pour lesquelles un financement a été accordé, sept prévoyaient la construction de collectifs passifs comprenant 422 logements en tout. Le coût moyen des 32 propositions de collectifs passifs était de 169 $/pi^2, ce qui se compare très favorablement aux 53 ensembles de logements non passifs, dont le coût moyen s'élevait à 165 $/pi^2. Housing Nova Scotia a eu une expérience semblable. Son premier duplex passif a été construit au coût d'environ 130 $/pi^2, alors que pour le deuxième, un entrepreneur a présenté une soumission d'un peu plus de 100 $/pi^2, ce qui est comparable au coût des autres ensembles d'habitation de l'organisme.

Les fournisseurs de logements abordables peuvent aussi faire d'autres économies liées à la construction de logements éconergétiques, au delà de la réduction des coûts des services publics. Des études antérieures des coûts-avantages de l'isolation des logements à coût modique ont révélé que ces économies peuvent être comparables aux économies de coûts d'énergie. Le fait de ne pas avoir à subventionner les taux, la réduction des radiations de mauvaises créances, des avis, des appels de clients et des coupures et reconnexions de services publics pour défaut de paiement des factures ainsi que l'accroissement de la valeur de la propriété figurent parmi les avantages créant ces économies.

Évaluation post-occupation

Certaines études portant sur les évaluations post-occupation d'immeubles éconergétiques passifs ont révélé des cas de surchauffe, phénomène qui peut être pire aux étages supérieurs d'immeubles de moyenne et grande hauteur. Certains craignent que la surchauffe des logements devienne un risque probable pour la santé dans un proche avenir à cause du changement climatique, de sorte qu'il faut prendre en compte le confort thermique en été lors de la construction d'immeubles. Afin de modéliser avec plus d'exactitude le risque de surchauffe, il faudrait que les concepteurs utilisent des outils de simulation horaire dynamique pour mieux le prédire.

Un certain nombre de sources ont indiqué que les ensembles éconergétiques qui dépendent de systèmes plus complexes de chauffage, de ventilation et de climatisation ont souvent eu un rendement inférieur en ce qui concerne les économies d'énergie et ont engendré des frais d'exploitation et d'entretien permanents considérablement plus élevés.

Entrevues avec des intervenants

En plus de l'examen des ressources documentaires existantes, des intervenants clés du secteur du logement abordable ont été interviewés pour obtenir des renseignements qualitatifs sur leur expérience passée et leurs intentions actuelles concernant la construction de logements abordables éconergétiques. Les réponses des intervenants ont ensuite été regroupées et résumées par catégories.

<u>Facteurs de motivation</u>

Les intervenants ont invoqué plusieurs raisons pour lesquelles ils construiraient des ensembles d'habitation abordables éconergétiques :

- satisfaire aux exigences imposées aux fournisseurs de logements abordables;
- chercher à atteindre un meilleur rendement pour favoriser l'apprentissage des moyens de parvenir à des niveaux croissants de rendement en prévision de changements futurs des codes;

- vouloir abaisser les coûts des services publics, soit pour les locataires ou les fournisseurs de logements abordables;
- choisir les stratégies passives pour tenter de réduire les coûts d'entretien et de remplacement.

Technologies et éducation

Les mesures mises en œuvre avec succès doivent :

- ne nécessiter que des interventions minimes ou nulles de la part des occupants,
- tenir compte du fait que les exploitants des immeubles manquent souvent de formation et ont un taux de roulement élevé,
- permettre aux occupants qui le veulent d'ouvrir leurs fenêtres en hiver et
- être simples à concevoir, à mettre en service et à utiliser.

Une fois un ensemble achevé, il est souvent nécessaire d'éduquer les locataires pour les aider à apprendre comment interagir avec l'immeuble, par exemple :

- comment réduire la consommation d'énergie;
- comment faire fonctionner un ventilateur récupérateur de chaleur (VRC) ou un ventilateur récupérateur d'énergie (VRE);
- comment et quand ouvrir les fenêtres pour obtenir un refroidissement passif (purge nocturne);
- comment modifier leur comportement pour s'adapter au temps de réaction plus lent des systèmes de chauffage par thermopompe géothermique.

Avantages et obstacles

Les avantages mentionnés comprennent l'amélioration de la qualité de l'air intérieur, un milieu de vie plus confortable et tranquille et une diminution du roulement et des coûts des services publics.

Les personnes interrogées ont relevé les obstacles suivants :

- le manque d'exemples de gros collectifs d'habitation passifs éconergétiques dont les coûts des services publics et les frais d'exploitation et d'entretien sont plus bas;
- les exigences en matière d'aménagement pour se conformer au système d'évaluation du rendement LEED (Leadership in Energy and Environmental Design^{MD}) qui font qu'il est difficile d'apporter des changements pour atteindre d'autres objectifs de rendement, comme ceux de la maison passive;
- le manque global d'études de cas donnant des renseignements sur les coûts de construction, les frais d'exploitation et d'entretien et les observations des locataires;
- l'hésitation à essayer ou approuver de nouveaux concepts innovateurs qu'ils ne connaissent pas bien;
- le court délai entre l'affectation de fonds pour les projets qui se fonde sur un concept préliminaire et l'établissement d'un concept complet (trois mois), qui n'est pas suffisant pour procéder à des études conceptuelles et une modélisation du rendement plus détaillées ou pour essayer de nouvelles choses;
- les promoteurs qui sont peu disposés à construire des immeubles respectant la norme de rendement de la maison passive s'ils doivent faire appel à un fournisseur unique pour les

fenêtres et les ventilateurs récupérateurs de chaleur (VRC), étant donné la disponibilité restreinte de produits à haut rendement sur le marché.

Paramètres de rendement

Les paramètres de rendement qui pourraient aider à évaluer la durabilité d'un immeuble collectif abordable passif éconergétique ont été examinés au moyen de la revue de la littérature et d'entrevues avec des intervenants. D'après les informations obtenues au moyen des entrevues, les paramètres qui intéressent le plus les fournisseurs de logements abordables sont l'intensité de la consommation d'énergie (kWh/m^2) et plusieurs paramètres liés aux coûts par aire de plancher (coûts d'immobilisations, coûts des services publics, autres frais d'exploitation et d'entretien et coûts prévus de réparation et de remplacement).

Bibliographie annotée

La bibliographie annotée présente les résultats de la revue de la littérature liés à la recherche, aux données financières et aux études de cas sur les logements abordables éconergétiques passifs et sur leur rendement, et portant notamment sur les collectifs d'habitation. La bibliographie annotée sert de fondement du rapport final global qui résume la littérature existante sur le sujet.

Conclusion

L'intérêt croissant pour la gestion des frais de logement et l'amélioration du rendement énergétique des logements abordables, les exigences toujours plus grandes à cet égard et l'accroissement futur prévu des exigences en matière de rendement énergétique dans les codes du bâtiment ont entraîné une hausse rapide du nombre d'ensembles passifs et à très faible consommation énergétique au cours des dernières années. Bien que l'atteinte de niveaux très élevés de rendement exige un recours à certains équipements mécaniques, comme les ventilateurs récupérateurs de chaleur (ou d'énergie), l'expérience passée a amené les fournisseurs de logements à recourir à des méthodes passives de réduction de la consommation d'énergie, notamment au moyen d'enveloppes de bâtiment extrêmement bien isolées et étanches et de fenêtres à triple vitrage à rendement élevé. Le but est de parvenir à une faible consommation d'énergie tout en rendant les coûts d'immobilisation abordables et en réduisant les frais d'entretien.

L'avantage d'utiliser l'enveloppe du bâtiment pour obtenir une consommation d'énergie très faible est que la méthode n'est pas tellement compliquée et que son efficacité est démontrée. En Pennsylvanie, où de nombreux ensembles de logements abordables respectant la norme de la maison passive sont construits, le changement le plus important des pratiques de construction consiste à ajouter environ 10 cm (4 po) d'isolation extérieure à des murs standard de 38 x 140 mm (2 po x 6 po). Pour y arriver, il faut apprendre à appliquer les mastics d'étanchéité et à installer les solins des fenêtres adéquatement, et à utiliser la meilleure méthode pour fixer l'isolant, le bardage et d'autres éléments de finition. En plus, il faut apprendre comment effectuer des transitions qui limitent les ponts thermiques et comment installer un pare-air continu pour rendre l'immeuble extrêmement étanche. Comme il ne s'agit pas de compétences très différentes de celles qui sont utilisées aujourd'hui, une fois que l'équipe de concepteurs et de constructeurs a réalisé un ou deux projets, elle peut apprendre à mettre en œuvre ces nouvelles pratiques efficacement dans les ensembles futurs.

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National Office
700 Montreal Road
Ottawa ON K1A 0P7
Telephone: (613) 748-2000

Bureau national
700 chemin de Montréal
Ottawa ON K1A 0P7
Téléphone : (613) 748-2000

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Table of Contents

1. Background

There is an increasing need for, and interest in, affordable housing models that can achieve improved levels of building performance in support of lower cost housing and to ensure the long term financial viability of affordable housing projects. In affordable housing developments, occupants often pay their own utility bills and this added cost can make even lower cost housing unaffordable. In cases where housing providers pay the utilities, increasing or added costs can limit the funds available to be put towards immediate or long term maintenance and repairs and client services.

One of the most promising and innovative responses to this challenge is through a "better building" approach using "passive" design and construction methods that can simply and effectively provide significant reductions in operating energy consumption while also providing a healthy living environment and other sustainable design benefits including improved building durability, resource conservation and reduced environmental impacts. Passive approaches to low-energy design focus on improving the design and performance of the building itself, with a big emphasis on a highly insulated and air-tight building envelope to significantly reduce operating costs and to avoid potential difficulties associated with more complex mechanical systems that are often deployed in an effort to reduce energy consumption.

Passive low-energy design and construction strategies are the principle features of the Passive House (Passivhaus) standard, which is often considered to be the most rigorous voluntary energy-based standard in the design and construction industry today. Applicable to almost any building type or design, the Passive House high-performance building standard is an internationally recognized science-based energy standard in construction. The benefits identified for employing the Passive House standard include fine-tuned control over indoor air quality and temperature with simple to use and durable systems, making them extremely quiet and comfortable throughout the changing seasons.

An overriding drive to keep construction capital costs low combined with a lack of research, experience and knowledge of design strategies, technologies and practices that can be applied to increase the performance of Multi-unit Residential Building (MURB) projects (particularly those in the affordable housing sector), has resulted in designers and owners being very cautious in the design of their projects. Within the affordable housing sector, time constraints and budget limitations often forestall any thoughts around the inclusion of design improvements and sustainable technologies and practices before the projects are even started. However, there are an increasing number of affordable housing projects pursuing better energy performance and sustainability features, across Canada and internationally, as evidenced in the CMHC Affordable Housing Project Profiles[1]. The extent to which passive principles in particular can be applied to low-energy affordable housing projects to achieve ultra-low energy consumption levels, reduced operating costs, increased occupant comfort and other benefits is a relatively new field which is of increasing interest to affordable housing providers.

[1] www.cmhc-schl.gc.ca/en/inpr/afhoce/afhoce/prpr/

In support of affordable housing providers, there is a need for field experience and evidence-based data on the performance of low-energy sustainable MURB projects and the technologies and systems used to build them. In addition to technical issues, there is a need to assess how a passive MURB can be financially planned and developed through a better understanding of the dynamics between higher initial capital costs (e.g. construction, including design and installed equipment) and lower operating and maintenance costs, especially considered over a longer lifecycle period (say 30+ years) - particularly in comparison to a more conventional code built MURB. There is also a need to better understand how increased capital costs in some areas (e.g. a highly insulated building envelope) can lead to and be balanced by lower costs for other building components, such as reduced heating and cooling systems.

In support of this approach, this research project was initiated to investigate, document and identify the literature and case studies of passive approaches to energy reduction in affordable housing, with particular attention to multi-unit residential buildings (MURBs). This report summarises the results from the literature review and associated key stakeholder interviews.

1.1 Energy Efficiency in Affordable Housing

Low income families spend a disproportionate amount of their income on energy compared to average households. For example, low income families in the US spend more than 17 percent of their incomes on household energy, compared to an average of just 4 percent for other households (Penney, 2015). Greater energy efficiency in communities where "fuel poverty" is prevalent — defined as paying more than 10 percent of total income for energy needs — has been found to be a low-risk investment whose dividends include both energy and non-energy benefits to all members of society. The situation and opportunities would be similar in Canada.

Many affordable housing projects include some energy efficiency elements. Whether affordable housing providers pay the energy bills, or occupants pay, energy consumption plays an important role in housing affordability. Increased demand for energy efficiency is not only an issue for affordable housing providers. Faced with rising energy costs, a greater concern for the environment and an increased focus on the comfort and health of their families, homebuyers are looking for homes that are more comfortable, healthier, energy efficient, environmentally friendly—and less expensive to operate. The 2015 Canadian Homebuilders Association (CHBA) Home Buyer Preference Study[2] found that three of the top four must-have home features relate to energy efficiency (1. Walk-in closets, 2. Energy efficient appliances, 3. Overall energy efficiency, 4. High-efficiency windows).

Despite an expanding number of performance labels and housing standards, the most recognized approach to reducing energy consumption in a cost-effective way has remained unchanged over the decades:

1. maximize the performance of the building envelope by adding more insulation,
2. pay attention to design details to increase the airtightness and reduce thermal bridging, and
3. add a heat recovery ventilation system to improve indoor air quality.

[2] www.chba.ca/members-area/homebuyer-preference-study.aspx

While there is some discussion as to what extent these three elements should be pursued, they are the fundamentals behind a passive design approach to affordable higher performance housing. Passive approaches focus on improving the design and performance of the building itself, with a big emphasis on a highly insulated and air-tight building envelope to reduce operating costs and to avoid potential difficulties associated with complex building and mechanical systems that are often deployed in an effort to reduce energy consumption or energy costs.

1.2 High Performance Labels, Programs and Standards

There are a number of high performance building labels, programs and standards that affordable housing providers can use to help improve energy efficiency and overall sustainability. Some of these rely on passive design approaches as a central component to their energy reductions, whereas others do not explicitly specify how energy savings are to be achieved.

1.2.1 Leadership in Energy and Environmental Design (LEED) [3]

Many affordable housing projects have been built to various levels of LEED. Some of jurisdictions have required projects to meet certain LEED objectives to qualify for funding, such as building to LEED Gold for projects in British Columbia. However, in many cases, the requirement is that projects meet the equivalent level of performance without actually getting the LEED certification. To avoid the costs associated with registering and certifying their projects, many affordable housing projects claiming to be built to LEED are not actually certified as such. To help address the cost barrier, the Canada Green Building Council offer the Affordable Green Homes Program, first piloted in 2013, that provides charitable housing projects with free registration and certification under the internationally-recognized LEED green building certification program.

LEED Canada for Homes works with any single-family home in the design or early construction phase. The program also works with existing homes completing a full gut renovation. LEED for Homes Midrise is similar to the LEED Canada for Homes rating system but is suitable for residential multifamily buildings 4-12 stories above grade. LEED Canada for New Construction and Major Renovations is a program for diverse building types ranging from offices to community centers, and is typically chosen for taller multifamily buildings.

1.2.2 Passive House Standard

Some of the very first modern, low energy houses—early Passive House prototypes—were built in the United States and Canada in the late 1970s, with the Saskatchewan Conservation House being one of the pioneers[4]. This concept drew favour in Europe, and the first pilot Passive House was built in 1990 in Darmstadt, Germany. The five key design elements of Passive House buildings include (James, 2015):

1. An optimal level of thermal insulation.
2. Thermally insulated window frames with high quality glazing and external shading to limit overheating.

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[3] www.cagbc.org/CAGBC/LEED/GreenHomes/Affordable_Green_Housing_Program/CAGBC/Programs/LEED/GreenHomes/Affordable_Green_Housing_Program.aspx?hkey=8607aea3-505c-4f10-9421-0610afc7107c

[4] http://www.passipedia.org/basics/the_passive_house_-_historical_review/poineer_award/saskatchewan_conservation_house

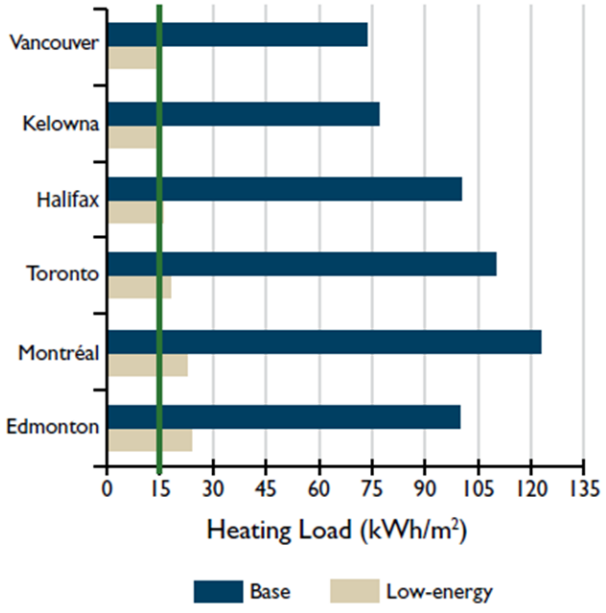
3. Careful design to achieve thermal bridge free construction to avoid unnecessary heat loss.
4. An airtight building envelope using an uninterrupted and continuous airtight layer.
5. Mechanical ventilation with heat recovery to ensure continuous supply of filtered fresh air.

The Passive House standard, developed in Germany by the Passive House Institute[5], has a few requirements that need to be met for certification:

- Space heating demand: ≤ 15 kWh/m^2/yr
  - Or specific heat load: ≤ 10 W/m^2
- Space cooling demand ≤ 15 kWh/m^2/yr
- Measured airtightness: ≤ 0.6 air changes per hour at 50 Pascals (ACH_{50})
- Primary energy demand: ≤ 120 kWh/m^2/yr

Even though the requirements might be relatively simple to understand and explain, they are quite stringent, and achieving them can be a challenge. One common criticism of the Passive House standard is that the requirements are the same regardless of the climate the building is to be constructed in. This means that the difficulty and the cost of achieving the standard varies substantially from region to region.

A recent study by CMHC examined if it was feasible to achieve Passive House levels of performance for an archetype 10-storey MURB in different Canadian climates using readily available technologies given its cold climate, existing design practices, and building codes (CMHC, 2014). Only buildings located in milder Vancouver and Kelowna climates met the targeted Passive House, 15 kWh/m², heating load, but significant space heating savings of 76% to 84% were achieved throughout Canada, with greater savings achieved in colder climates (Figure 1). As detailed in the Cost Benefit chapter later in this report, these modeled archetype MURBs were found to be cost effective in many Canadian jurisdictions.



[5] http://passiv.de/en/

Figure 1: Modelled space heating energy consumption of archetype MURB comparing code-compliant construction (Base case) and low-energy construction in various Canadian jurisdictions (CMHC, 2014).

For retrofit projects, the Passive House Institute has developed the EnerPHit certification, which provides a slight relaxation of the performance targets compared to new construction:

- Space heating demand (Q_H): ≤ 25 kWh/m^2/yr
- Measured airtightness: ≤ 1.0 air changes per hour at 50 Pascals (ACH_{50})
- Primary energy demand: ≤ 120 kWh/m^2/yr + ((Q_H - 15 kWh/(m^{2}yr)) -1.2).

1.2.3 Passive House Adapted to Regional Climates

Given the challenges of achieving Passive House certification in cold climates, there have been some jurisdictions that have developed their own requirements to account for this, such as in a number of Scandinavian countries (Jacobson, 2013). Sweden adopted its own "passivhus" standard in 2007, which was updated in 2012, and has thousands of dwelling units certified. Its 2012 standard includes:

- Targeted heating loads that vary by climate: (≤19 W/m^2 climate zone 1, ≤18 W/m^2 climate zone 2, and ≤17 W/m^2 climate zone 3)
- 2 W/m^2 subtracted from allowable heating load if floor area is greater than 400 m^2
- "Certifikat" awarded during planning, "Verifikat" awarded after 2 years of successful energy monitoring.

In Norway, NS3700 was adopted as a national standard for "Passivhus" construction in 2010 and includes a maximum space heating demand that is calculated using an equation that considers climate and floor area (reducing maximum heating demand for larger buildings), as well as having minimum R-value requirements – exterior walls RSI-6.7 (R-38), roof RSI-7.7 (R-44), floor RSI 6.7 (R-38), and windows/door U_{SI}-0.8 (U-0.14).

Similar modifications have been developed in the US by the Passive House Institute U.S. (PHIUS) at the request of the US Department of Energy (US DOE), to address limitations of applying a German developed standard in North America (Wright & Klingenberg, 2015). The reasoning provided for the need to develop a North American specific Passive House standard included:

- Passive House standard was found to not be responsive to the wide diversity of climate and energy market conditions in North America.
- Using European energy metrics for North American climates has forced solar-driven designs that tend to overheat and have very high cost required envelopes.
- Passive House use of an Excel based Passive House Planning Package (PHPP) as the modelling tool with its simplified static calculations under predicts cooling and heating loads year round and cannot predict indoor thermal comfort accurately. It cannot be used to size the mechanical system in extreme climates.
- The low PHPP defaults for electrical loads are grossly unrealistic for North America.

In addition, the design targets developed by PHIUS were cost optimized by climate using the BEopt optimisation tool. Given that cost is a moving target over time, PHIUS proposes to have the targets revised every 3 to 5 years. Unlike the relatively simple Passive House performance requirements, the

PHIUS maximum heating and cooling demands and loads is calculated with a set of equations that factor in local climate, and electricity price.

Table 1 provides the resulting maximum heating and cooling demand and peak loads using the PHIUS equations in different Canadian climates using $0.11/kWh for electricity costs. As can be seen, space heating demand targets can vary substantially depending on climate. Following such an approach would make achieving PHIUS Passive House certification much more achievable in the colder Canadian climates than using the European Passive House certification approach. PHIUS also has higher electrical base-loads more typical for North America, and raised the overall source energy above 120 kWh/m^2/year, with the intention that these increases would be temporary and would decrease as industry adjusts.

Table 1: Example maximum heating and cooling demands and peak loads following PHIUS equations

Location	Maximum Heating Demand (kWh/m^2yr)	Maximum Cooling Demand (kWh/m^2yr)	Maximum Heating Load (W/m^2)	Maximum Cooling Load (W/m^2)
Vancouver	17.4	0.3	17.9	12.5
Calgary	24.7	0.5	24.5	14.7
Edmonton	26.5	1.2	24.5	14.8
Victoria	17.7	0.0	16.8	12.9
Cranbrook	23.6	0.0	23.5	14.4
Kamloops	19.8	1.1	23.0	16.0
Fort St. John	30.5	0.0	25.7	12.4
Prince Rupert	23.8	0.0	18.7	9.2

1.2.4 Net-Zero Energy

The net-zero energy concept for buildings has gained a lot of attention in the last 15 years. The basic idea behind net-zero energy is that a building can combine aggressive energy efficiency measures with on-site renewable energy generation such that the renewable energy generated offsets energy consumption on an annual basis.

CMHC's EQuilibrium™ Housing Demonstration Initiative, which took place between 2006 and 2014 showcased that net-zero and near net-zero energy buildings could be built with existing technologies across Canada. The demonstration homes integrated a wide range of technologies, strategies, products and techniques to reduce a home's environmental impact to a minimum. They also featured on-site renewable energy systems to provide clean energy to help reduce annual consumption and costs. The initiative followed the projects from conception to occupation and included one year of monitoring. Many important lessons were learned from these projects. One of these projects, Urban Ecology, was an affordable housing duplex built in Winnipeg, Manitoba. One of the key findings was that passive design strategies implemented in the projects, such as super insulation, high performance windows and air-tightness, were easier to design, model and implement, and tended to outperform renewable energy and mechanical systems. More information on the EQuilibrium™ Housing Initiative can be found on the CMHC website[6]. Since the EQuilibrium™ Housing initiative, a number of other programs and labels have been developed around net-zero. Passive House Plus, a new level of performance set out by the Passive House Institute is essentially a Passive House building that targets net-zero annual energy consumption, and Passive House Premium goes beyond net-zero consumption into the realm of net-energy production.

[6] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/

In 2016, the Canadian Home Builders Association (CHBA) launched their Net Zero Energy Labelling Program Pilot[7] for buildings that are not greater than 600 m^2 (6458 ft^2) in area. Homes need to achieve annual energy consumption for space conditioning and domestic water heating that is at least 50% lower than that of a reference house built to the building code, and have a net annual energy consumption that is less than 0.5 GJ (140 kWh).

Reaching a net-zero energy target may not be achievable for taller affordable mid to high-rise MURBs given their limited amount of space to mount renewable energy systems. Smaller buildings such as single family homes have more room to mount renewable energy systems on a per footprint area basis. Even in the context of California's climate with limited space heating needs and relatively abundant solar energy, a study (California Energy Commission, 2012) found that taller affordable housing projects have a challenge to meet zero energy targets, and that it was not feasible for buildings beyond three stories using current technology. Note that this three storey limit would depend on building size, shape, orientation and local solar resources. A 16-unit, four-storey, Passive House Plus certified apartment building was built in Innsbruck, Austria in 2015[8], demonstrating that the three storey limit is not absolute.

1.2.5 Living Building Challenge

The Living Building Challenge is a building certification standard that not only targets net-zero energy consumption, but also includes challenging goals in terms of net-zero water use, and a number of stringent material selection criteria. In 2014, the International Living Future Institute (ILBI)[9] released a framework for affordable housing providers to overcome social, regulatory and financial barriers to achieving Living Building Challenge Certification (International Living Future Institute, 2014). They contend that the Living Building Challenge can enhance the positive impact of affordable housing while mitigating the persistent inequalities often present in low-income communities.

The Institute performed a modelling study of meeting their net-zero energy goal for an archetype 100,000 ft^2, four storey, affordable housing project, and found that that net-positive energy is feasible in each of the regions studied, but the degree of difficulty varies greatly depending on the climate and available solar resources. They found that affordable housing projects must strive for an energy use intensity (EUI) of between 44.1 and 62.4 $kWh/m^2/yr$ (14-20 $kBTU/ft^2/yr$) to keep the building's energy demand within the available solar resources, representing a 49-73% reduction versus typical construction in the US. Note that for net-zero energy consumption, the maximum EUI would decrease with every storey added, making it progressively harder to achieve.

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[7] http://www.chba.ca/uploads/net%20zero%20energy%20housing%20council/nze%20labelling%20program/netzerostandardpilot_vp01.pdf

[8] http://www.passivehouse-international.org/download.php?cms=1&file=2015_08_04_Passive-House-Plus_Apartment-Building_Press-Release.pdf

[9] https://living-future.org/

The framework is developed by first giving an overview of the Living Building Challenge, and then discussions following three Case Study Examples of affordable housing projects that evaluated the design implications of updating from their actual construction to meeting the Living Building Challenge:

1. The Rose[10], Minneapolis, MN: The Rose has 90 units (47 affordable and 43 market rate), including 12 units for formerly homeless families and individuals. Original design of the Rose project targeted full Living Building Certification, however, the project team encountered social, regulatory and financial barriers that prevented them from meeting that initial goal.
2. South Second Street Studios, San Jose, CA. A five-story, 9,300 m^2 (100,000 ft^2), mixed-use building that incorporates 79 efficiency units, 23 units for the developmentally disabled, 25 for the chronically ill. This project is pursuing LEED Platinum and studied the steps necessary to achieve the Living Building Challenge.
3. Capital Studios, Austin, TX: 135 Single Room Occupancy (SRO) apartments, is the first affordable housing project to be built in downtown Austin in 45 years. Built to the requirements of the Austin Energy Green Building Program and Enterprise Green Communities Criteria. It used the Living Building Challenge for design inspiration.

The Institute addressed some of the challenges that would be faced by affordable housing providers based on the outcomes of this initial project. For example, the need for on-site black water treatment or composting toilets was found to be quite challenging for multi-family affordable housing projects and as a result, the Institute created a new temporary alternate compliance path for multi-family affordable housing projects that allows black water to be sent to a municipal sewer system.

The study also found that while meeting the strict materials selection requirements was critical to protecting occupant health and supporting local economic development, the additional soft costs for research and hard costs for replacing specific materials made it difficult to implement in the current market. The Institute plans to conduct more research and outreach to help reduce these soft costs.

The Institute will select five affordable housing projects to serve as Living Building Challenge pilot projects over the next year and will provide in-depth technical assistance to build upon current successes. In 2016, the Institute presented a five-part webinar based on their work to date (last session in June 2016), to introduce the Living Building challenge to affordable housing providers[11]. This and their ongoing work will be quite relevant to affordable housing providers in Canada.

1.3 Increased Energy Efficiency Requirements in Codes

Building energy efficiency requirements have been increased and will likely continue to increase in the future as the various levels of government try to reduce greenhouse gas emissions (GHG) to help mitigate climate change. Draft plans from the government of BC call for new public sector buildings to be near net-zero energy starting immediately, and all buildings by 2030 to be near net-zero (British Columbia, 2016). Ontario's draft plan calls for support of net-zero energy buildings across the province

[10] http://casestudies.uli.org/wp-content/uploads/sites/98/2015/12/TheRose_CaseStudy.pdf
[11] https://living-future.org/events/affordable-housing-five-part-webinar

through updates to Ontario's Building Code, incentive programs, and removal of regulatory barriers (Ontario, 2015).

The level of emissions reductions related to the building sector become even more apparent when looking at achieving the global climate change goal of keeping an average global temperature rise below 2ºC. A study (Architecture 2030, 2014) done to evaluate a pathway of achieving this goal for the global building sector found that:

- All new buildings and major renovations would need to be carbon neutral by 2030.
- A minimum of 2% to 3% of the total existing building stock each year would need to be renovated to meet an emissions intensity reduction of 50% below the regional (or country) average.
- All building product related emissions would need to meet a GHG reduction target of 50% by 2030.

Some jurisdictions are adopting the Passive House Standard to help achieve their GHG reductions targets. Since 2007, the city of Frankfurt has required all municipal buildings to meet the standard, and since 2008 so has the City of Wels, Austria. In Vorarlberg, Austria, the Passive House Standard is mandatory for all new social housing projects. The city of Heidelberg made the Passive House Standard mandatory for the entire Bahnstadt development, making it one of the largest Passive House sites in the world (NAPHN, 2015). Established on the site of a former freight yard, the 280-acre redevelopment area will eventually provide housing for 5,500 people and office space for 7,000.

California's San Francisco Bay Area, and particularly the Silicon Valley region, is emerging as a Passive House development hotbed. Early adoption of Passive House is giving this region an edge when it comes to fulfilling California's goal of requiring all new residential construction to be Net Zero Energy Buildings by 2020 and all new commercial construction by 2030 (NAPHN, 2015).

A number of US cities are adopting policies that encourage the adoption of Passive House in affordable housing projects. As described in (Frappé-Sénéclauze, 2015), Qualified Allocation Plans (QAPs) establish scoring criteria to assess projects, and some grant additional points for Passive House projects:

- Pennsylvania Housing Finance Agency (2014): The agency grants 10 points (out of 130) for developments that meet Passive House certification requirements under iPHI or PHIUS. As a result, in the first year of the policy, 39 of the 85 projects submitted (46%) were PH. The agency funded seven PH projects, totaling 422 units. Cost increment per square foot was less than 2%.
- New York State Homes & Community Renewal (2015): The agency awards five points (out of 100) for projects seeking Passive House certification or other green standards (Enterprise Green Communities, LEED, National Green Building Standard).
- Another 35 US states are looking at how housing agencies can incorporate PH scoring in their QAPs.
- A new proposed requirement in NY that is under committee review would require Passive House for any NYC capital project above two million dollars (either PHIUS or iPHI).

2. Case Studies

There are an increasing amount of projects that have been developed to achieve very high levels of energy performance utilising some passive low-energy design concepts in the process. This Chapter will outline some of these projects with a focus on affordable housing projects, and MURB projects that implemented passive design strategies to achieve ultra-low levels of energy consumption.

2.1 New Construction

2.1.1 Canadian Projects

Table 2 outlines the Canadian projects that will be presented in this section.

Table 2: Canadian Projects Presented in this Report

Project Name	Location	Building Type	Performance Target	Status or Year Built	Affordable Housing
Southeast False Creek Net Zero Building	Vancouver, BC	8-storey	Net-zero	2010	Yes
Chapelview Apartments	Brampton, ON	16-storey	LEED platinum	2010	Yes
Bedford Roadhouse	Nelson, BC	Triplex	Passive House	2013	No
North Park Passive House	Victoria, BC	6-unit multi	Passive House	2014	No
Housing Nova Scotia Passive House Pilot Project	Truro, NS	Duplex	Passive House	2015	Yes
Vancouver Coastal Health Staff Housing	Bella Bella, BC	6-unit townhouse	Passive House	2015	No
Social Housing Duplex	Quaqtaq, Nunavik	Duplex	Passive House inspired	2015	Yes
Salus Clementine	Ottawa, ON	4-storey	Passive House	2016	Yes
Marken Design+Consulting	Vancouver, ON	10-storey	Passive House	Design	n/a
Intermet Housing Society	Edmonton, AB	16-unit townhouse	Passive House	Planned	Yes
Cordage Green	Welland, ON	44-unit townhouse	Passive House	Planned	partial
Station Point Greens	Edmonton, AB	16 storey	Passive House	Planned	No

Cornerstone Architecture	Vancouver, BC	6-storey	Passive House	Planned	No

Southeast False Creek Net Zero Building, Vancouver, BC

The Southeast False Creek (SEFC) Net Zero building built in Vancouver in 2010 was Canada's first net-zero multi-unit residential building[12]. It is an eight-story affordable senior's residence with 67 units, including six street-level townhouses. Passive design strategies include: optimizing building orientation, maximizing insulation, appropriate placement of thermal mass, and optimizing daylight and natural ventilation opportunities. Energy efficiency features were expected to reduce energy consumption by 68%. Reports on actual energy performance were not found.

To achieve its net-zero energy target, the building planned to make use of waste heat from the refrigeration system of a neighbouring grocery store to provide space heating for the building. A 45 square-metre (486 ft^2) solar thermal system located on the roof of the building and an additional array on an adjacent building, were to provide the remainder of the energy to meet a net-zero balance. During the summer, the solar array could provide hot water to the building and any excess heat be sold to the Neighbourhood Energy Utility (NEU) for use in adjacent buildings.

Chapelview Apartments, Brampton, Ontario

Chapelview Apartments, built in 2010 for the Regional Municipality of Peel, is the first LEED Canada Platinum social housing building[13]. The project was expected to achieve 50% energy savings and 46% indoor water savings compared to conventional construction. Each apartment unit has an independent ventilation system. The project, which was constructed under a modest budget, also features a number of sustainability features.

Bedford RoadHouse, Nelson, BC

Bedford RoadHouse constructed in 2013, is a project that began in 2009 as a response to an RFP put out by the Province of BC to build "Super Efficient New Construction"[14]. The triplex includes two 55.6 m^2 (600 ft^2) units and one 112.2 m^2 (1,200 ft^2) unit. Key aspects of the project include:

- RSI-10.4 (R-59) walls encompass a triple-layer stud frame packed with cellulose, which incorporates a standard 6-mil polyethylene vapor barrier.
- The final airtightness rating came in at 0.2 ACH_{50}.
- The roof is a standard truss with an additional installation cavity to achieve RSI-21.1 (R-120).
- The basement is an unheated service space and is not considered part of the Passive House envelope.
- Roof designed with ideal slope for future photovoltaic and solar thermal panels, and the combined boiler and domestic hot water tank has a solar loop built in, to make the building net-zero capable.

[12] www.greenbuildingaudiotours.com/buildings/sefc_net_zero_building
[13] http://leed.cagbc.org/leed/profile_files/10392_4_Chapelview-Narrative.pdf
[14] http://naphnetwork.org/NAPHN_NZEB_2015_V2/NAPHN_NZEB_2015.html

- Modelled space heating demand of 14 kWh/m^2/yr.

North Park Passive House, Victoria, BC

The North Park Passive House project in Victoria, constructed in 2014, is a 6-unit Passive House condominium project[15] (see case study in Chapter 4). Key features include:

- The walls consist of a 38 × 200 mm (2 × 8 in.) structural wall insulated with dense-pack cellulose and a 38 x 89 mm (2 x 4 in.) interior service cavity insulated with rock wool.
- Each unit is ventilated with its own heat-recovery ventilator (HRV).
- The small, supplemental heat load is met with electric resistance heating.
- A solar photovoltaic (PV) array on the roof generates energy and an income stream through the local net metering program.
- Modelled space heating demand of 11 kWh/m^2/yr
- Measured air leakage of 0.5 ACH_{50}.

HNS Passive House Pilot Project, Truro, Nova Scotia

In 2015, Housing Nova Scotia (HNS) built a pilot passive house duplex in Truo, Nova Scotia[16]. HNS contracted Passive House E-Design to convert an existing house plan to meet the PHIUS climate adjusted Passive House standard. Key aspects of this project include:

- Each unit is 188 m^2 (2,030 ft^2) and features three bedrooms.
- Global Construction awarded contract to build with$1,350/m^2 ($125/ft^2) approximate construction costs.
- ICF basement, and 38 × 140 mm (2 × 6 in.) above grade walls with rockwool exterior insulation.
- Estimated annual heating costs of $350, to be paid by HNS.

Vancouver Coastal Health Authority Staff Housing, Bella Bella, BC

A new multi-unit Passive House project of six two-storey attached townhomes was constructed in Bella Bella, BC, for the Vancouver Coastal Health Authority[17]. The project, constructed by Britco, claims to be Canada's first modular multi-unit residential project to achieve Passive House certification. On the coldest day of the year, each unit in this complex will have a peak heating load of about 600 watts. Modular construction was chosen for the remote island location as a cost saving measure; the project was built for $2.6 million, about $500,000 less than if the project was constructed on site.

Social Housing Duplex, Quaqtaq, Nunavik

Quebec's social housing agency has teamed up with Makivik Corp. and the Kativik Municipal Housing Bureau to build a pilot project in Nunavik as a new housing model that it is better suited to the North[18]. The housing unit design took inspiration from "Passive House" requirements with the walls and roof being highly insulated and sealed and the windows being triple glazed.

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[15] http://naphnetwork.org/NAPHN_NZEB_2015_V2/NAPHN_NZEB_2015.html
[16] www.efficiencyns.ca/tmpimages/Ramzi%20Kawar.pdf
[17] www.vancouversun.com/mobile/business/vs-business/bella+bella+barge+project+delivers+high+efficiency+housing/11742013/story.html
[18] www.nunatsiaqonline.ca/stories/article/65674housing_model_on_trial_in_nunavik_community/

Salus Clementine, Ottawa, ON

The 42-unit, 4-storey, Salus Clementine project constructed in Ottawa to the Passive House standard, will serve men and women living with serious mental illness[19]. The project was funded by Ottawa Salus, the City of Ottawa, and the provincial and federal governments through the Investment in Affordable Housing for Ontario (IAH) Program. One of the reasons for choosing to build to Passive House was to keep the operational costs low such that more funds could be used for client services. Key features of the project include:

- Exterior wall composed of light steel frame structure with 305 mm (12") thick structural insulated panels (SIPS) attached to the outside to achieve RSI-11.4 (R-65).
- The RSI-13.2 (R-75) roof assembly also incorporates 305 mm (12") SIPS with integral wood I-joists.
- A high efficiency, 454 L (120 gal) capacity, gas boiler provides heating for space and domestic hot water.
- Modelled space heating energy demand of only 12 kWh/m^2/yr.

Marken Design + Consulting, Passive House MURBs

Marken Design + Consulting is part of a project team proposing to develop a 10 storey Wood Hybrid Highrise in B.C. aiming for Passive House certification[20]. In addition, they have partnered with KOKA Architecture and developed a design for a prefabricated adaptable mixed-use, Passive House certified, residential building and are marketing it for affordable housing in the Vancouver market. The main features include:

- Four storey mixed use,
- turn-key concept with a comprehensive cost report,
- passive solar design,
- triple pane windows,
- HRV for every apartment,
- solar photovoltaic (PV) electricity generation,
- energy efficient appliances, and,
- other sustainability features.

Intermet Housing Society, Edmonton, AB

A 16-unit, non-profit townhouse development, is slated to be constructed on the site of Westmount Presbyterian Church in Edmonton[21]. Their goal is to become the first net-zero energy multi-family project in Canada. Intermet Housing Society of Edmonton will lease the property and use it for non-profit rental homes. Key features of the project include:

- Three- and five-bedroom, 3 ½ storey townhomes aimed at large families.
- Energy efficiency features include geothermal heating, solar PV panels, super insulation and efficient lighting and appliances.

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[19] http://naphnetwork.org/NAPHN_NZEB_2015_V2/NAPHN_NZEB_2015.html
[20] www.markenprojects.com
[21] http://edmontonjournal.com/news/local-news/edmonton-church-land-slated-for-canadas-first-multi-family-net-zero-emissions-housing-project

- Cost premium of less than 10 per cent more than a typical townhouse, an expense expected to be easily recouped from utility cost savings.
- Aiming for Passive House performance.

Cordage Green, Welland, ON

Cordage green is a proposed, 44 unit, two-storey, Passive House townhouse project in Welland, ON, [22]. Cordage Green, a non-profit organisation, will utilize an equity/life lease funding model that enables home ownership for those with lower income and inability to cover large down payments required by banks for traditional mortgages. It will offer a limited number of loans to offset purchase price, that will be repayable when owners have the ability to do so, or at the time of resale.

Station Point Greens, Edmonton, AB

Station Pointe Greens is a proposed Passive House certified 219-unit residential and commercial development in Edmonton, Ab[23]. The initial design concept was done in 2009 and it was one of the projects featured in CMHC's EQuilibrium Communities Initiative[24]. The team considered a number of design strategies, with the latest passive design having the following features, including:

- RSI-10.6 (R-60) wall, with a 356 mm (14") Polycore exterior insulated finish (EIFS) wall system.
- A green roof with 356 mm (14") of sloped insulation that would achieve RSI-12.3 (R-70).
- RSI 8.8 (R-50) under-slab rigid insulation.
- Triple Glazed Solarban 60 windows with Argon fill providing a U-Value of USI-0.74 (U-0.13).
- Electric baseboard for heating and mini-split air conditioning units for cooling.
- In-suite ventilation would be supplied by an ERV, the hallway would also have an HRV plus electric coils.

The team estimated that the operation and maintenance costs for the building (including green loan financing) would be $346/month per dwelling unit for the passive design compared to $480/month for conventional construction.

Cornerstone Architecture Passive House Projects, Vancouver, BC

Cornerstone Architecture has three large Passive House apartment complexes at various stages of development[25] in Vancouver, BC:

- Skeena is a 6-storey 85 unit apartment building aiming to be the largest Passive House certified building in Canada.
- Its East 57th Avenue project is a proposed 6-storey 96 unit apartment building.
- Its Fraser St. building is a 4-storey 75 unit rental complex.

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[22] www.cordagegreen.ca/

[23] Hancock, J., B. Scott, 2013. Station Pointe Greens – The Journey to Net-Zero Affordable Housing, Journal of Green Building **8** (1), pp. 3-21. http://www.collegepublishing.us/jgb/samples/JGB_V8N1_a01_hancock.pdf

[24] www.cmhc-schl.gc.ca/en/inpr/su/eqsucoin/

[25] www.cornerarch.com/passive-house/

Note that these projects are not affordable housing projects. However, as mentioned in the interview with a representative with the City of Vancouver (Appendix A), they are serving as examples of what can be achieved for future affordable housing projects in the Vancouver

2.1.2 International Projects

With tens of thousands of Passive House projects in Europe, and countless others around the world, there are many potential projects to highlight in this section. This section will focus on low-energy affordable multi-unit residential projects with climates similar to Canada, and will focus on US examples as they would have more similar construction practices and challenges. Table 3 outlines the projects that will be presented in this section.

Table 3: International projects presented in this report

Project Name	**Location**	**Building Type**	**Performance Target**	**Status or Year Built**	**Affordable Housing**
Place of Hidden Waters	Tacoma, Washington	20 unit townhouse	LEED Platinum	2012	First Nations
zHome	Issaquah, Washington	10 unit townhouse	Net-zero	2012	Partial
Bellfield Townhomes	Philadelphia, Pennsylvania	3 unit townhouse	Passive House	2013	yes
The Mennonite	Brooklyn, New York	24 unit, 4 storey	Passive House	2014	yes
Knickerbocker Commons	Brooklyn, New York	24-unit, 4 storey	Passive House	2014	yes
Stellar Apartments	Eugene, Oregon	6-unit, 3 storey	Passive House	2014	yes
Uptown Lofts	Pittsburgh, Pennsylvania	3-storey	Passive House	2015	yes
Orchards at Orenco	Hillsboro, Oregon	57 unit, 3-storey	Passive House	2015	yes
Ankeny Row	Portland, Orgegon	5 unit townhouse	Passive House	2015	partial
The Rose	Minneapolis, Minnesota	90-unit apartment	International Living Future Institute	2015	mixed-income (affordable

					and market-rate units)
River Market	Kansas City, Missori	276 unit, 6 storey	Passive House	Under construction	yes
Cornell Student Housing	New York, New York	352 unit, 26 storey	Passive House	Under construction	Student housing

Place of Hidden Waters, Tacoma, WA

This $6.6M LEED Platinum certified 20-unit housing project is a culturally and environmentally responsive new model for the Puyallup Tribe in the Pacific NW[26], completed in 2012. The buildings are designed to emulate the rectangular, shed roofed form of a traditional Coast Salish longhouse using a variation of the modern townhouse courtyard building. The project was managed and built by tribal members—labor crews from the Puyallup Nation Housing Authority (PNHA) combined with an experienced construction manager who developed training apprenticeships. Key aspects of the project include:

- Structural insulated panels with excellent air sealing and triple pane windows.
- Ground source heat pumps for both domestic hot water and hydronic heating systems.
- The residential buildings are sited along an east-west axis to allow for prevailing summer breezes and for passive solar heating/cooling.
- Designed with a "solar-ready" roof design for future installment of a photovoltaic array, which is targeted to yield a zero-energy building.
- The modular design allowed for the crews to learn on the first units and speed up construction for the rest of the development.

zHome, Issaquah, Washington

zHome, is a ten-unit net-zero energy townhome project built in Issaquah, Washington[27]. zHome is part of a larger sustainable village which integrates market rate and affordable housing. zHome is the market rate component of the village, and the YWCA Family Village is the affordable component, although one of the ten units was being used as a long term education center, and will become an affordable housing unit in 2016. The project costs, excluding land, came to $622,000 USD for soft costs and $2,412,000 USD for hard costs. Key features of the project include:

- RSI-6.7 (R-38) Walls– 38 × 140 mm (2 × 6 in.) wood framing with mineral wool as infill insulation and 83 mm (3.25") continuous expanded polystyrene exterior insulation.
- RSI10.6 (R-60) Roof – Two SIP-like panelized sections were used, one 38 × 200 mm (2 × 8 in.) and one 38 × 250 mm (2 × 10 in.) stacked atop each other, using standard wood framing and expanded polystyrene.

[26] www.ecotope.com/wp/wp-content/uploads/2014/05/130611_14_CS-HUD-Place-of-Hidden-Waters.pdf
[27] http://living-future.org/case-study/zhome

- RSI-1.8 (R-10) Under-slab expanded polystyrene insulation.
- Double paned low-e, argon filled Pella fiberglass windows. A sensitivity analysis was performed assessing use of triple paned windows which were determined to not be cost effective due to the minimal incremental benefit once other measures had been applied.
- Heating and hot water provided by individual ground-source heat pumps served by a common ground loop of fifteen 67 meter (220 ft) deep vertical boreholes. Space heating utilises in-floor hydronic tubing under concrete slab and bamboo flooring.
- Each home is equipped with its own a heat recovery ventilator.
- Daylighting design coupled with energy efficient LED and fluorescent lighting used throughout.
- Highly energy efficient appliances – Top of the range Energy Star certified appliances.
- Each unit is equipped with a solar Photovoltaic (PV) system ranging in size of 4.8, 6.0, 7.0 kW, and a community PV system for all common loads, including outdoor lighting and the large ground source well field pumps.

Belfield Townhomes, Philadelphia, PA

Constructed in 2013, the three-unit, 177.8 m^2 (1920 ft^2), 4 bedroom, 3 bathroom, Passive House townhomes were designed to provide affordable housing for very low-income residents[28]. The intention of this project was to be a model of affordable and sustainable housing for the City of Philadelphia. The state of Pennsylvania subsequently added the Passive House performance option to its evaluation criteria for affordable housing project proposals, which then saw 7 additional Passive House projects funded in 2015. The homes are designed as high performance buildings utilizing the Passive House standard and to approach zero-energy status with the addition of a rooftop solar PV. This project was the recipient of the 2014 International Passive House award presented by the Passive House Institute (PHI) in Darmstadt, Germany and a second Place Award winner in Affordable Housing by the Passive House Institute US (PHIUS). Key features include:

- \$1,400/m^2 (\$130/ft^2) construction costs, comparable to other affordable housing projects.
- Triple glazed, PVC windows with RSI-1.6 (R-9), SHGC of 0.63.
- RSI-5.9 (R-33.6) walls, 2x6 with dense pack cellulose and two layers of 25.4 mm (1") exterior foil-faced poly-iso with joints staggered and taped.
- Modelled heating energy demand of 14 kWh/m^2/yr.
- 0.4 ACH_{50} measured airtightness.

The Mennonite, Brooklyn, New York

Completed early in 2014, an \$8.5-million, four-storey, 24-unit apartment complex was completed in Bushwick, Brooklyn, which is touted as the first multi-family affordable apartment complex built to the Passive House standard in the U.S[29]. Key features of the project include:

- 15 apartments set aside for handicapped residents and eight units of affordable housing to people who make 30% of the city's median income.
- Two small boilers located in a mechanical room on the roof serve the entire complex.

[28] www.onionflats.com/projects/affordable/belfield-townhomes.php
[29] www.nydailynews.com/new-york/brooklyn/affordable-passive-house-apartments-open-article-1.1761553

- 16 solar thermal panels are located on the roof.
- Ridgewood Bushwick and its partner, the United Mennonite Church, are estimated to save around $23,000 per year in energy costs.
- Energy recovery ventilators serving the units are located in the building's basement.

Knickerbocker Commons, Brooklyn, New York

A second $8.5 million, 24-unit, apartment building was completed by Ridgewood Bushwick Senior Citizens Council in 2014 to the Passive House standard[30]. It features similar design features as The Mennonite project including placing the boilers on the roof, which eliminated the need for the chimneys that conventional buildings use to pull drafts of air to the basement to cool the boilers between cycles, leaking energy along the way. This project features foam and stucco on the exterior of the masonry wall with large wedges of foam that shade the windows in the summer.

Stellar Apartments, Eugene, Oregon

Completed in 2014, the $7.2M Stellar Apartments project is a 54-unit affordable-housing rental complex for St. Vincent de Paul Society, where one of the complex's 12 buildings was built to the Passive House standard and the others to the less-rigorous Earth Advantage standard[31]. Graduate students from the University of Oregon are monitoring the Passive House building and one of its neighbors over the course of two years. Key features of the Passive House building include:

- RSI-8.3 (R-47) exterior wall with 38 × 140 mm (2 × 6 in.) framing with dense pack fiberglass, plywood sheathing air barrier, and 102 mm (4") of exterior polyiso.
- Cost of Passive House unit was $1,566/m^2 ($145/ft^2) compared to $1,200/m^2 ($111/ft^2) for Earth Advantage building.
- RSI9.0 (R-51) floor consisting of 305 mm (12") TJI with dense pack fiberglass.
- RSI-15.7 (R-89) roof using trusses with 737 mm (29") of loose fill fiberglass.
- Cascadia 325 series (fiberglass) fixed / casement window frames and Cardinal 180/180, triple pane, low-e, argon glazings USI-0.85 (U-0.15), SHGC 0.54.
- Ventilation system consists of six UltimateAir RecoupAerator 200DXs.
- Zonal electric resistance heaters for space heating.
- Measured airtightness 0.50 ACH_{50} .
- Cooling relies on a night flush strategy.
- All units comply with Earth Advantage Certification, which includes Energy Star rated appliances and lighting; low VOC paints, finishes, sealants and adhesive; and low-flow water fixtures.

Uptown Lofts, Pittsburgh, Pennsylvania

The Uptown Lofts is a mixed-income housing project in Pittsburgh's Uptown neighborhood and received its Passive House certification (PHIUS+) in 2015[32]. Costs totaled $9.5 million USD, including two

[30] www.nydailynews.com/new-york/brooklyn/affordable-passive-house-apartments-complete-article-1.1774462
[31] www.svdp.us/what-we-do/affordable-housing/rental-housing/completed-projects/stellar-apartments/, www.phius.org/projects/1174
[32] www.phius.org/projects/1188

buildings, which together provide 47 new apartments: 23 affordable units in one and 24 units for young adults moving out of foster care in the other. Key construction features of the project include:

- Exterior Wall: 38 × 140 mm (2 × 6 in.) wood stud with fiberglass cavity insulation, with 76 mm (3") of poly-iso rigid foam continuous exterior insulation, to achieve RSI-6.3 (R-36) total.
- Floor: Concrete slab on grade with 127 mm (5") extruded polystyrene insulation, RSI-4.6 (R-26.4) total.
- Roof: 457 mm (18") roof truss with fiberglass cavity insulation, 102 mm (4") continuous poly-iso rigid foam exterior insulation, RSI-12.5 (R-70.7) total.
- Insulated fiberglass framed windows
- Cold-climate air-source heat pump for heating and cooling
- Air-tightness of 0.6 ACH_{50}

Orchards at Orenco, Hillsboro, Oregon

Completed in June 2015, the Orchards at Orenco is a $14.6 million USD, 57-unit, affordable housing development constructed in Hillsboro[33]. The three-story, L-shaped building frames a prominent street corner in the highly walkable Orenco Station neighborhood. Project features include:

- A fully insulated, thickened-edge slab.
- Exterior walls are 38 × 250 mm (2 × 10 in.) stud with blown-in fiberglass and 38 mm (1.5") exterior mineral wool insulation.
- Open web truss roof with 305 mm (12 ") of polyisocyanurate foam that sits on top.
- The mechanical system, which is housed in three insulated roof-top pods, consists of three energy-recovery ventilators (ERVs), each of which is coupled to a single heat pump for primary heating and summer tempering.
- Back-up heating through electric radiant cove heaters in each unit facilitates tenant control of their environment.
- Modelled heating energy demand 17.35 $kWh/m^2/yr$, with peak load of 7.47 W/m^2.
- Measured air tightness of 0.13 ACH_{50}.

Ankeny Row, Portland, Oregon

Completed in March 2015, Ankeny Row cohousing project features five two-story townhouses, one loft and one common studio[34]. Ankeny Row is constructed to the Passive House standard and is Net Zero Energy Ready. The owners of Ankeny Row are retiring couples with a strong desire to age in place in the heart of the city while minimizing their living expenses and environmental footprint. Key features of the project include:

- Floor plans that accommodate aging in place.
- Deep overhangs shade the large, south-facing windows on the topmost floor, while awnings protect the lower and ground-floor windows.
- Mini-split heat pumps for heating and cooling.

[33] http://naphnetwork.org/NAPHN_NZEB_2015_V2/NAPHN_NZEB_2015.html
[34] http://naphnetwork.org/NAPHN_NZEB_2015_V2/NAPHN_NZEB_2015.html

- The RSI-8.8 (R-50) wall assemblies include I-joists that are 241 mm (9.5”) deep filled with cellulose.
- The mono-sloped wood trusses in the roof assembly are 711 mm (28”) deep and are filled with cellulose insulation.
- All of the lumber and most of the finished wood is Forest Stewardship Council (FSC)-certified.

The Rose, Minneapolis, Minnesota

Constructed in 2015, The Rose is a 90-unit mixed-income apartment project, part of a multiphase redevelopment project that includes 47 affordable units and 43 market-rate units in a two-building configuration[35], modelled to consume 72% less energy than a code compliant baseline (International Living Future Institute, 2014). The project team tried to keep overall construction costs in line with comparable affordable housing projects (total development costs per unit $301K USD). Seven of the units will be reserved for households experiencing homelessness and 15 of the three-bedroom units will serve tenants paying 30 percent of their income for rent. The rents for the units will range from $636 for a 48.3 m^2 (522 ft^2) efficiency unit up to $1,560 for a two-bedroom, market-rate unit. Key features of the project include:

- Two four-story buildings aligned in an east–west layout to maximizing solar gain.
- Spray foam insulation for exterior walls, with RSI-7.0 (R-39.5) ground floors using 38 × 140 mm (2 × 6 in.) construction clad with Enduramax masonry insulated units, and RSI-5.5 (R-31.5) upper floors with 38 × 140 mm (2 × 6 in.) construction clad with Nichiha fiber cement panels.
- RSI-14 (R-80) roof and RSI-1.8 (R-10) under the slab.
- Pella Impervia windows with RSI1.9 (0.34) U-value, 0.29 Solar Heat Gain Coefficient (SHGC), and 55% visible light transmission, and a 24% Window-Wall Ratio.
- Heating and cooling from high-efficiency (COP 3.4) Mitsubishi cold climate air-source heating pumps.
- Central dedicated outdoor air system (DOAS) with heat recovery.
- 16 Kingspan Thermomax DF100 74 m^2 (800 ft^2) solar thermal panels provide 34% of domestic hot water heating.
- A series of underground cisterns totaling 14 m^3 (500 ft^3) collect and store rainwater on site.

River Market, Kansas City, Missouri

A 276 unit Passive House apartment complex started construction in early 2016 in Kansas City[36]. The $62 million USD project will feature 406 mm (16”) concrete walls and make use of ERVs. Twenty per cent of the units are slated for low income tenants with rents ranging from $550 to $750/month with the remainder being market rate apartments ranging from $1000 to $2400/month. A number of instruments helped finance this project:

- Kansas City has committed $2.9 million in street and green space improvements to the site.
- $49 million fixed-rate, government-insured mortgage loan through U.S. Department of Housing and Urban Development.

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[35] http://casestudies.uli.org/wp-content/uploads/sites/98/2015/12/TheRose_CaseStudy.pdf
[36] www.kansascity.com/news/business/development/article56612913.html

- Financing is coupled with issuance of $30 million in tax-exempt Multifamily Housing Revenue Bonds authorized by the Planned Industrial Expansion Authority and sold by Ameritas.
- Project received federal and state low-income tax credits plus a 10-year, 100 percent property tax abatement followed by a 15-year, 50 percent abatement on the project's added value. Because of the abatements, the developers agreed to pay $20,000 a year in payments in lieu of taxes to the taxing jurisdictions, such as Jackson County, Kansas City Public Schools and the Kansas City Public Library.
- Partnership agreement with Berkshire Hathaway's Affordable Housing Partners, which invested tax credit equity in the project.

Cornell Student Housing Passive House Highrise, New York, NY

Construction started in 2015 on a 26-storey, 352-unit residential high-rise that is set to become the world's largest and tallest residential project certified by the Passive House Institute (PHI), and will house students, faculty and staff[37]. The development will be part of Cornell University's Tech Campus – all of the buildings on the new campus will meet the city's climate change goals of achieving an 80% GHG reduction by 2050. Once complete, the building is estimated to have an overall energy consumption that is 70% less than that of a conventional new multifamily building.

The building's exterior envelope comprises of a custom designed RSI-5.6 (R-32) curtain wall facade that is being constructed off-site and delivered with high-performance windows (median U-value of 0.17 Btu/h·ft^2·F [0.96 W/m^{2}K]) intact, allowing for the quality control necessary to create an extremely air-tight building envelope. Structural thermal breaks are going to be used for balcony slabs and for the building canopy.

2.2 Retrofits

Realizing high-performance affordable housing retrofits is an even larger challenge than building new projects. A study in the Netherlands looked at eight large-scale renovation projects in the social housing sector to examine what barriers existed that led them to typically implement conventional energy systems and middle of the road insulation levels (Hoppe, 2012). All eight of the social housing projects intended to adopt energy efficiency measures, yet only three ended up implementing them. Many barriers were identified that may also be relevant for Canadian social housing projects.

Housing association related barriers:

- Need to acquire additional funding to co-finance energy efficiency measures because they were not considered profitable investments.
- Resentment of local authorities which often set high demands to meet political goals, yet housing associations bear the costs.
- Energy performance issues are given secondary importance in decision making.
- Bad experiences from previous projects.
- Lack of support from tenants.

[37] www.swinter.com/Collateral/Documents/English-US/Worlds_Largest_Passive_House_Presentation.pdf

Tenant related barriers:

- Reluctant to have rents increase even if net-benefit was calculated and presented to them.
- Project delays led tenants to become impatient and demand compensation.
- Tenants fear change and appreciate energy systems they are familiar with.

2.2.1 Canadian Projects

The construction of ultra-low energy consumption MURBs in Canada is very new, and applying this concept to retrofits is even newer. There have been a few examples of single family homes that have been retrofitted to achieve high levels of performance including the Now House, a retrofit project that took part in the CMHC EQuilibrium™ Housing Demonstration Initiative, which saw a 60-year old wartime house being retrofit to a near net-zero energy home[38]. There have also been a couple of single family houses retrofitted to EnerPHit, including one in Winnipeg[39], MB, and one in Oakville[40], ON. There have also been examples of social housing providers that have made efforts to improve the energy efficiency of their building stock such as the Windsor Essex Community Housing Corporation[41].

This section will focus on one particular retrofit project from Vancouver, BC, which features a 13-storey apartment building that underwent a major building envelope retrofit. This project was the most relevant MURB project to implement passive design strategies during a retrofit found in the literature for Canada.

Belmont Project, Vancouver, BC

Originally constructed in 1986, The Belmont is a 13-storey residential building on the west side of Vancouver that underwent a building enclosure renewal project in 2012[42]. The ongoing project includes the collaboration between a number of stakeholders including the federal government, provincial government, utility companies and engineering consultants.

The existing exterior walls were exposed cladding with 50 mm (2”) of foam insulation at the inside, with an overall effective R-value of RSI-0.7 (R-4). For the renewals project, the walls were over-clad with 89 mm (3.5”) of mineral wool insulation behind stucco and metal panel cladding. The cladding and insulation were held in place using fibreglass ‘Cascadia Clips’, which significantly reduce thermal bridging compared to a more traditional metal girt cladding system. This assembly resulted in an overall effective R-value of RSI-2.8 (R-16) for the exterior walls.

With a window-to-wall ratio of 50%, the windows accounted for a significant portion of heat loss. The existing windows consisted of double glazing with air fill and no low-e coatings in non-thermally broken aluminum frames. These were replaced with triple-glazed windows with fibreglass frames, improving the window U-value from about USI-3.1 (U-0.55) to USI-0.97 (U-0.17).

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[38] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/noho/index.cfm
[39] www.suncertifiedbuilders.com/en/duvet-house
[40] www.passivehouseontario.ca/ph-retrofit.html
[41] www.fcm.ca/Documents/presentations/2013/SCC2013/On_the_Path_to_EQuilibrium_EN.pdf
[42] www.sabmagazine.com/blog/2013/06/10/the-belmont-building-envelope-renewal-vancouver-bc/

Airtightness improvements were made to the enclosure through installation of a liquid-applied air and water barrier over cracks in the concrete, best practice detailing at interfaces and penetrations, and new airtight windows. The initial pre-retrofit airtightness was 0.71 cfm/ft^2 at 75 Pa. Following the retrofit, the airtightness dropped to 0.32 cfm/ ft^2 at 75 Pa.

Energy savings as a result of the enclosure renewals project were estimated through whole building energy modelling, and are predicted to be 20% in overall building energy, and 90% for in-suite space heating energy.

A study was done to see what retrofits would have been needed to achieve the EnerPHit Passive House retrofit certification (RDH Building Science, 2016). As designed and implemented, the deep energy retrofit of the Belmont will be close to the EnerPHit standard after the planned HRV installation is complete. Heating demand calculated using the PHPP is 41 kWh/m^2, compared to the EnerPHit standard of 25 kWh/m^2. The study found that only minor improvements would be needed to reach the EnerPHit standard, including changing to high solar gain windows, insulation of thermal bridges (specifically at the soffit, roof parapet, and window installation), and whole building airtightness testing per the Passive House standard (testing with vents sealed). The incremental costs associated with these measures are relatively minor, estimated at $30,000 to $50,000 added to the $3.6 M project. The report cautions that further analysis would be needed to measure the impact that the zero cost measure of adding high solar gain windows would have on the thermal comfort of occupants.

The project was heavily instrumented to analyse pre- and post-retrofit performance. The next phase of the project will start in 2016 where each suite will be fitted with its own HRV. Adding ventilation to each suite is important to account for the building envelope airtightness improvements.

2.2.2 International Projects

This section features three US MURB retrofit projects. The first two examine retrofit projects that targeted Passive House certification, and the third is a LEED for Homes Multifamily Platinum Certification project.

Weinberg Commons, Washington, DC

Weinberg Commons is an affordable housing project comprised of three 1960's era brick and block buildings, which had single pane, aluminum frame windows[43]. Twenty-four apartments will be for low-income families at rents less than $1,000 a month, and the other 12 will provide permanent supportive housing for formerly homeless families. A tested airtightness level of 0.54 ACH_{50} was achieved. All 3 buildings, totaling thirty seven 2 bedroom apartments, completed an extensive retrofit in 2015. All 3 buildings used the same assemblies and systems to achieve the Passive House certification criteria (with one of the three to seek actual certification). One of the main elements of the retrofits was attaching I-joists to the exterior of the existing brick walls to create a thick insulation cavity.

[43] http://passivetopositive.com/projects/weinberg-commons/

McKeesport Downtown Housing, McKeesport, PA

This multi-phase retrofit project involves an 84 unit, 6,020 m^2 (65,000 ft^2), multi-family YMCA building originally built in 1922 for those at risk for homelessness[44]. This project underwent the retrofit while half occupied at all times, and is the first pre-certified Passive House multi-unit retrofit project. Key elements include:

- Walls consist of existing brick veneer or EIFS over terra cotta structural tile and original plaster with new 203 mm (8") interior spray foam insulation and metal stud wall with new gypsum interior finish.
- Existing timber framed wood sheathed roof with 241 mm (9.5") interior spray foam insulation and 114 mm (4.5") exterior polyisonene insulation under new roof membrane.
- Zola uPVC triple glazed windows with 0.50 SHGC.
- Ventilation system is comprised of three UltimateAire 2000DX ERVs.
- Heating and cooling system utilises ground coupled (geothermal) heat pumps distributed throughout building serving banks of tenant rooms.
- Airtightness of 2 ACH_{50} achieved (1 ACH_{50} targeted). Blower door testing process was complicated as the building was partially occupied throughout construction. The Team suspects that test results were inaccurate, but re-testing would have been too disruptive to residents and owner.

Castle Square Apartments, Boston, MA

Retrofitted in 2011-12, Castle Square Apartments is a 51,900 m^2 (540,000 ft^2) mixed-use property built in the 1960s that is comprised of 500 affordable apartment units and 1,850 m^2 (20,000 ft^2) of retail space[45]. The project website provides a "How to Guide" that provides some of the logic behind how they arrived at the final scope of work. Castle Square was awarded a LEED for Homes Multifamily Platinum Certification. The property consists of four mid-rise buildings and 19 town house buildings containing one, two, three and four-bedroom apartments. The deep energy retrofit focused on the 192 apartments in the seven-storey buildings.

The existing wall consisted of RSI-0.5 (R-3) brick and concrete construction. For the first step of the wall retrofit, a liquid-applied air and water control membrane was painted onto the exterior of the building's original brick walls. A mineral fiber air flow suppression layer was then added, which is made of mineral fiber insulation to also stop air movement. Insulated metal panels (Kingspan Panels) were installed on top of the mineral fiber. The RSI-7.2 (R-41) rated, 127 mm (5") panels consist of rigid foam high density insulation material within a thin sheet of metal laminated to each side. They provide insulation, shed rain water and snow, and provide the aesthetic finish for the building.

The existing 70% efficient atmospheric boilers were replaced with 94.5 % efficient sealed combustion boilers. The existing leaky central exhaust system was sealed using Aeroseal, where holes are sealed from the inside of the ducts with a polymer based sealing agent injected into duct systems after exhaust grilles at each floor are removed and duct openings are temporarily blocked.

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[44] www.phius.org/projects/1132
[45] www.castledeepenergy.com/

The total cost of the Castle Square deep energy retrofit was $8,177,783 USD for 192 apartments or $42,593 per apartment. This includes the cost of everything related to heating, cooling, and hot water. It does not include the cost of high efficiency lighting and Energy Star refrigerators. However, in the case of Castle Square (like most existing buildings slated for renovation) incremental cost may be a more appropriate measurement. The total incremental cost of the deep energy retrofit at Castle Square was $3,460,486 or $18,023 per apartment.

Castle Square Apartments is modeled to reach a 72 % reduction in energy usage. Before the renovation, gas for heating and hot water at Castle Square Apartments (192 apartments) cost $194,000 per year. After the retrofit, gas is expected to cost $50,000 per year. Similarly, electricity costs are expected to drop from $397,000 per year down to $181,000.

3. Passive Low-Energy Design Practices and Technologies

This chapter presents different technologies and design practices used in high performance passive low-energy buildings. As seen in the case studies, any number of different approaches and technologies and combinations thereof can be implemented. Making use of building energy modelling will allow the designer to ensure that the selected approaches meet the performance expectations of the project. Good design also needs to be followed by proper construction execution to ensure that the building performs as intended.

Technologies and design practices implemented in low to mid-rise wood-frame MURBs can be quite different than those found in high-rise buildings. Most of the literature and case studies are based on wood-frame construction. Arena (2014) presented on some of the differences between low-rise and high-rise construction, with some of these highlighted differences presented in different sections of this chapter. She noted that high-rise MURBs generally have higher cooling demand, which increases the need to focus on ensuring good occupant thermal comfort.

3.1 Site Planning Features

Unlike in passive solar design strategies of the past that relied extensively on passive solar gains, in passive low-energy design strategies, solar orientation plays less of an important role. Passive low-energy design strategies rely on superinsulation and airtightness to minimise the amount of energy (solar or otherwise) required to condition a space. Proskiw and Parekh (2010) performed modelling on the optimisation of a net-zero energy house and found that changing the house's orientation from south to south-east or south-west only increased total energy consumption by 1% to 2% regardless of house size or location. Significant performance reductions did not occur until the orientation exceeded 90% off south. However, it is likely that thermal comfort would have varied more substantially, depending on orientation.

South-facing windows can be more easily fitted with overhangs that can provide shade in the summer and allow sunlight to penetrate in the winter. Another advantage of a southerly orientation is that it can facilitate the minimal use of east and west facing windows, which can help prevent overheating. When

looking at passive low-energy design strategies, it is important to evaluate the solar availability of a given site and develop a shading strategy to help alleviate potential overheating issues.

3.2 Building Form Considerations

Passive low-energy design is more easily achieved in buildings that are more compact. Passive House design guidelines refer to a favourable compactness ratio where the area to volume (A/V) ratio is less than 0.7 m^2/m^3. As can be seen in Figure 2, multi-family buildings typically achieve this favourable compactness ratio. In addition to this ratio, using a simple building envelope shape, that avoids steps in walls, dormer windows, etc., makes it easier to implement passive low-energy design as it minimises thermal breaks and simplifies the implementation of the air barrier system.

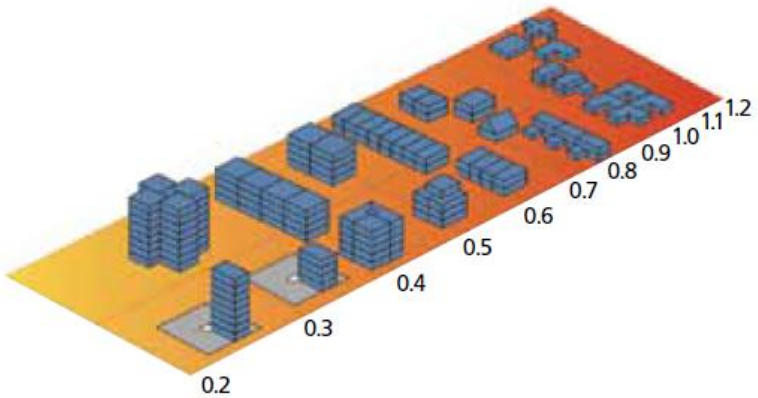

Figure 2: Passive House Institute diagram showing compactness ratio of different building forms

Form and internal space layout can also be influenced by orientation and favourable window placements. In the Station Point Greens project in Edmonton, the design originally had a tower with a double-loaded corridor design, with more than half of the suites being north-facing, and therefore had no direct access to solar gains (Hancock, Scott, 2013). After adding a goal to achieve Passive House certification, the project was redesigned to have a single-loaded corridor with all suites having good southern exposure. Note that many Passive House multi-family buildings being built in the U.S. are using double-loaded corridors.

Morisson Hershfield (2014) found that design decisions made by architects can have a big impact on the overall building thermal performance. Decisions that lead to more building interface details will typically lead to additional heat flow. Examples include articulating architecture, glazing broken up by small areas of opaque walls, and glazing orientation. Some thermal bridges can be completely avoided or substantially decreased, such as concrete shear walls.

3.3 Building Envelope Details

Low-energy building envelopes can be achieved in many ways, and different solutions can be evaluated based on thermal and moisture control, durability, buildability, material use, cost and environmental factors. This section presents different wall systems that can be built to achieve high insulation values,

and other elements that impact the performance of the building envelope, namely thermal bridges, windows and air-tightness.

3.3.1 High Performance Wall Systems

Most of the case studies and literature references are based on wood-frame construction. The information presented on high R-value wall systems are divided into two sections; one focused on wood-frame construction and the other on non-combustible construction that is typical of high-rise MURBs.

3.3.1.1 Wood-Frame Construction

Whether buildings are targeting Passive House certification, net-zero energy consumption or other high performance targets, one common design attribute is the use of a super-insulated building envelope. Figure 3 shows the different insulation levels achieved in the EQuilibrium™ Housing demonstration projects (CMHC, 2014) using a number of different types of wall assemblies. There are two important considerations when building a high performance wall: construction method and level of insulation. The "best" choice for a wall system will vary according to project goals, region, fluctuating material prices, building design and type, and builder experience and preferences.

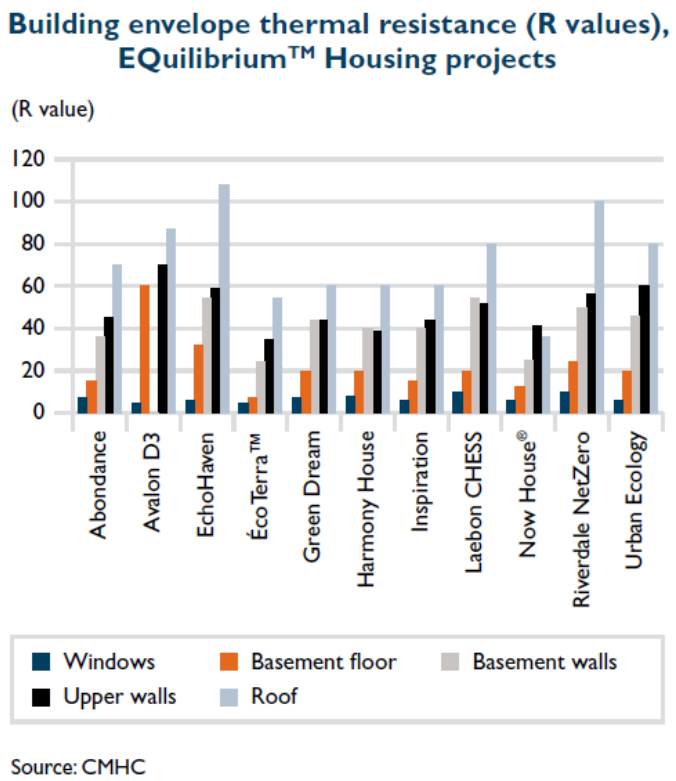

Figure 3: Different insulation levels achieved in the EQuilibrium™ Housing demonstration projects (CMHC, 2014)

Proskiw and Parekh (2010) conducted a study for Natural Resources Canada (NRCan) that examined the most cost-effective insulation values to use to achieve net-zero energy consumption for a house. The

results indicate an optimal range of RSI-0 to RSI-1.8 (R-0 to R-10) under the slab, RSI-4.2 (R-24) in basement walls, RSI-5.3 to RSI-7.0 (R-30 to R-40) for main walls, and RSI-10.6 to RSI-14.1 (R-60 to R-80) in the roof, with the low end of the range suitable for warmer coastal climates. Note, however, that these recommendations were developed with cost optimisation data from March 2008.

Working with builders in cold climates in the U.S., Steven Winter Associates (2011) highlights three approaches to build walls that are RSI-5.3 (R-30) and beyond, that are well-established methods, use readily available materials, and are buildable by contractors without substantial additional equipment or sub-contractors, involving:

- Double framed walls with blown or sprayed insulation;
- 38 x 89 mm (2 x 4 in.) or 38 × 140 mm (2 × 6 in.) insulated, framed walls with exterior rigid foam insulation;
- Structural insulated panels (SIPs).

Steven Winter Associates (2011) documents key components, advantages, and challenges for each wall system, including: Material choices and options; Structural issues, durability, and moisture management; Requirements of builders and trades (framing, insulation, plumbing, electrical, siding, etc.); and Cost considerations.

Rickets and Finch (2015) developed an illustrated guide of four common RSI-3.9+ (R-22+) above grade walls and two below grade walls. For each wall system, the guide presents key considerations, discussion on cladding attachment, information on critical water, air and vapour barriers, possible insulation types, and environmental considerations. The four exterior walls presented include:

1. Split insulated walls 38 x 89 mm (2 x 4 in.) or 38 × 140 mm (2 × 6 in.) construction with different types of exterior insulation),
2. Exterior insulated walls,
3. Double stud walls, and,
4. Deep stud walls.

The Cold Climate Housing Research Centre developed the REMOTE Wall system (Residential Exterior Membrane Outside-insulation TEchnique) that is based on a split insulated wall with either (8 x 89 mm (2 x 4 in.) or 38 × 140 mm (2 × 6 in.) construction and 102 mm to 152 mm (4" to 6") of rigid exterior insulation (Benesh, 2009). In the REMOTE Wall, the vapor barrier is applied to the outside of the sheathing, as opposed to the inside of the stud framing. They promote it as a cold climate construction technique that addresses moisture control, air tightness, air quality, and adequate insulation. They have developed a design manual that provides a detailed guide on how to successfully implement the wall system in the field including many diagrams and pictures[46].

Jacobson (2012) presented a study that evaluated the exterior building envelope of 8 passive houses built in cold climates (Scandinavia, EU, and US) to examine the important design elements (calculating R-values, thermal bridges, critical layers for moisture performance, and embodied carbon). The Passive

[46] www.cchrc.org/sites/default/files/docs/REMOTE_Manual.pdf

House projects examined included a number of building envelopes: TJI with blown-in fiberglass, Insulated Concrete Form (ICF) with exterior EPS, structural engineered panel with exterior expanded polystyrene insulation (EPS), Structural Insulated Panel (SIP) panel, advanced framing with sprayfoam, double-stud wall with blown-in cellulose, advanced 38 × 140 mm (2 × 6 in.) framing with exterior mineral wool, prefab wall panel with exterior mineral wool, and concrete mass wall with exterior mineral wool. The average R-values of these walls were:

- Above grade wall RSI-11.1 (R-62.9) Target: RSI-10.6 (R-60)
- Roof: RSI-14.8 (R-83.8) Target: RSI-14.1 (R-80)
- Floor slab: RSI-11.8 (R-67) Target: RSI-10.6 (R-60)
- Average airtightness 0.46 ACH @50Pa

A thermal bridge analysis of key transitions showed that there was no great difference between envelope types for linear thermal bridges. As long as adequate attention was given to the key details during the design phase, thermal bridges could be limited.

Jacobson (2012) also presents the results of a lifecycle assessment of the eight walls performed using Athena. Spray polyurethane foam blown with hydrofluorocarbon (HFC) blowing agents has almost 100 times greater global warming potential than fiberglass, per unit area per R-value. Similar results were seen with extruded polystyrene (XPS). This resulted in the carbon payback of the advanced frame envelope with spray polyurethane foam (SPF) to be 23 years, compared to 7.5 years for the mass wall envelope, and an immediate carbon payback for the double stud envelope. Energy payback for the mass wall envelope was 4.4 years, for the ICF envelope it was 2.7 years, and for the double stud envelope it was immediate.

Hygrothermal Impacts of Different Walls

An important design consideration when looking at different wall assemblies and designs is to consider the hygrothermal performance of the wall (i.e. risk of condensation within the assembly and its ability to dry). One analysis of high R-value walls indicated that assemblies constructed with oriented strand board (OSB) on the exterior of all the insulation should employ a vented cladding to assist in drying of that layer regardless of the type of insulation in the cavity (Arena & Mantha 2013). Drying to the interior is severely limited in these walls, therefore, drying to the exterior must be enhanced.

Rickets and Finch (2015) remarked that for double-stud walls and deep-stud walls, the relatively large amount of insulation installed to the interior of the wood sheathing increases the risk of moisture accumulation within these assemblies. To limit the outward flow of water vapour, a vapour barrier should be installed on the interior of the innermost wall section. The use of an interior air barrier, which could also play the role of the vapour barrier (sealed poly approach) is recommended to prevent the flow of air into the insulated cavity from the interior as well as to reduce the potential for convective looping. In addition to the interior air barrier, a secondary exterior air barrier such as a vapour permeable self-adhered sheathing membrane or sealed sheathing can also be used to reduce wind penetration and improve the overall assembly airtightness. Figure 4 presents the results of a hygrothermal analysis that shows the importance of proper assembly and having a very airtight building to reduce the potential for mould growth in thick wall assemblies.

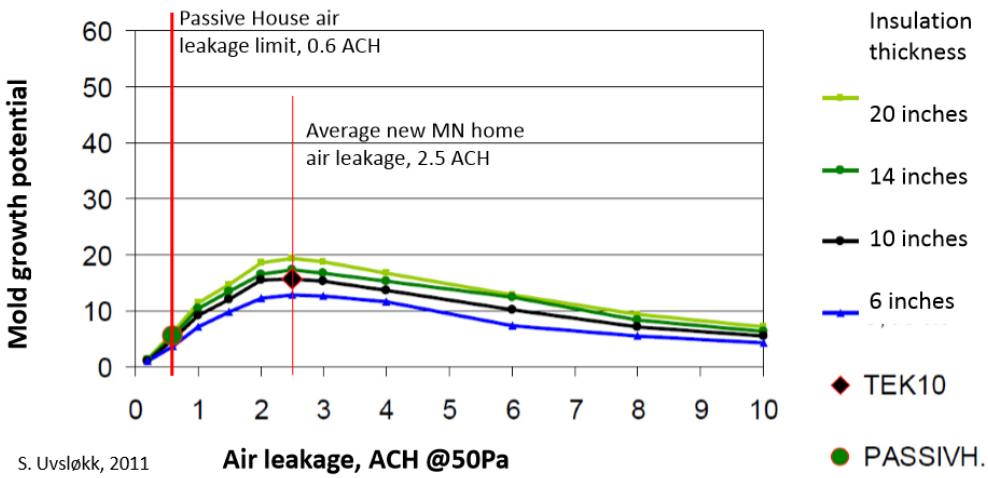

Figure 4: Mould growth potential as a function of building airtightness (Jacobson, 2012)

When using an impermeable exterior insulation, the National Building Code (NBC) Table 9.25.5.2 requires a certain insulation ratio that indicates the minimum amount of exterior insulation to use in different climates, with increasing amounts of exterior insulation required in colder regions. Arena & Mantha (2013) found that based on modeling results, a minimum of 50% of the total cavity wall R-value should be provided by the impermeable insulation in climates zones 4 through 6 (between 3000 and 5000 heating degree days (HDD)), and 60% for climate zone 7 (between 5000 and 7000 HDD). Note that these values are higher than what is required the NBC (20% and 30%, respectively). Since outward drying in these assemblies is limited, the use of a relatively permeable interior vapour barrier such as a smart vapour retarder or vapour retarder paint is recommended (Rickets & Finch, 2015).

The National Research Council of Canada (NRC) performed computer modelling to investigate the change in risk of condensation in wall assemblies that used impermeable exterior insulation, which were compared with a reference 38 × 140 mm (2 × 6 in.) wall (Hamed, 2014). The R-values of the outboard insulation investigated were RSI-0.7, 0.9 and 1.1 (R-4, R-5 and R-6), with a wide range of Water Vapour Permeance (WVP) from 2 (vapour tight) to 1800 ng/(Pa•s•m²) (vapour open). The study found that hygrothermal performance of a wall system greatly depends on the "combined effect" of the three main environmental parameters, namely, Heating Degree Days (HDD), Moisture Index (MI) and wind speed. The study found that all wall systems that incorporated exterior insulation had a lower risk of condensation and resulting mould growth. The exterior insulation helps keep the wood sheeting warm and dry, and also reduces thermal bridging and heat loss. These results have also been observed at the Coquitlam Test Hut near Vancouver[47].

Table 4, shows the results of another hygrothermal analysis done on various walls (Straube & Smegal, 2009). The hours of potential condensation are reduced from 4,379 hours with 38 × 140 mm (2 × 6 in.) framing down to 1,532 hours with the addition of 101 mm (4") of EPS rigid foam on the outside. The double-stud wall and truss walls have a higher potential for condensation, which can be reduced by adding a layer of sprayfoam with the cellulose.

[47] http://buildingscience.com/documents/special/vancouver-test-hut

Table 4: Results of hygrothermal analysis done on different wall assemblies (Straube & Smegal, 2009)

Wall Assembly	Rated R	Measured R-Value	Hrs of Potential Condensation
Less than R-20 Walls			
2x4, 16" oc, R-13 fiberglass batt, OSB	13	10.0	--
2x4 adv frame, 24" oc, R-13 fiberglass batt, OSB	13	11.1	4,503
2x6 16" oc, R-19 fiberglass batt, OSB	19	13.7	--
SIP 3.5" EPS	13	14.1	--
2x6 adv frame, 24" oc, R-19 fiberglass batt, OSB	19	15.2	4,379
ICF 8" ICF, 4" EPS	14.8	16.4	--
2x6 adv frame, 24" oc, 5.5" R-21, 0.5 spray foam, OSB	24	16.5	0
ICF 14" cement w/ rockwool	17.4	17.4	--
2x6 adv frame, 24" oc, 2" spray foam, 3.5" cellulose	23	17.5	934
R-20 Walls			
2x6 adv frame, 24" oc, 5" R-29 spray foam, OSB	29	19.1	0
2x6 adv frame, 24" oc, R-19 fiberglass batt, 1" R-5 XPS rigid	24	20.2	3,813
ICF 15", 5" EPS	20.6	20.6	--
2x6 adv frame, 24" oc, 2x3 R-19 +R-8 fiberglass batt	27	21.5	4,594
Greater than R-30			
Double-stud walls with 9.5" R-34 cellulose	34	30.1	4,576
2x6 24" oc adv frame, EIFS w/ 4" EPS rigid foam	31.4	30.1	1,532
Double-stud 2" spray foam, 7.5" cellulose	36.2	32.4	2,284
2x6 24" oc adv frame, R-19 fiberglass batt, 4" R-20 XPS	39	34.5	1,189
SIPS with 11.25" EPS	36	36.2	--
Truss wall 12" R-43 cellulose	43	36.5	4,622
Offset frame walls with exterior spray foam	40.6	37.1	0
-- = unkown			

3.3.1.2 Non-Combustible Construction

Buildings made of steel and concrete have different challenges than those associated with wood construction. To date, many of the net-zero energy projects and passive house examples have come from low-rise wood-frame buildings. There are less literature resource materials that offer guidance on the design and construction of non-combustible building envelopes following passive low-energy design strategies. However, with the advent of some notable demonstration buildings like the Passive House Cornell Student Housing highrise, this is starting to change.

The first step at improving the performance on non-combustible construction, would be to evaluate and reduce the impact of thermal bridging at interface details. An analysis of buildings with concrete walls insulated on the inside with National Energy Code for Building (NECB) 2011 prescriptive insulation levels and common details, found that the effective U value of the opaque walls was three to four times below the NECB 2011 prescriptive levels, as shown in Table 5 (Morisson Hershfield, 2014). Although the NECB calls for minimum R-values of RSI-3.6 (R-20), the actual performance is closer to RSI-0.77 (R-4.3) when the heat loss through the thermal bridging elements is taken into account. Note that values listed as BETA Calculation Value in the table list the effective U-values of the wall systems considering thermal bridging.

Table 5: Impact of considering thermal bridging using BETA method for common Part 3 buildings (Morisson Hershfield, 2014).

Building Type	NECB 2011 Zone 5 U-Value $\frac{W}{m^2K}$	BETA Calculation Value $\frac{W}{m^2K}$	% Incr. U-Value	Total Energy Difference ekWh/m²	Energy Cost Difference $/m²
Commercial Office	0.28	0.88	215	11	$ 0.41
High-Rise MURB	0.28	1.27	352	12	$ 1.08
Hotel	0.28	1.41	402	21	$ 0.62
Large Institutional	0.28	1.07	285	36	$ 1.20
Low-Rise MURB	0.28	1.29	359	13	$ 1.21
Non-Food Retail	0.28	0.55	96	12	$ 0.34
Recreation Centre	0.28	0.75	170	8	$ 0.35
Secondary School	0.28	1.36	389	14	$ 0.48

The Morisson Hershfield (2014) study found that using exterior insulated finish system (EIFS) was a cost effective way of reducing the impact of thermal bridging. They note that EIFS was more commonly utilized in the past because this type of system is inexpensive and provided thermally efficient wall assemblies but fell out of favour following some performance issues, but that EIFS systems have evolved since then to be more durable yet still offer a cost effective and thermally efficient alternative to other types of claddings. In comparison to exterior insulated steel assemblies, EIFS does not have a significant advantage in terms of thermal performance and energy savings because large thermal bridges can be insulated with any exterior insulated assembly. The advantage comes more from the construction costs savings with EIFS compared to exterior insulated assemblies with cladding. On the other hand, the study notes that split and interior insulated assemblies are not only inefficient from an assembly perspective, but are shown to be even more inefficient when the impact of interface details is included in determining an overall U-value. More energy savings can be realized with exterior insulated assemblies than compared to split insulated assemblies. They also look at a few new emerging technologies and applications, including:

- Vacuum insulated panels (VIP) in insulated glazed units for glazing spandrel sections called Architectural Insulated Module (AIM) manufactured by Dow Corning. AIM applications included spandrel sections for window-wall, conventional curtain-wall, high performance curtain-wall, and unitized curtainwall.
- Structural thermal breaks manufactured by Schöck for several applications, including cantilevered concrete balconies, concrete parapets, interior insulated poured-in-place concrete walls, concrete to steel connections (like balconies), and steel to steel beam penetrations.
- Cladding attachments incorporating thermal breaks and innovative materials from various manufacturers.

Arena (2014) looked at curtain wall facades for high performance MURBs as these are common. Curtain walls are typically steel framed, are non-structural, and are designed to span multiple floors. Advantages of curtain walls are that they offer continuous insulation on the exterior of the building, and that panels can be constructed in factory, which can result in less variability of installation quality. Disadvantages come from the attachment of the panels to the building and to each other, which can lead to areas of possible thermal bridges and air infiltration. Other challenges indicated are that the final air sealing is done from the exterior; alignment of air, water, and vapor barrier is difficult; and that fire rated insulation is needed.

In a CMHC (2014) analysis that looked at the feasibility and cost-effectiveness of building a 10 storey MURB to near Passive House levels of performance, they considered a wall assembly that represented one of the best performing systems analyzed in Morrison Hershfield's "Building Envelope Thermal Bridging Guide" (Morrison Hershfield, 2014). The wall has exterior insulation secured with non-conductive clips and interior spray foam insulation. The wall system's approach included no spandrel panels and reduced the balcony connections' thermal conductivity by half or more. Non-conductive window frames and connections reduced the linear losses even further. Fully accounting for thermal bridging and linear losses, the resulting wall system had a thermal resistance of RSI-5.4 (R-31). Including interior spray foam insulation not only helped to improve the wall's modelled thermal resistance, but it also improved the modelled air tightness. Better air tightness not only reduced the infiltration, but also improved the overall performance of the heat recovery systems. Different levels of building envelope performance were used depending on the climate as seen in Table 6.

Table 6: Low-energy design features of archetype MURB by climate (CMHC, 2014)

Component	Vancouver	Kelowna	Edmonton	Toronto	Montréal	Halifax
Wall thermal resistance	RSI-4.5	RSI-4.6	RSI-5.4	RSI-5.4	RSI-5.4	RSI-5.4
Additional linear losses through walls	17%	15%	14%	14%	14%	14%
Roof thermal resistance	RSI-5.6	RSI-6.9	RSI-9.1	RSI-7.4	RSI-9.1	RSI-8.3
Floor thermal resistance	RSI-4.6	RSI-4.6	RSI-4.6	RSI-4.6	RSI-4.6	RSI-4.6
Window percent	35%	30%	30%	30%	30%	30%
Window conductance	USI-0.91	USI-0.91	USI-0.68	USI-0.68	USI-0.68	USI-0.68
Window SHGC	0.55	0.55	0.39	0.39	0.39	0.39
Natural infiltration (ACH)	0.1	0.1	0.1	0.1	0.1	0.1
Heat recovery effectiveness	0.70	0.80	0.80	0.80	0.80	0.80

Source: EnerSys Analytics Inc.

Insights from the case studies examined earlier in this report included:

- The Station Point Green Project in Edmonton is planning on using 356 mm (14"), RSI-10.6 (R-60), Polycore wall system (Hancock & Scott, 2013). It's a local product comprised of EPS styrofoam panels with an imbedded steel stud and can be designed and manufactured to multiple sizes and thicknesses. The main benefits of the Polycore wall system were the flexibility of the finish

that could be applied to the panel, the lack of thermal bridging issues because the steel stud is imbedded in the Styrofoam panel at the interior face, the small incremental cost to increase the R-Value (just the cost to add a few extra inches of Styrofoam), and the fact that it was a local manufacturer. The downside of this product was that it was lacking proper fire-rating for the height of Station Pointe Greens and had never been installed on anything higher than three stories.

- The Cornell Passive House high-rise MURB used a custom designed RSI-5.6 (R-32) curtain wall facade that is being constructed off-site and delivered complete with high-performance windows.
- The Castle-Square retrofit in the U.S. used EIFS consisting of 127 mm (5”), RSI-7.2 (R-41), insulated metal insulation panels (Kingspan Panels) that consist of rigid high density foam insulation material within a thin sheet of metal laminated to each side. They provide insulation, shed rain water and snow, and provide the aesthetic finish for the building.

Interface details are not only important when looking at thermal bridging; they also play an important role in building durability. RDH (2001) studied the performance of building envelopes for high-rise buildings in Vancouver following a number of building envelope failures. They found that moisture penetration at interfaces between assemblies and at details within assemblies is the dominant cause of moisture problems in high-rise buildings, indicating a need for the better design of these critical details. Rainscreen assemblies were identified as being required for most buildings. The study noted that durability expectations for assemblies, details, components and materials should be better articulated in standards and guidelines to facilitate the use of materials that will be durable in the service environments. In particular, corrosion resistance was identified as an area requiring greater guidance as was the use of more moisture resistant sheathing products such as glass fibre faced gypsum sheathing.

3.3.2 Thermal Bridges

Wood-frame construction is inherently more thermally efficient due to the lower conductivity of wood compared to concrete, steel-frame, and masonry construction. As a result, the impact of thermal bridges caused by wood framing is less than materials typically used in non-combustible construction (see Fig. 5). The low conductivity of wood also makes it easier to account for thermal bridging in calculations because lateral heat flow is less of an issue and assumptions of parallel path heat flow are more valid for most wood-frame details. Figure 5 also demonstrate that although the impact of thermal bridging is less in wood-frame construction, it is not negligible.

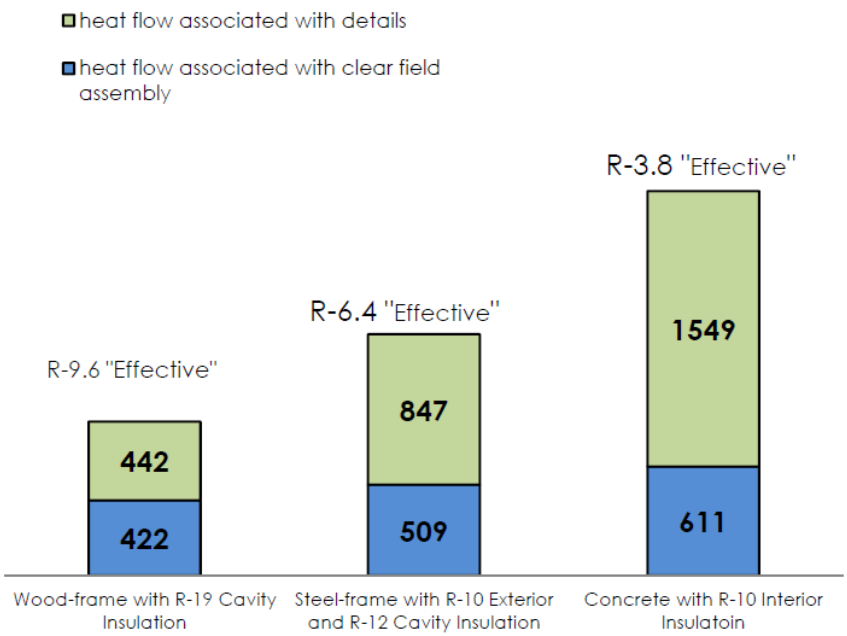

Figure 5: Comparison of relative contribution of heat flow (W/K) to the effective thermal resistance (ºF ft^2 hr/BTU) for different construction types (Morrison Hershfield, 2014). Clear field assembly represents a wall with no penetrations or disturbances.

Morrison Hershfield (2014) developed the *Building Envelope Thermal Bridging Guide – Analysis, Applications & Insights* for a number of stakeholders in B.C. The primary objective of this guide was to address the obstacles currently confronting industry, with regard to thermal bridging, by:

1. Providing a catalogue of the thermal performance of common envelope assemblies and interface details directly relevant to construction in BC.
2. Providing information that makes it easier for industry to comprehensively consider thermal bridging in building codes and bylaws, design, and whole building energy simulations.
3. Examining the costs associated with improving the thermal performance of opaque building envelope assemblies and interface details, and forecasting the energy impact for several building types and climates.
4. Evaluating the cost effectiveness of improving the building envelope through more thermally efficient assemblies, interface details, and increasing insulation levels.

Although the guide was developed for B.C., it is applicable to other locations and as such has garnered National and International attention and use. The guide ranks the different assemblies as Efficient, Improved, Regular or Poor, with the linear heat transfer coefficient of the Efficient assemblies being 0.2 W/m·K. This is a significant improvement compared to what is often built today, but does not quite achieve Passive House levels of performance. Passive House construction aims for thermal bridge free assemblies, which they refer to as linear transmittance of heat flow below 0.01 W/m·K. If a design can show that thermal bridges will be lower than this target, then they don't need to be accounted for in the modelling. The BC Homeowner Protection Office, CMHC and other partners have initiated a project in 2016 that will add assembly details to (Morrison Hershfield, 2014) to develop building assemblies that

meet the very stringent Passive House criteria, and develop design guidance for non-combustible MURBs with the results.

The Morrison Hershfield (2014) analysis of the impact of thermal bridges found in common practice was informative. For example, for high-rise multiunit residential buildings, cantilevered balconies which represented approximately 2.7% of the total opaque wall area, accounted for 15% to 30% of a wall's heat loss. Another interesting result was the impact of window placement within the wall. Passive House construction stipulates that the windows should be in-line with the wall's insulation to avoid thermal bridging. The analysis confirmed that window placement makes a difference. The linear transmittance of a thermally broken aluminum window installed in a pre-cast sandwich panel increased from 0.048 W/m·K when efficiently aligned, to 1.058 W/m·K with an unaligned uninsulated perimeter. When the length of the perimeter of each window in the building is added up, these linear heat transfer coefficients can make a large impact on energy use.

The analysis also showed that increasing the amount of insulation in assemblies without considering the impact of thermal bridging is not an effective strategy to reduce energy as its associated costs will be met with only marginal energy savings. Conversely, adding more insulation and improving details at the same time can result in real energy savings. Notwithstanding the general message that paying attention to interface details pays off more than adding insulation, more insulation is sometimes a good solution. For example, adding insulation outboard of the metal framing of glazing spandrel sections can result in appreciable reductions in U-value and energy use.

The *Building Envelope Thermal Bridging Guide* (Morrison Hershfield, 2014) provides thermal bridging coefficients for hundreds of assemblies with more being adding over time through periodic updates of the publication. However, even with this great resource, there are bound to be assemblies and design configurations that are not included in the guide. Designers will need to assess the performance of these assemblies with THERM, or other 2D and 3D modelling tools. PHIUS has developed an online 4-hour tutorial on how to use THERM[48] that could serve as a starting point for designers needing to account for thermal bridging.

3.3.3 Windows and Shading

When it comes to windows, size, type and location can make a big difference to building energy consumption and occupant comfort. In a high performance building in Canada, the windows would typically have the following characteristics:

- Triple glazing with inert gas fill
- Thermally broken frame (insulated frame)
- Warm edge spacer
- Low-emissivity glass coatings, and
- Multiple airtight seals.

High performance triple glazed windows will cost more than an equivalent area of exterior wall, and will have a much lower R-value than the wall. Thus windows should be used strategically, balancing their

[48] www.phius.org/get-professional-training/software-training-programs/therm-introduction

benefits (providing views, daylighting, natural ventilation, solar heating) with their drawbacks (potential glare, overheating, higher relative heat loss and costs).

3.3.3.1 Windows and Thermal Comfort

Passive House Institute guidelines call for a maximum window U-value of 0.8 W/m^{2}K, and 0.85 W/m^{2}K when factoring the thermal bridging associated with the installation ($U_{w,installed}$). This criterion was developed for Central European climates to meet comfort requirements that stipulate that the window's interior surface temperature should not fall below 17ºC when it is -10ºC outside. Many parts of Canada experience colder temperatures that would require even higher levels of performance to meet the Passive House Institute comfort criterion (see Table 7).

Table 7: Acceptable window efficiency for different climates to meet Passive House comfort criterion (Hopfe & McLeod, 2015)

Climate	External Design Temperature	Maximum $U_{w,installed}$ W/m^{2}K	Maximum U_w W/m^{2}K
Arctic	-34ºC	0.45	0.40
Cold	-16ºC	0.65	0.60
Cool-temperate	-5ºC	0.85	0.80
Warm-temperate	5	1.30	1.25

The EQuilibrium Housing InSight bulletin[49] on the Riverdale NetZero Passive Solar Design discusses the passive solar design elements that were implemented at the Edmonton duplex. It used triple glazed U_{SI}-0.77, high-SHGC , on the south-facing wall, U_{SI}-0.67, low-SHGC, triple glazed windows on the East/west façade, and U_{SI}-0.56 quadruple glazed windows on the North façade. The windows had soft low emissivity coatings (2 coatings on the triple pane windows, and 3 on the quadruple pane), Argon gas fill, "warm edge" spacers, and fibreglass frames filled with polyurethane insulation. Despite using higher U-values than what is recommended in Table 7, the windows performed well and the project's design heat load met the Passive House requirement of 15 kWh/m^{2}K. The builder indicated that he would rethink the use of the quadruple glazed windows in future projects stating that they were too heavy to handle by one person, which increased installation costs and that combined with their increased capital cost, may not warrant their marginal relative energy benefit.

3.3.3.2 Window Performance Standards

The Passive House Institute certifies windows from different manufacturers that meet their performance requirements. It is not necessary to import these typically European windows for a Passive House project in North America. The testing and rating protocols used in Europe are different than those used in North America. A recent report compared the differences between the different

[49] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/eqho_007.cfm

international window standards (RDH, 2014). They found that there was no direct correlation that could convert a U-value from one standard to another. Some of the relevant findings include:

- Passive House building energy modeling tools require center of glass solar heat gain "g-values," whereas the NFRC/CSA Solar Heat Gain Coefficient (SHGC) is a whole window value. This study shows that whole window solar heat gain values can be up to 50% lower than centre of glass values.
- NFRC/CSA U-values are modelled at peak heating conditions (-18ºC) whereas ISO and Passive House use a higher outdoor temperature (0ºC ISO, varying by climate in PH) that is more representative of annual temperatures. These boundary conditions lead North American manufacturers to optimise glazing spacing at roughly 13 mm (0.5"), whereas European windows tend to have wider gaps of 16 to 18 mm (0.6-0.7").

Based on the two findings above, the study notes the importance of using the appropriate U-value and SHGC/g-values when performing whole building energy simulations specific to the modelling software being used and to make sure windows were evaluated using the same standard when comparing different window products.

For projects that want certified windows for the North American market, PHIUS has started to certify windows using EN-673, EN-410, and ISO 10077-based calculation methods[50]. Certified windows are not required for passive solar projects. What's important is that high performance windows are used, and that the window properties used in the modelling are those required for the specific modelling tool.

3.3.3.3 High Performance Windows in Non-Combustible Construction

Many of the high performance windows available on the market are made of combustible materials. These can be used in a Part 3 non-combustible building, but special design requirements need to be followed. Senez (2015) explains combustible window sashes and frames are permitted provided that [Sentence 3.1.5.4.(5)]:

1. Each window in an exterior wall face is an individual unit separated by non-combustible wall construction from every other opening in the wall,
2. Windows in exterior walls in contiguous storeys are separated by not less than 1 m (39") of non-combustible construction, and
3. The aggregate area of opening in an exterior wall face of a fire compartment is not more than 40% of the area of the wall face.

These requirements developed for fire considerations, would work well with passive design considerations. Limiting the window area to 40% of the wall would be advisable in terms of energy efficiency and thermal comfort considerations, and the 1 m (39") separation between units would help with the distribution of daylighting within the building.

[50] http://www.phius.org/phius-certification-for-buildings-and-products/phius-product-data-certification/certified-data-for-windows-program

3.3.3.4 Window Shading

The use of shading devices is an important aspect of passive low-energy design. Properly designed shading devices can block out high summer sun while allowing the lower winter sunlight to penetrate into the space. Shading can be provided by natural landscaping or by building elements such as awnings, overhangs, and trellises. Shading devices can have a dramatic impact on both the building's performance and appearance. As such, it should be considered early in the project to allow it to be well integrated in the overall building architecture. Given the wide variety of buildings and the range of climates, specific design guidelines are not possible. However, the Whole Building Design Guide from the National Institute of Building Science in the U.S. makes the following design recommendations[51]:

1. Use fixed overhangs on south-facing glass to control direct beam solar radiation. Indirect (diffuse) radiation should be controlled by other measures, such as low-e glazing.
2. To the greatest extent possible, limit the amount of east and west glass since it is harder to shade than south glass. Consider the use of landscaping to shade east and west exposures.
3. Do not worry about shading north-facing glass since it receives very little direct solar gain.
4. Remember that shading effects daylighting; consider both simultaneously
5. Do not expect interior shading devices such as Venetian blinds or vertical louvers to reduce cooling loads since the solar gain has already been admitted into the building. However, these interior devices do offer glare control and can contribute to visual acuity and visual comfort.
6. Study sun angles. An understanding of sun angles is critical to various aspects of design including determining basic building orientation, selecting shading devices, and placing potential solar renewable energy technologies.
7. Carefully consider the durability of shading devices. Over time, operable shading devices can require a considerable amount of maintenance and repair.
8. When relying on landscape elements for shading, be sure to consider the cost of landscape maintenance and upkeep on life-cycle cost.
9. Shading strategies that work well at one latitude, may be completely inappropriate for other sites at different latitudes. Be careful when applying shading ideas from one project to another.

For highrise buildings, shading is difficult and costly to incorporate. Optimal values for solar heat gain coefficient (SHGC) could be as low as 0.3 for all facades, but needs to be verified through building energy modelling (Arena, 2014). Too low of a SHGC and the primary energy demand is too high, but too high results in potential overheating and high cooling energy demand. It is important to consider that since MURBs typically have a higher occupant density, which increases internal gains per unit floor area from people and appliances, this in turn increases cooling energy demand, while lowering heating energy demand. To get around the lack of sun-shading overhangs, vertical shading elements can be used. Arena says that even setting the window back in the thick wall (towards the interior, known as an "innie") can help, as can shading from balconies. In any case, windows are key in balancing the heating, cooling, and total energy use requirements, so these projects should expect to do a lot of modeling to develop optimal design options.

[51] www.wbdg.org/resources/suncontrol.php

3.3.4 Air-tightness

Building an airtight building has many benefits, including improved durability, improved thermal comfort and reduced energy consumption. There are many air-barrier approaches that can be used to achieve an airtight building envelope. Some have the air-barrier on the inside wall surface, including the airtight drywall approach, and sealed polyethylene, whereas others have the air barrier on the outside such as the sealed sheathing or sheathing membrane. There could also be a combination of several materials and methods, as long as there is an unbroken air barrier between conditioned space (indoors) and unconditioned space (outdoors, attic, crawlspace, and attached garage).

Rickets and Finch (2015) outline five design requirements to achieve an effective air barrier:

1. All the elements (materials) of the air barrier system must be adequately air-impermeable.
2. The air barrier system must be continuous throughout the building enclosure including at transition and penetration details.
3. The air barrier system must be structurally adequate or be supported to resist air pressure forces due to peak wind loads, sustained stack effect, and mechanical equipment such as fans.
4. The air barrier system must be sufficiently rigid or be supported so that displacement under pressure does not compromise its performance or that of other elements of the assembly.
5. The air barrier system should have a service life as long as that of the wall and roof assembly component or alternately be easily accessible for repair or replacement.

Achieving very high airtightness levels is very important in preventing condensation issues in thicker super insulated walls. The Passive House standard calls for a minimum airtightness of 0.6 ACH_{50}, whereas Proskiw and Parekh (2010) suggest a value of 0.5 ACH_{50} for net-zero energy homes. Not many builders in Canada have built to this level of airtightness, with most energy efficient builders more used to the R-2000 program airtightness requirement of 1.5 ACH_{50}. Figure 6 shows the achieved airtightness results of the different EQuilibrium Housing demonstration projects, which fell between Passive House and R-2000 levels for all of the new built projects.

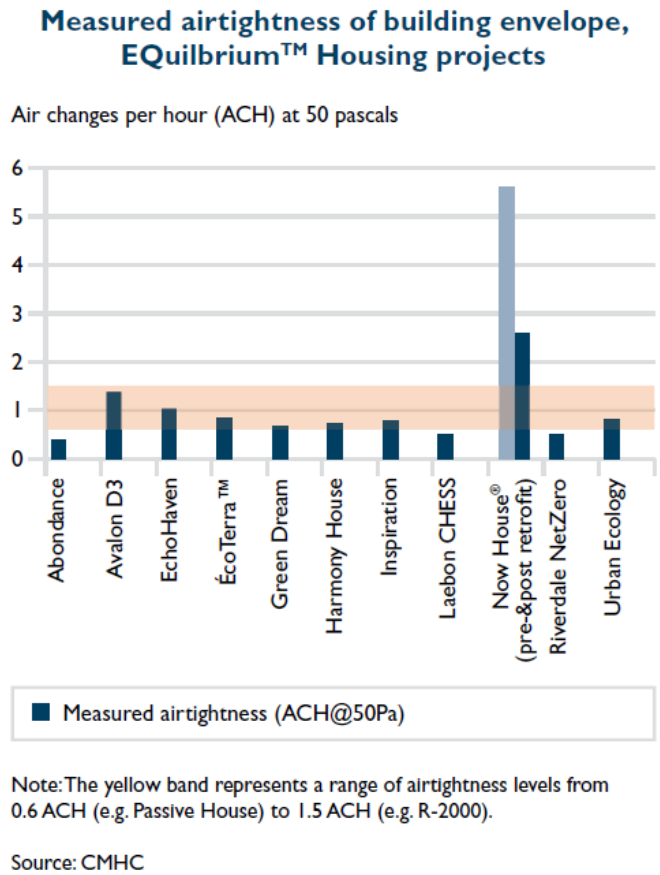

Figure 6: Airtightness levels achieved in EQuilibrium Housing demonstration projects (CMHC, 2014)

In terms of durability, Steven Winter Associates (2015) highlights that caulking, the industry standard for air sealing, has a 20 year lifetime for keeping water out of buildings whereas some tapes are rated to last 100 years but have not yet proven that in the field given that they have not been around that long. Passive House Institute design guidelines call for durable air-barrier materials, and consider masking tape, polyurethane foam and silicone joints to be non-durable.

For MURBs, the Passive House airtightness testing requires that (McClead, et al.):

- If the communal and circulation areas (foyer, corridors and staircases) in a block of flats are all within the thermal envelope (built to Passive House standard) then the block will be tested as a whole building.
- For terraced and semi-detached houses, the partitioning walls between units needs to be airtight, and the units must be tested separately.

In addition to following the 15 critical air sealing details provided in the *2012 IECC Multifamily Air Sealing Guide*, Klocke, et al (2014) suggests the following is critical for multifamily dwelling projects to achieve their airtightness goals:

- Reducing air leakage starts during the design development process; design teams must make decisions that allow for the air leakage requirement to be met.

- Construction teams must understand the design teams' intent while incorporating their experiences from previous successes and failures. Implementation is crucial; subcontractors will not meet their air leakage reduction goals without heightened awareness, support and oversight.
- Until design and construction teams become familiar and comfortable with the tasks required to meet the air leakage requirement, construction schedules will be slowed down and implementation costs will be high.

3.4 HVAC Systems

3.4.1 Mechanical Ventilation

Making buildings more airtight is a relatively inexpensive measure that can generate big energy savings. However, if a building is made airtight, mechanical ventilation must be installed to ensure that there is adequate fresh air inside to maintain good indoor air quality and vent pollutants and moisture generated indoors. Mechanical ventilation provides superior indoor air quality compared to air infiltration through doors, windows and other openings. The use of a heat recovery ventilator (HRV) or energy recovery ventilator (ERV) allows heat from the exhaust air to be recovered by preconditioning the incoming fresh air.

The Passive House Institute developed its own set of quality criteria for Passive House ventilation systems:

- Minimum supply temperature of 16.5ºC at -10ºC
- Minimum rated HRV efficiency of 75%
- Maximum power for fans/control of 0.45 Wh/m^3
- Maximum standby losses of 1 W
- Maximum air leakage in HRV of 3%
- Control with 70%, 100%, 130% of design ventilation rate
- Maximum noise in HRV room of 35 dB, living space 25 dB
- Minimum outdoor air filter of F7, and exhaust air filter of G4 based on European Standards EN 779 and EN 1882. In North America, this would be equivalent to an outdoor filter of MERV 13-14 and an exhaust filter of MERV 7-8 where Minimum Efficiency Reporting Value (MERV) ratings are based on the ASHRAE 52.2 test method.

Passive House also calls for frost protection with normal operation down to -15ºC without switching off the supply air fan. Four HRV defrost strategies dominate the North American Market (Grunau & Carven, 2015):

1. Fan shut off: supply air fan is turned off, and system acts as an exhaust-only system.
2. Damper-based defrost: HRV switches from an outdoor air supply, to an indoor air supply. Quicker defrost than fan shut-off, but it still functions as an exhaust only system.
3. Recirculation defrost: HRV recirculates the return air from the heat exchanger back into the house supply port. Typically occurs for a specific time period (e.g. 10 minutes). This strategy results in a neutral pressure in the home, but without any fresh air intake during the defrost cycle. This is the most common defrost strategy used in HRVs for cold climates.

4. Preheat defrost strategy: Fresh air is heated prior to entering heat exchanger core. Uncommon strategy in North America, with one reason being that HRVs with electrical heaters are not eligible for Energy Star qualification in Canada.

It should be noted that fan shut-off and damper-based strategies result in negative house pressure, which could potentially lead to back-drafting of combustion appliances in very airtight houses. If using these strategies, the designer would need to evaluate the potential for back-drafting.

Of the four defrost mechanisms used in North America, Passive House only allows options for HRV frost protection that rely on some form of preheat, including:

- Air subsoil heat exchanger
- Brine subsoil heat exchanger
- Electric pre-heat
- Hydronic pre-heat

Grunau and Carven (2015) evaluated the applicability of using a Passive House HRV in Alaska compared to other North American units (see Table 8). They found that in some cases, the preheating may be necessary to meet minimum ventilation requirements while preventing the HRV from freezing up. They found that preheating can offer continual fresh air all year long without pressurizing the building; however, it comes with an energy penalty. Ventilation standards could be maintained on an hourly basis depending on the defrost strategy and ventilation rate. In cold weather, the ventilation rate could be increased such that minimum requirements can be achieved when operating intermittently. Although if ventilation rates are kept high all year to account for cycling during defrost, then it would lead to an energy penalty from over-ventilation.

Table 8: Summary of findings from indoor air quality study (Grunau & Craven, 2015)

	House 1 (Tamarak House, Northeast)	House 2 (Birch House, Northwest)	House 3 (Willow House, Southeast)	House 4 (Spruce House, Southwest)
Ventilation Unit	Venmar EKO 1.5 ERV	Zehnder ComfoAir 350 HRV	Venmar EKO 1.5 HRV	Venmar EKO 1.5 HRV
Frost Protection Type	Recirculation	Preheat	Recirculation	Recirculation
Ventilation Settings	Continuous ventilation at minimum fan speed	Continuous ventilation at minimum fan speed	Ventilation at high speed for 20 min/hr, recirculation for 40 min/hr	Continuous ventilation at minimum fan speed
Measured Total Supply Air Flow (delivered to house)	80 CFM	52 CFM	76 CFM	78 CFM
Total portion of the time the unit was in recirculation mode during the monitoring period	27%	0%	67%	41%
Hourly average fresh air supply to the house	**58 CFM**	**52 CFM**	**25 CFM**	**46 CFM**
ASHRAE 62.2 recommended ventilation rate	55 CFM	55 CFM	53 CFM	53 CFM

Most Passive House buildings are designed to be naturally ventilated in the milder months of the year without the HRV (Hopfe & McLead, 2015). This seems to be a deviation from their winter operation

requirements that restrict turning off the HRV at all. If the indoor air quality (IAQ) is so sensitive that supply cannot be interrupted for defrost, relying on occupants to open windows to maintain IAQ may be inadequate. The HPO Heat Recovery Ventilation Guide for Houses and Heat Recovery Ventilation Guide for Multi-Unit Residential Buildings[52] recommend that the HRV is to run continuously. If overheating is a potential issue in the space, a summer bypass for HRVs in Passive Houses is recommended.

It is important that ventilation systems are not only designed correctly, but that they are built according to plan, and commissioned to verify performance. Occupants also need to be educated on the proper use of the ventilation system.

When looking at the indoor air quality of 24 high performance homes in California, Less, et al (2015) found a number of issues that had been reported on ventilation systems, including failed duct attachments to units, air recirculation due to incorrect connections, erratic cycling from low to high speed outside occupant control, clogged outdoor air inlets, ERV turned off by occupants, and poor control strategies and operation (or lack thereof).

For MURBs, designers have the option between individual and centralized ventilation systems. Table 9 outlines some of the advantages and disadvantages of both methods.

Table 9: Comparison of compartmentalized and central ventilation systems (Arena, 2014)

	1	2
	Individual ERV	**Central ERV**
Penetrations	**Façade** - 2 penetrations/apartment - separation exhaust/supply 10' NYC Mech Code - exhaust 2' from apt window, 4' neighbor	**Rooftop only**
Metering	Resident Meter (ERV)	Owner Meter (ERV)
Pros - Arch	- No slab penetrations	- No horizontal ducts
Cons- Arch	- 10' façade separation - Ceiling height issues - Ductwork, Aesthetics	- Floor space reduction - Large slab penetrations - Rated shafts
Pros- MEP	- Continuous, boost flow achievable - PH certified units available	- Continuous, boost flow achievable
Cons - MEP		- Variable flow rates achievable, complexity of controls - Rooftop ERV compliance with PH testing would be beneficial, currently unknown
PH Compliance/Testing	Precedent for unitized ERV to provide flow rates	No precedent for central balanced system w/ HR in US
Operations	- In-unit maintenance, - Filter change 3x/yr	- Rooftop maintenance
First Cost	similar	

[52] https://www.hpo.bc.ca/heat-recovery-ventilation-guide-houses and https://hpo.bc.ca/heat-recovery-ventilation-guide-multi-unit

3.4.2 Heating Systems

Builders of high performance housing that have a highly insulated and airtight building envelope need to design space-heating systems (and cooling if required) to match the substantially reduced energy loads. Not taking into account the reduced load can lead to inefficient operation, premature wear and tear, and a missed opportunity to save money from buying a smaller heating system and associated ducting. Relying on old rules of thumb to design a heating and cooling system for a low-energy housing project runs the risk that it will not be able to perform as desired.

A recent study looked at the actual heating loads of super-insulated homes compared to results from the Air Conditioning Contractors of America's Manual J8 (MJ8) and the Passive House Planning Package software (Arena, 2015). For the two occupied homes, MJ8 calculations resulted in heating loads that are on average 56% higher than actual measured design heating loads; PHPP calculations resulted in loads that were 34% higher than measured on average. Based on these results, the Consortium for Advanced Residential Buildings (CARB) recommends that designers use a method other than MJ8 for calculating design heating loads for super-insulated buildings and that thermal inertial and internal gains be included in sizing calculations. Doing so results in a closer approximation of the building's design load and still provides a slight buffer zone. However, they caution that if the system size is to be closely matched to the load, the project team must verify the performance and that third-party testing and inspections are necessary to ensure the home is constructed as designed.

The heating demand can be reduced to such a degree that options not typically thought of as energy efficient become acceptable because they can be sized small enough to meet the small demand. Proskiw and Parekh (2010) evaluated the cost effectiveness of different heating options to achieve net-zero energy consumption in houses. The selection of the optimum space heating system was very climate dependent. In Maritime locations, electric baseboard heating was the most cost-effective system identified. In Prairie and Northern locations, either electric baseboards or a Ground Source Heat Pump (GSHP), with a minimum rated COP of 4.0 was recommended. Results for Eastern Canadian locations were similar to those of the Prairies except the GSHP was only recommended for larger houses. Note that new cold-climate air-source heat pump technologies that are now emerging on the market that offer relatively high COP at a lower cost than GSHP were not evaluated in (Proskiw and Parekh, 2010). Note that these cold-climate air source heat pumps were used in the CMHC EQuilibrium™ Housing demonstration project, Harmony House[53], for heating the home and its domestic hot water.

Arena (2014) provided some design guidance for heating and cooling systems for high performance high-rise buildings. Energy efficient heating and cooling systems both need to be provided with individual controls to accommodate different comfort levels. A couple of options were discussed:

- Using a central boiler with window air-conditioner: offers lower first cost, and can properly size heating system. However through-wall AC units are typically inefficient, leakage is hard to control and it introduces a thermal bridge through the envelope.
- Individual air handlers: easy to meter occupants' individual energy use. However, systems with the small capacity required for high performance buildings are not readily available.

[53] http://www.cmhc-schl.gc.ca/odpub/pdf/67866.pdf?fr=1463520614574

- Mini-splits: easy to meter occupants' individual energy use. They are the most efficient option for a combined (heating and cooling) system, and part load operation is easily achieved. One disadvantage is their higher relative cost and the need for exterior space for the outside unit.

3.4.3 Cooling Systems

For some buildings in some parts of Canada, good passive low-energy design could eliminate the need of a cooling system. This requires careful consideration of local climate, building envelope performance, window size, placement and properties (especially solar heat gain coefficient [SHGC]) in conjunction with shading strategies. Many passive low-energy designed buildings rely on night flushing, which vary in sophistication from having occupants control windows to having an automated mechanical ventilation system night flush. These can be effective in climates that have a large diurnal temperature swing. However, a warming climate, longer heat waves and temperatures that don't drop in the evening can limit the effectiveness of traditional passive cooling strategies (Hopfe & McLeod 2015). Willand et al, (2015) highlight the need to consider summer thermal comfort and cost of cooling in energy efficient projects, indicating that in the context of a changing climate and rising ambient temperatures, overheating of homes will present a likely health risk in the near future. This can be especially important for vulnerable people that are often housed in social and affordable housing projects. Although high efficiency heat pump systems may not be the most cost effective heating system in super-insulated homes, their ability to provide both heating and cooling can help ensure year round thermal comfort for occupants.

3.4.3.1 Predicting Overheating Through Modelling

There have been indications that Passive Houses certified buildings built in Canada's cold climate could rely too heavily on passive solar gains for space heating, which in turn could lead to overheating issues (Wright & Klingenberg, 2015). Passive House's reliance on a steady state model in PHPP is not that accurate in terms of cooling and dehumidification loads as well as in its ability to predict overheating. Dynamic, multi-zone hourly simulation would be required for this (Hopfe & McCleod, 2015).

Therefore, relying on a steady state modelling program like HOT2000 or PHPP to predict the thermal comfort in MURBs is not recommended. There are a number of dynamic modelling tools that can be used. For those seeking Passive House certification, WUFI Passive[54] is a modelling tool that links a dynamic simulation model with the PHPP calculation, and a hygrothermal analysis component, which promises to solve a number of the limitations of either relying only on PHPP, or having to use multiple tools.

3.4.3.2 Building Envelope Penetrations Associated with Air Conditioners

Steven Winter Associates (2011) completed a study that examined the building thermal performance impact of building envelope penetrations associated with distributed heating, ventilating, and air conditioning (HVAC) equipment such as window air conditioners (ACs), sleeved ACs, and packaged terminal air conditioners and heat pumps (PTACs and PTHPs). They estimated that in New York City

[54] www.wufi.com

alone, air leakage associated with this equipment is generating heating losses estimated to cost around $150 million per year.

Physical testing of sixteen different AC and PTAC units in eleven buildings revealed that the infiltration losses through leaks and poorly-fitting installations are far greater than might be expected, and that the leakage area associated with the average unit in this sample was 38 cm^2 (6 in^2). The primary cause of the leakage was found to be a lack of long-term integrity in the installation kits for window ACs and poor fit and sealing for sleeved units and PTACs. Innovations in operations and maintenance, including improved installation kits, are found to offer the most immediate benefits, while development of suitable split systems to minimize wall penetrations offer the possibility of greater improvements long-term. Note that the 2012 IECC Multifamily Air Sealing Guide (Klocke, et al 2014) says not to use packaged terminal air conditioners and heat pumps for these reasons.

4. Cost-Benefit Studies

Cost is very important when evaluating different affordable housing projects. This includes both first costs, as well as operating and maintenance costs. In addition, affordable housing projects can have different priorities and can rely on different forms of financing, from grants to long term low-interest financing, that a typical private or commercial project would not have access to. This Chapter presents results from the literature review regarding the different elements that relate to cost, and will focus on how this affects affordable housing providers.

4.1 Affordability

The overall capital cost of a project is often the only metric that is reported and examined when looking at the affordability of a home or building. However, simply looking at the capital cost of a project only provides part of the affordability picture and whether the building represents good value for money over the long term. In order to assess the true value of a building, it is important to look at costs over the building's life cycle. Table 10 shows a breakdown of the types of costs associated with a project over its life cycle.

Table 10: Treemap showing breakdown of a Life Cycle Assessment report (Hopfe & McLeod 2015)

Life cycle assessment							
Capital			Operational		End of life		Externalities
Land purchase	Construction	Finance	Energy & utilities	Maintenance, management	Residual value	Disposal	Impact to society & environment

Even though life cycle costing would enable a better comparison of the overall cost-effectiveness of different buildings, there are many unknowns in the analysis that require assumptions that can significantly impact the projected value. Galvin (2014) presents a study that discusses the impact that these critical assumptions have on the projected cost-benefit of a project. This literature search found that most Passive Homes are reported to cost between 5 to 15% more to build than conventional

homes. The limitation of any cost-effectiveness study is the need to set values for unknowable variables such as future fuel price rise, investor's discount rate and financing costs. Galvin argues that an investor can't rely on cost-benefit studies in literature since they rely on these critical default assumptions. He argues that prospective investors and homebuyers should select what value to use for the future price of energy, financing and discount rate, based on their risk tolerance and values, rather than rely on fact-based values assumed to be given correctly by experts.

In addition to the limitations of cost-benefit studies based a set of critical assumptions about future costs and performance, it is also difficult to accurately assess the difference in capital costs of a project between a high performance design compared to conventional construction due to another required series of assumptions. For example, in a recent cost-benefit study of the North Park Passive House project in Victoria (Synergy Sustainability Institute, 2015), they assumed that the conventional construction would use a hydronic radiant heating system instead of the electric radiant panels used in the Passive House, adding $30,000 to the cost of the conventional construction. The use of this more costly base case heating system reduces the incremental cost from $77.3K down to $47.3K.

The study points out that the incremental cost analysis depends on the construction quality of the base case. If the base case is a high-end million dollar condo, the resulting percent increase in capital cost would be lower than upgrading a low-cost social housing project. As part of their analysis, Synergy Sustainability Institute (2015) looked at a 6-plex social housing project built in 2008, and estimated what its upgrade cost would have been to bring in up to the Passive House standard. Although this analysis required a number of assumptions based on previous and current construction costs, they estimated that the upgrade cost would have been around $100K, or 17%. The construction cost of the project had been on the low-end at $1,340/m^2 ($124/ft^2), compared to typical costs of $1,674-$1,858/m^2 ($155-$172/ft^2) estimated for 2008 in Victoria, magnifying its relative cost increase to build to Passive House.

In another project, the Stellar Apartment project in Oregon used base case buildings designed to consume 10% less energy than code and rely on baseboard heaters, no ventilation system and other low-cost measures, achieving a low capital cost of $1,200/m^2 ($111/ft^2). Stellar Apartment[55] then upgraded their base design to Passive House performance levels with a resulting total project cost of $1,566/m^2 ($145/ft^2). While still a reasonable cost, it was 30% more than their initial baseline design cost. They acknowledge that they could have reduced the upgrade costs based on their experience with this pilot project. Their future projects are "*Passive House informed*" where they applied some of their learning experiences to upgrade the performance of their base building, to achieve a performance between their base case and Passive House.

Kondratenko (2014) presented upgrade costs for social housing projects built to Passive House compared to conventional buildings in Antwerp and reported much higher increased costs compared to others found in the literature, at over 40% with upgrade costs of 450 €/m² (1,563 €/m² versus 1,109 €/m²), although the report points to a wide range of results, with some passive house buildings costing much closer to conventional construction. The average building cost of the social housing projects in

[55] Based on discussions with Nora Cronin at St. Vincent De Paul Society, full transcript of interview is found in Appendix A.

the Exemplary Buildings programme in Belgium was reported as 1,516 €/m², with the lowest being 950 €/m², and most expensive projects cost 2,600 €/m².

Other non-energy related aspects such as the design layout, the size of the living room, bedrooms and overall building, the choices of appliances, etc. had a much bigger influence on the total building cost than energy efficiency features. In addition, choices in a building project relating to ecological materials, water recuperation systems, green-roofs, etc., also had a strong influence on the building costs. Therefore all these aspects need to be taken into consideration when evaluating the additional costs that are directly related to the building's energy performance.

Instead of focusing on incremental costs, one can look at the total cost of building passive-low energy housing, and compare it to typical costs of other affordable housing projects. When Housing Nova Scotia built their first Passive House (PHIUS standard) project, it cost around $1,400/m^2 ($130/ft^2). In their second duplex, the winning bid[56] for the contractor was at just over $1,080/m^2 ($100/ft^2). Both projects are within the same price range as their conventional construction projects.

When Pennsylvania adopted an approach in 2014 to provide points to Passive House (PH) projects in the evaluation of affordable housing project proposals, many affordable housing project proposals were submitted that showed little to no extra capital costs compared to other proposed projects (McDonald, 2015). In 2015, they received 85 multi-family project proposals, of which 39 were awarded funding and 7 of those projects (totalling 422 units) were Passive House. Overall, costs of the proposed projects showed negligible difference between PH and non-PH projects:

- 32 PH projects (37.6% of projects) Average cost = $1,825/m^2 ($169/ft^2)
- 53 NON-PH projects Average cost = $1,780/m^2 ($165/ft^2)

A similar experience was also reported in Philadelphia:

- 7 PH projects (30.4% of projects) Average cost = 2,300$/m^2 ($213/ft^2)
- 16 NON-PH projects Average cost = $2,200/m^2 ($204/ft^2)

Another method of looking at the cost effectiveness of capital upgrades is to combine the capital cost increase with energy savings and generate a cost of energy saved (e.g. $/kWh of electricity saved). The cost of saved energy can either be compared to the current or projected utility costs, or as is often done in net-zero energy building projects, the cost can be compared to the cost of producing solar electricity. This can work in evaluating the cost effectiveness of different measures in net-zero energy projects that have sufficient roof area to accommodate a large enough PV system to offset energy consumption. However, in larger multi-family projects with high occupant densities, there would be a maximum roof area available for potential solar PV electricity generation that could be installed to offset consumption, such that energy efficiency measures that may be less cost effective than the PV would still need to be implemented to achieve a net-zero energy target.

A limitation of this method is that it could lead to progressively less energy efficient buildings as the cost of PV continues to decrease (see Fig 7), which could lead to comfort and durability issues, as well as

[56] Based on discussion with Ramzi Kawar at Housing Nova Scotia, full interview transcript is found in Appendix A.

going counter to reducing overall societal energy consumption and related GHG emissions. For example, Jacobson (2013) present a quick comparison of the difference between investing $6,000 on a PV system compared to upgrading to super-efficient windows:

- $6000 investment in 3 kW PV = 4000 kWh/yr of electricity generated resulting in an estimated $440 of annual savings ($0.11/kWh)
- $6000 investment in 7 m^2 (75 ft^2) Optiwin windows = 1350 kWh = $76 of natural gas savings per year ($1.50/therm)

With a limited capital budget, these types of analysis can help assess different options, although it is important to keep in mind additional overall benefits of various measures in terms of occupant comfort, durability, aesthetics, etc.

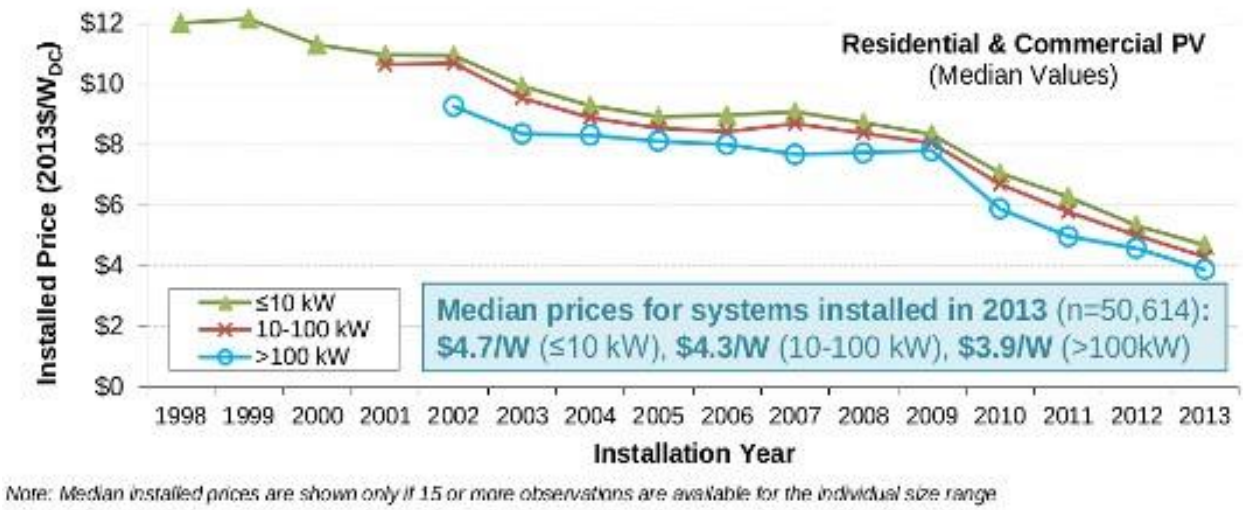

Figure 7: Installed price of photovoltaic systems in the U.S. (Barbose & Darghouth 2015)

CMHC (2014) presented a regional economic analysis of approaching Passive House levels of performance for an archetype 4,000 m^2 (43,200 ft^2), concrete-and-steel, 10 storey MURB. The low-energy solution included:

- Wall assembly: 127 mm to 152 mm (5” to 6”) inches semi-rigid exterior insulation secured with non-conductive clips + interior spray foam insulation (improved the airtightness)
- Balcony connection which reduced thermal conductivity by half
- Roof insulation of RSI-5.6 (R-32) to RSI-9.1 (R-52)
- Baseline spray foam insulation below the concrete slab
- Window-wall ratio of 30 to 35%
- Triple- and quadruple-pane fiberglass windows
- Heat recovery ventilation for corridor ventilation
- Electric baseboard heating

The analysis found that it was cost-effective to build close-to Passive House levels in most regions in Canada by greatly reducing the heating requirements and then switching to a cheaper electric resistance heating system (see Table 11). Only in Edmonton and Toronto where electricity rates were 6.4 and 4.4 times higher than the equivalent gas rates was it found to be not cost-effective. The study found that it was cost-effective when electricity costs were less than roughly four times the respective natural gas prices (in consistent units of measurement). Note that cost-effectiveness was a secondary consideration in putting together strategies for the low energy cases with their main objective was to reduce the heating load to as close as they could practically come to 15 kWh/m² of space heating load.

Table 11: Energy and cost savings of passive solar MURB in different regions of Canada (CMHC, 2014)

Location	Heating load (kWh/m²)		Total energy (kWh/m²)		Economic results*	
	Base	Low-energy	Base	Low-energy	Payback Period	Internal rate of return
Edmonton	99.8	23.8	234.9	141.1	>30 yrs	N/A
Montréal	122.7	22.5	263.4	140.2	6.7 yrs	20.3%
Toronto	109.9	17.9	239.1	127.0	>30 yrs	5.5%
Halifax	100.4	15.7	223.0	120.4	8.2 yrs	17.1%
Kelowna	76.9	14.4	185.3	110.8	10.4 yrs	13.2%
Vancouver	73.7	13.9	176.7	106.4	11.7 yrs	8.1%

*30-year analysis based on 5% discount rate, 2% inflation and 3% energy cost escalation.
Source: EnerSys Analytics Inc.

4.1.1 Cost Savings in Heating and Cooling Equipment due to Reduced Loads

Proponents of very low-energy buildings often talk about tunnelling through the cost barrier. What they mean is that by implementing a super-insulated airtight building envelope, significant capital cost savings can be achieved on heating and cooling equipment. Many Passive House projects rely on adding a small electric heater to the ventilation system as their heating system. In fact, the peak heating load requirement in Passive House of 10 W/m^2 was derived based on finding the maximum amount of heat that could be comfortably distributed through the ventilation system.

However, the peak heating load of 10 W/m^2 is very difficult to achieve in extreme cold temperatures such as those in Scandinavia and Canada, such that space heating cannot generally be met using ventilation air alone. Projects in these locations typically achieve Passive House certification through the reduced heating demand target of 15 kWh/m^2 per year. The cheapest current option for both Scandinavian and North American passive houses is to use supplemental electric resistance heat (Jacobson, 2013). For example, the modelled Vancouver 10-storey high-rise that achieved a 13.9 kWh/m^2 space heating demand, had a peak heating load of 16.2 W/m^2 (CMHC, 2014). Therefore even for a high-rise MURB in a mild coastal climate, which would represent one of the easiest cases to achieve the peak heating load target, it was still over 60% beyond the required 10 W/m^2 for ventilation air space heating.

That is not to say that there are no cost savings associated with the heating system. Going from a base case of a hydronic radiant heating system to an electric radiant heating system resulted in $30,000 of

savings in the North Park Passive House project. Being able to eliminate a furnace and associated ductwork would also result in both maintenance and capital cost savings. However, if the base case building already assumes electric baseboard heating, then little capital cost savings would be expected for the heating system.

4.2 Other Cost Benefits

Schweitzer and Tonn (2003) conducted a literature review to examine non-energy savings cost-benefits of weatherizing low income homes. Savings were divided into three major categories and each with subcategories: ratepayer benefits (payment related benefits, service provision benefits), household benefits (associated with affordable housing, and those related to safety, health and comfort), and societal benefits (environmental, social or economic). The study found that a total lifetime non-energy related benefit of $3,346 (2001 dollars) per household, with societal benefits much larger than the ratepayer and household benefits. Non-energy cost-benefits were estimated to be higher than the net-present value of energy savings value of $3,174. These benefits included:

- Related benefits to ratepayer: avoidance of rate subsidies, lower bad-debt write-off, reduced carrying cost on arrearages, fewer notices and customer calls, fewer shut-offs and reconnections for delinquency. There is a large range of reported cost-benefits in the literature from $38 to $467.
- Ratepayer service provision benefits: fewer emergency gas service calls, transmission and distribution loss reduction, and insurance savings, ranging from $72 to $283.
- Household benefits for affordable housing: water and sewer savings, property value benefits, avoided shut-offs and reconnections, reduced mobility, and reduced transaction costs, ranging from $62 to $8663.

5. Non-Monetary Challenges and Benefits

5.1 Non-Monetary Challenges

One of the main negative attributes of Passive Houses found in a number of literature sources indicated that overheating could be a problem. Larsen, et. al (2012), examined the indoor environmental quality (IEQ) of eight different Passive Houses constructed in Denmark. All houses failed to meet the criteria of having a maximum of 100 hours above 26ºC and 25 hours above 27ºC, with 5 out of 8 houses experiencing excessive temperature problems more than 10% of the time. The problem with irregular heat distribution between rooms underlines the need for analysing a house as a number of temperature zones, with the heat loss and heat loads differing from one zone to the next. Reported CO_2 levels vary from house to house, depending on the amount of ventilation provided. For high-rise buildings, overheating may be more of a concern in upper floors, as observed in Jojasa et al., (2015) and Pretlove and Kade (2016).

Other potential issues encountered by design teams include limited product availability when targeting Passive House certification using Passive House certified products, and lack of qualified design professionals and tradespeople. However, as the popularity of Passive House and other high

performance standards continues to increase, issues with product availability and lack of training will decrease.

5.2 Non-Monetary Benefits

5.2.1 Indoor Environmental Quality

Willand, et al. (2015) conducted a literature review of 73 documents from 28 energy efficiency improvement programs to provide a realist review of impacts of residential energy efficiency interventions on householder health. Three key pathways to health improvements were considered:

1. warmth of home,
2. affordability of fuel, and
3. psycho-social factors.

Some of the highlights of the study findings include:

- Overall, the study found that interventions improved winter warmth and lowered relative humidity in the home, leading to cardiovascular and respiratory health improvements.
- Feeling of home as a safe haven strengthened householder perceived autonomy and enhanced social status, leading to positive mental health. Financial considerations played a secondary role in improved mental health.
- Three studies reported educating householders on appropriate ventilation practices, but it seemed that this was not effective in changing householder habits.

Less, et al. (2015) conducted a research study that used pollutant measurements, home inspections, diagnostic testing and occupant surveys to assess indoor air quality (IAQ) in 24 new or deeply retrofitted homes designed to be high performance green buildings in California. The study found that high performance homes can achieve acceptable and even exceptional IAQ by providing adequate general mechanical ventilation, using low-emitting materials, providing mechanical particle filtration, incorporating well-designed exhaust ventilation for kitchens and bathrooms, and educating occupants to use the kitchen and bath ventilation. Homes without active particle filtration had particle count concentrations approximately double those in homes with enhanced filtration.

Ringer (2014) conducted a study that compared radon levels of about 100 low-energy and passive houses compared to conventional new houses. Radon levels were about one-third lower in the low-energy houses. However, certain features and bad practices can cause high radon in low-energy houses, such as buildings that featured ground-coupled heat exchangers made out of concrete, which had 1.5 to 2 times more radon compared to those made out of plastic. A study of 163 retrofit buildings found that radon levels increased 26% on average after retrofits, with window replacements causing the greatest increase. These findings highlight the need to consider ventilation in conjunction with retrofits that increase airtightness.

5.2.2 Durability

The Passive House Institute provides design guidance that requires designers to consider the lifespan of a building in the range of 100 years. Thinking in this timeframe can help in selecting longer lasting building materials and systems. Super-insulated high performance buildings will not necessarily be

durable by default. Designers need to evaluate different building systems to make sure that they will perform for the specific design in a given location. Performing a hygrothermal analysis of the building envelope will help ensure the long term durability of the envelope system. However, performance does not stop at the modelling and design stage. If the hygrothermal performance of the wall depends on a really tight building envelope, this needs to be achieved in practice and verified through on-site testing. Also, if the airtightness is achieved through the use of an interior air barrier, it may require some homeowner education to ensure that they do not compromise the integrity of the air barrier when doing future renovations.

5.2.3 Resilience

Great strides in energy efficiency are required to address the resiliency of society including energy security, climate change and sustainable consumption (Kelly, 2010). Passive House and other high performance building standards can be part of this global resiliency. At the homeowner level, these low-energy designed buildings also offer resiliency to absorb future increases in energy costs. Super-insulated, low-energy passive designed buildings can also be more resilient in the face of power outages, keeping interior spaces more comfortable for a much longer time than conventional construction. Adding on-site renewables with battery back-ups would further improve resilience and independence, which could offer a number of benefits, such as to help prevent the required relocation of an entire social housing complex during extended power outages.

6. Post-Occupancy Evaluation Studies

Buildings do not always achieve the level of performance that was predicted at their design stage. Reasons for this are numerous and can include:

- Accuracy of the modelling tool.
- Actual weather conditions differ significantly that the average weather conditions used in the model.
- Different actual occupancy than modelled.
- As-built conditions do not match what was modelled due to changes made after the design stage, or assumptions on performance such as air leakage that were not met in practice.
- Occupant behaviour impacting the energy use such as opening windows in winter, setting heating set point temperature higher than modelled, having more base electrical loads than predicted, etc.

This chapter will look at studies that have looked at the post-occupancy performance of high performance housing.

The Bernhardt Passive House had an actual energy use that was 35% higher than predicted by the PHPP model (Synergy Sustainability Institute, 2015). This was made up of 39% higher consumption for electricity and 33% higher consumption for natural gas (see Fig. 8).

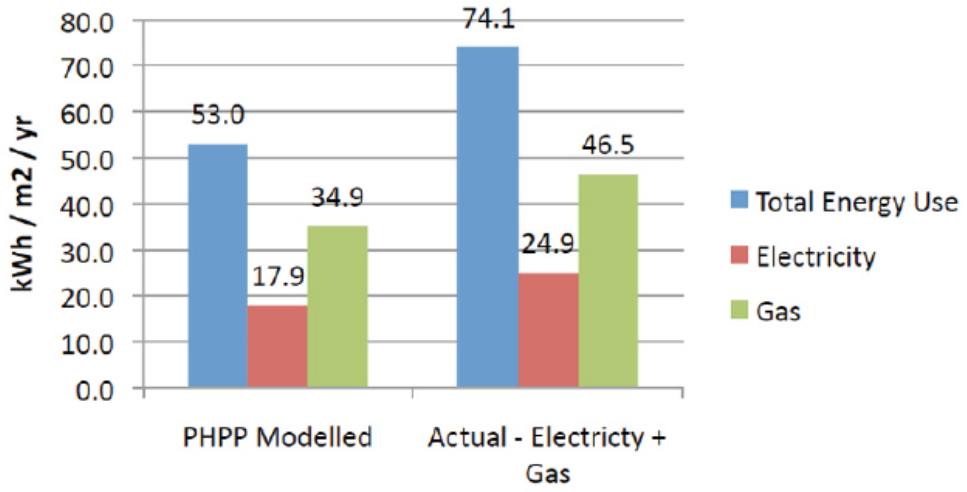

Figure 8: Comparison of actual and modelled energy use at Bernhardt Passive House (Synergy Sustainability Institute, 2015)

Reasons attributed to the higher than modelled energy use in the Bernhardt project involve elements that were not accurately accounted for in the performance model, including:

- Heating set point temperature of 22ºC instead of 20ºC as modelled
- Poorly functioning heating coil
- Two home offices
- Charging of construction equipment batteries at home
- Lower than modelled appliance efficiencies.

In studying the performance of eight different Passive Houses, Larsen et al. (2012) found a great variation in the measured electricity consumption with a factor of three between the highest and lowest levels of consumption. Seeing as the PHPP calculation is based on a series of assumptions (e.g. a room temperature of 20ºC, a standard outdoor climate and a given internal heat load), it is not possible to make a direct comparison of the recorded energy consumption values and the calculated values (Larsen, et. al 2012). Most houses in the study operated were heated to 23ºC, which in this case cost approximately 6-8 kWh/m² a year.

Rojasa et al. (2015) studied measured indoor environmental data collected during long-term monitoring of a social housing project built to the PH standard in Austria. The indoor temperature, CO_2 concentration and relative humidity levels were continuously logged in 18 of the 354 apartments. The volatile organic compound concentrations were also measured before the tenants moved in. Furthermore, a survey using questionnaires and interviews was performed to evaluate the occupants' satisfaction levels. For comparison, six dwellings of a similarly constructed low-energy building, but without mechanical ventilation were also measured within this project. In general, the satisfaction level within the social housing complex built to the PH standard was very high. Average indoor temperature distribution of PH projects during winter showed a surprisingly large difference compared to the low-energy housing and to other documented PH projects in Germany. Overheating during summer seemed

to be an issue especially in the top-floor apartments. This re-emphasizes the limitations of the PHPP modeling and the need for good shading solutions and possibly air conditioning.

Pretlove and Kade (2016) performed a post occupancy evaluation of social housing designed and built to the Code for Sustainable Homes levels 3, 4 and 5 in the U.K.. General findings include:

- Generally comfortable, about half reported some overheating, especially in upper floors.
- Occupants did not understand how HRV's worked.
- Additional technologies resulted in additional complexity, which increased the risk of failure.
- Significant variations between dwellings in terms of energy and water consumption due to occupant behaviour.

The observation that additional technologies and the resulting complexity can present challenges in achieving performance was observed in EQuilibrium Housing demonstration projects where complexity of systems introduced issues in various stages of the projects including: design, modelling, installation, commissioning, documenting, controlling, operating, maintaining, and homeowner training (Green, 2013). It was also an observation made by BC Housing projects that were built to LEED Gold as seen later the interviews in Chapter 8. Galvin (2014) presents a study of 90 low energy dwellings in southern Germany that looked at modelled versus actual consumption for buildings targeting 3 different energy levels:

- Lowest energy buildings Modelled 23.6 kWh/m^2 actual 88 kWh/m^2.
- Medium targets Modelled 37 kWh/m^2 actual 58 kWh/m^2,
- Higher consumption targets Modelled 50 kWh/m^2 actual 51 kWh/m^2.

More complex HVAC systems in the lower energy buildings under-performed, making their actual performance worse than the buildings that targeted higher consumption targets. Note that the issue might not always be with how the technologies are performing, but can potentially also be associated with how these technologies are evaluated in the energy modelling.

Galvin (2014) also presented a study of 109 Passive House dwellings that found a range of heating consumption from 1 to 48 kWh/m^2 with an average of 20.5 kWh/m^2, or 37% higher than targeted. He concludes that the average household is likely to consume about 40% more than modelled for both passive house and conventional houses.

Dean, et al. (2012) found a number of technology related issues when monitoring the performance of a net-zero energy low-income residential housing development in Lafayette, Colorado:

- A couple of issues with solar domestic hot water (SDHW) system (wiring and piping); some issues with ground-source heat pump operation.
- More than expected shading losses of PV system.
- Buildings suffered from overheating, as overhangs that were designed were not installed.
- The automated natural ventilation systems were not designed correctly and did not provide adequate cooling to the duplex units.
- The residents in duplex #2 used 2.5 times the lighting and miscellaneous plug load energy use as duplex #1, emphasizing the importance of occupant education and training programs.

7. Performance Indicators for Sustainable MURBs

Part of the literature search was directed towards examining potential performance indicators that could be used to characterize the sustainability of MURB projects, particularly those applicable to affordable housing. There are a number of sustainability rating systems (e.g. LEED[57] and Green Globes[58]) that assign a number of points for different design attributes to provide an overall sustainability rating. The information in this Chapter aims to identify one or two performance metrics in different areas of sustainability (energy consumption, water usage, indoor environmental quality, environmental impact, material consumption, waste management, affordability) to see if relevant performance indicators can be developed to clearly communicate modelled and actual performance.

Note that elements of sustainability specific to affordable housing MURB projects also exist. For example, Wallbaum et al. (2012) developed a sustainability assessment tool geared towards assessing affordable housing construction technologies and used the following 10 sustainability indicators:

1. initial costs,
2. durability,
3. economies of scale and mass production,
4. time schedule and degree of prefabrication,
5. requirements of production and construction processes,
6. maintenance costs,
7. modularization and flexibility,
8. local value creation,
9. interface to basic services, and,
10. recycling and demolition ability.

The results of the study showed that how sustainability is defined and ranked with various indicators can change the perception of the sustainability of some technologies. For example, concrete was a top-ranking material despite its high carbon emissions, based on its durability and mechanical strength, how it's easily mixed with other construction materials, produced from handcrafted level to industrial scale, and has a long tradition in construction education and research. Most promising technologies were closely connected to local production of materials. No one technology emerged as a solution to sustainable affordable housing, but combining multiple top-ranking technologies can provide an optimized solution.

Depending on how performance metrics are defined and evaluated can impact how useful they are in helping shape and assess projects. Halsall Associates (2013) presented the following seven key characteristics for evaluating the effectiveness of performance metrics:

1. Realistic;
2. Informative;
3. Clear/Transparent;
4. Manageable;

[57] Information about LEED in Canada can be found at: http://www.cagbc.org.
[58] http://www.greenglobes.com/home.asp

5. Relevant;
6. Measureable; and,
7. Impactful.

7.1 Energy Consumption

Energy consumption is the most commonly modelled and measured performance metric for buildings. Given its importance in impacting operating costs and its related emissions and environmental impacts, energy consumption will be an important metric when evaluating the sustainability of a MURB affordable housing project. There are a number of ways that energy use can be presented:

- Energy Use Intensity (EUI) reported in kWh/m^2. This metric is typically more favourable to larger buildings since the total building energy consumption is spread out over a larger overall surface area, making the EUI less than for a smaller building.
- Comparison of predicted or actual energy use to baseline construction E.g. 25% better than a code built building. The percentage cannot be directly measured, and changes as the baseline code performance increases.
- Total energy use. This particular metric benefits smaller buildings as only overall energy consumption is reported and energy consumption typically increases as size increases. To facilitate comparison between buildings, total energy use per unit could be used. This would also benefit builders with smaller units, but it would make it a more relevant comparison.
- Instead of energy use, utility costs can be reported in a similar fashion, using either total energy cost, or a cost per unit area. Given the large difference in cost of natural gas compared to electricity, this metric can be useful for affordable housing providers as an energy metric as it reflects the affordability and can be used to compare buildings that have different mixes of energy sources.
- EnerGuide Rating System (ERS) scale of 0 to 100. The ERS scale is used for small scale residential buildings that fall under part IX of the National Building Code. It is useful at comparing two different designs, but less so in evaluating how a building is actually performing as it is difficult to present actual energy use values in a rating scale. Natural Resources Canada has recently upgraded the EnerGuide for Houses label. Instead of using a rating scale from 0 to 100, the label will provide the predicted total energy consumption of the home, as well as a comparison to the predicted energy use of a typical code built new house (see Figure 9). NRCan provided the following advantages of using the updated EnerGuide for Houses label (Frye, 2013):
    - Straightforward portrayal of energy performance: lower score = less energy use.
    - Performance metric familiar for consumers – similar to appliance and automobile ratings.
    - Reference point provided.
    - Energy improvement and targets can be expressed in straight percentages.
    - Easy comparison of homes - good design is reflected in rating, and size matters.
    - Energy source neutral and better aligned with National Building Code.

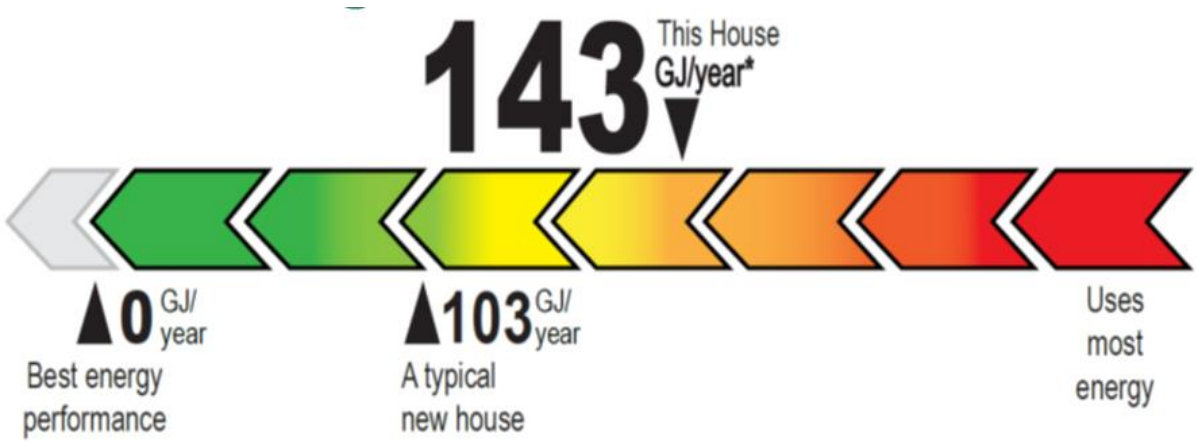

Figure 9: New look for EnerGuide for Houses Rating System (ERS) label

There a many ways to measure and compare the energy performance of different buildings. There are some metrics that would be more applicable to comparing new buildings or alternative building designs, whereas other metrics would be more useful for evaluating how a building is actually performing. Ideally, the metric would make use of data that already exists.

7.2 Water Consumption

Water consumption can be decreased through the use of water efficient fixtures, coupled with using water that is collected, purified, and reused on-site. Similarly to energy consumption, water use could be modelled following Water Use Intensity (WUI) based targets (L/m^2), however, this metric would not be as relevant as for energy. It would be impossible to provide meaningful comparison between buildings as floor area would skew the results, and large buildings would benefit. Water use per occupant would be more appropriate. Alternatively, there could be a comparison of predicted water use to baseline construction, as is done in Green Globes, which awards different amount of points depending the percentage savings achieved.

However, given the limited amount of water use modelling being done, coupled with the large impact that occupant behaviour has on overall water usage, water consumption performance would be best compared using actual consumption numbers. Water consumption could be recorded with the following metrics:

- Total water use per occupant (litres per occupant per year).
- Amount and percent of rainwater used, and,
- Percent greywater reuse.

Alternatively, where water is metered and paid for, the metrics could be evaluated in terms of costs per occupant or cost per dwelling.

7.3 Indoor Environmental Quality

Measurable, quantifiable metrics to predict the indoor environmental quality (IEQ) performance of a building is more difficult to achieve at the design stage. There could be a metric that measures the

percentage of materials that were used that were rated to have low or no-VOC. However, this would be a difficult metric to quantify and compare between buildings. When it comes to developing performance metrics based on actual performance, a couple of possibilities exist:

- Measured CO_2, VOC and radon levels reported in terms of average and peak values.
- Measured VOC and radon levels reported as a percentage of maximum allowable values.
- Overheating reported in number of hours above certain threshold temperatures.
- Measuring and reporting indoor temperature and relative humidity.

The difference in air pressure and forces impacting a MURB on upper floors compared to its lower floors due to stack effect and wind forces can result in a wide range of air leakage issues and also overheating between dwelling units on different floors. IEQ metrics for MURBs would need to account for a potential wide variation in IEQ within the same building.

7.4 Environmental Impacts

When reviewing the literature and conducting interviews with affordable housing providers, metrics related to environmental impacts that would be measurable and relevant to affordable housing were sought out. At the design stage, one can perform a life cycle assessment (LCA) to assess a full range of impacts associated with all cradle-to-grave stages of a building: from extraction of raw materials through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Impacts taken into account typically include (among others) embodied energy, global warming potential, resource use, air pollution, water pollution, and waste. These assessments are a useful way to evaluate the overall impact of a building, and can help designers assess different design strategies to minimise the impact of their project. However, metrics developed based on an LCA are beyond the simplified performance metric being examined for this report. For those interested in LCA, the ATHENA® EcoCalculator for Assemblies[59] provides LCA results for several hundred common building assemblies, and more detailed studies could be done using the ATHENA® Impact Estimator for Buildings.

There are a number of environmental metrics that can be used for evaluating the performance of MURBs. One obvious one that is related to energy use is the CO_2 equivalent emissions. This can be reported in a number of different approaches:

- CO_2e per unit area (similar to EUI, this metric benefits larger buildings).
- CO_2 emissions below a certain baseline target.
- Total CO_2e emissions per capita or per dwelling unit.

Other performance metrics that can be measured at the design stage include:

- % of wood source from certified sustainability harvested forests.
- % of reused material or with recycled content.
- % surface that's permeable or captures rainwater runoff.

[59] http://www.athenasmi.org/our-software-data/overview/

7.5 Material Conservation

A material conservation metric that is measurable and relevant to affordable housing providers is less evident; not that material conservation is not an important goal, but that it is more easily encompassed in overall rating systems like LEED and Green Globe. One metric that is used in LEED is the Waste factor, which represents the percentage of framing material ordered in excess of the estimated material needed for construction. LEED wants projects to aim to keep the waste factor under 10%. It is not clear how easily this could be measured and implemented in the field and if affordable housing providers would relate to the reported value.

Another potential parameter that relates to material conservation would be the expected life of the building and its systems. A building that is designed with systems and components that are made to last, will conserve materials in the long run. This metric could potentially be calculated based on annualized replacement costs reported in Depreciation Reports, which provide anticipated maintenance, repair and replacement costs projected over 30 years. The challenge would be to have consistent methodologies and assumptions used in developing the depreciation reports in order to have a value provide meaningful comparisons between projects.

7.6 Waste Management

Green building projects aim to reduce the waste of energy, water and materials used during construction. During the construction phase, one goal should be to reduce the amount of material going to landfills. This can be measured in terms of the percent of waste materials diverted from landfill. Some jurisdictions are implementing regulations that are trying to increase the waste diversion rate from construction projects. A project should have a waste management plan that details how waste should be collected and sorted on-site to maximize diversion rates. In addition to construction waste, a well-designed building also helps reduce the amount of waste generated by the occupants by providing on-site solutions, such as compost bins, to reduce waste going to landfills. This can also be measured in terms of percent of organics diversion, percent of recycling, or overall waste diversion rates.

7.7 Affordability

When looking at affordability there are a number of direct costs that can be measured and reported:

- Overall construction cost per unit area
- Financing costs
- Utility costs
- Other ongoing operating and maintenance costs
- Annualized repair and replacement costs

The overall affordability of a project would be a combination of these different costs. There are other elements of the project that could impact affordability. For example, LEED and Green Globe give different levels of points depending on the number of basic and lifestyle amenities that are within walking distance from the project. If a building can be placed in a location where occupants don't need to own a vehicle, this can result in large annual savings for them. Aging in place features can help seniors avoid costs associated with moving as they grow older.

8. Industry Interviews: 10 to Ten

To help gather more information on the potential challenges and perceived benefits of passive low-energy approaches to affordable housing, a series of ten 10-question interviews were conducted with affordable housing providers. Interviewees were selected based on having experience with an affordable housing project that implemented energy efficiency design strategies and technologies. Some were selected based on their involvement with projects highlighted in the Case Studies presented in this report, while others were selected based on projects found in CMHC's Affordable Housing Project Profiles database[60] that featured energy efficiency measures. A representative from BC Housing was also included to gain from their experience in building numerous projects to LEED Gold performance as mandated by the province of British Columbia. The list of people interviewed and associated projects is found in Table 12.

[60] www.cmhc-schl.gc.ca/en/inpr/afhoce/afhoce/prpr/

Table 12: List of people interviewed for project

Organisation	Project	Project Details	Contact
BC Housing	Numerous projects, BC	LEED Gold requirement	Bill MacKinnon, Mgr, Energy Management
Housing Nova Scotia	HNS Passive House pilot, Truro, NS	Passive House duplex built in 2015	Ramzi Kawar, Mgr, Building Design
City of Vancouver	SEFC Net Zero, Vancouver, BC	8-storey, 67 units, built in 2010, 68% energy savings	Sean Pander, Mgr Green Buildings Pgm
Centretown Citizens Ottawa Corporation	Beaver Barracks, Ottawa, On	250 unit mid-rise, 2012, GSHP + energy efficiency	Graeme Hussey, Development Mgr
County of Dufferin	40 Lawrence Avenue, Orangeville, ON	30 unit, 3 storey, GSHP + ICF construction	Steven Piercey, Facilities Mgr
Wood Buffalo Housing & Development Corp.	Stony Mountain Plaza, Fort McMurray, AB	125 unit, 4 storey, prefab, GSHP + energy efficiency	Bryan Lutes, President
Ottawa Community Immigrant Services Organisation	140 Den Haag, Ottawa, ON	64 unit, 8 storey, LEED Silver, R-38 walls	Marie-Josée Houle, Executive Director
Stellar Apartments, St. Vincent de Paul Society	Stellar Apartments, Eugene, Oregon	6 unit, 3-storey Passive House	Nora Cronin, Project Manager
Onion Flats Architecture	Belfield Townhomes, Philadelphia, PA	3-unit Passive House townhouse	Tim McDonald, President & CEO
Habitat for Humanity Canada	Various projects in Canada	Requirements vary by project	Director, Safety & Build Programs

Responses from the interviews are summarized in the following section, grouped into five different categories: Drivers; Experiences with Technologies and Design Practices; Post-occupancy Experiences; Benefits and Barriers; and Other Sustainability Performance Metrics. The full interview responses are found in Appendix A.

8.1 Drivers

One of the main drivers of implementing energy efficiency measures that was consistent throughout the interview responses was to the need to meet minimum performance requirements to qualify for affordable housing funding and programs. A few respondents indicated reasons for going beyond the required performance levels to help prepare themselves for future increased performance requirements. Another driver was the desire to lower the utility costs, either for tenants if they pay for them, or for affordable housing providers to keep their operating costs down. A number of respondents opted specifically for passive low-energy design strategies to try to reduce maintenance and replacement costs. A number of respondents had bad experiences with previous energy efficiency projects that relied on more complex HVAC systems to reduce energy use, which resulted in both unrealised energy savings plus unexpectedly high maintenance costs.

One respondent, Onion Flats in Philadelphia, is on a mission to have all affordable housing providers adopt Passive House as a performance standard, and has had significant success. Their reasoning is that all new buildings will need to meet Passive House level of performance by 2030 to meet greenhouse gas reduction commitments. Affordable housing is the ideal group to target to drive this transition to Passive House. Notwithstanding that they would benefit the most from low utility costs; affordable housing projects have well structured financing mechanisms and competitive funding competitions that can make developers and builders innovate and adopt new construction methods at a competitive cost. These same teams of builders, developers and architects can then make use of their experience to build to Passive House levels of performance for market housing.

8.2 Experiences with Technologies and Design Practices

A number of the respondents indicated success in adopting passive low-energy design strategies, as they were typically low cost and easy to maintain. Most adopted low-flow toilets and fixtures, as well as energy efficient appliances and lighting as they have proven to be cost-effective measures. Experience with measures that are successfully implemented typically need to:

- require little to no occupant controls,
- take into account that building operators are often untrained and have high turnover,
- be accommodating for occupants that open windows in winter,
- be simple to design, commission and operate.

Examples of specific technologies that were adopted and have had issues include:

- In-floor radiant heating due to controls, design, and maintenance issues,
- Air-source heat pumps due to poor quality equipment and installation. A number of projects have had the heat pumps decommissioned in favour of back-up natural gas heating.
- Ground-source heat pumps have been less problematic for a number of buildings, although some design issues occurred, and there was a need for additional operator training. Natural gas prices have dropped so much that it would have been more cost-effective to simply use natural gas back-up heaters in one project.

- Many issues occurred with solar domestic hot water heating, from a design not being able to handle peak solar conditions and resulting in overheating, to designs that cannot operate in winter due to insufficient solar resources.

Regardless of the design and technologies used, there was an identified need for tenant education. Specific instances where tenant education was required include:

- How to adjust behaviour to accommodate for the slow response time of ground-source heat pump heating systems.
- How to operate HRV/ERV to control indoor air quality and moisture issues.
- How and when to open windows for passive-cooling through night-time flushing.
- How to use a thermostat to reduce heating consumption. Many tenants tend to crank up the heat when they come into the house because they feel cold in that instant. Room temperatures climb to uncomfortable conditions, then windows are opened, and summer clothing is worn in winter.

One developer that has worked in many affordable housing projects targeting Passive House certification has seen a very similar design emerge regardless of climate, involving:

- Mid-rise multi-family buildings with double-loaded corridors (although single-loaded corridors could improve performance as shown in the Station Pointe Greens project [Hancock,& Scott, 2013]),
- 2x6 construction with exterior insulation,
- High-performance triple-glazed windows, and,
- Airtight building envelopes.

8.3 Post Occupancy Evaluation

Of the buildings that have been built to very-low energy and Passive House levels of performance, tenants seem to love their buildings overall. In general, tenants comment that they have better air quality, are quieter, and have a more consistent indoor temperature than their previous accommodations. Stellar Apartment tenants found the units hot in the summer, but this was mostly addressed by educating them on how and when to open windows to flush the dwellings at night when it is cooler outside. The three units in the Bellfield Townhomes were extensively monitored and found that monthly utilities ranged from $30/month to $90/month depending on the unit. The dwellings were equipped with a washer and dryer, which many low-income friends and families did not have. One unit actually opened their home to friends and families to use the washer and dryer, resulting in over 140 loads per month.

A number of other affordable housing buildings that have targeted various levels of energy performance were monitored. BC Housing monitored four LEED buildings and found that the two lower-technology buildings were close to meeting their performance targets, whereas the buildings with the more complex mechanicals consumed around 20% more energy than expected. Higher than anticipated consumption may be attributed to complex design, poor quality equipment and installation, poor operation and maintenance practices, and occupant behaviour (i.e. open windows). The Stony Plaza building in Fort McMurray underperformed in part due to a controls error; instead of having the back-up

natural gas only top-up heating when back-up heating is called for, it instead turned off the GSHP and switched to the natural gas system when back-up heating was needed. Due to the low-cost of natural gas, this mistake was actually saving them money, as the natural gas prices are at a third of what they had anticipated when doing their pay-back analysis.

8.4 Benefits and Barriers

Interviewees highlighted a number of benefits of building low-energy passive designed buildings including the anticipated reduced utility costs, better indoor air quality, more comfortable and quieter living environments, and lower occupant turnover.

One barrier that was identified was that some affordable housing programs do not factor in energy savings in determining financing amounts. However, a couple of interviewees pointed out that it can also be a "risk" to factor in lower energy and operating costs in determining how much a provider can afford to borrow - if the resulting energy savings do not materialize, or if unexpected maintenance costs arise, then affordable housing providers can be in a difficult financial position. A few respondents had this challenge in previous green building projects, which can make them more reluctant to build energy efficient buildings in the future. Wood Buffalo Housing & Development indicated that there was no issue in financing more costly energy saving measures provided that there was good debt-coverage (i.e. rents paid financing costs).

Some interviewees indicated resistance from contractors to adopt new technologies and practices, especially those that work with the same contractors over the years. Some developers are reluctant to build to Passive House if they need to sole-source specific products, such as windows and HRV's, due to limited market availability of high performance products. Overall, builders and contractors appear less hesitant to try out new technologies and practices than are the board of directors and staff of affordable housing agencies/non-profits, given that the providers are the ones that will have to live with the building after it's constructed.

Other barriers that were identified by interviewees include:

- Lack of awareness and examples of larger MURBs built to Passive House that show lower utilities and Operation and Maintenance (O&M) costs.
- Too many different performance labels, such that industry is not sure what to use. Plus if a project management team is committed to a specific approach, such as LEED for example, it can be difficult to introduce a different approach.
- Lack of overall case studies that report on construction costs and O&M costs as well tenant feedback.
- Some reluctance from Authorities Having Jurisdictions to try new innovative concepts that they are not familiar with.
- The short turn-around time from when projects are awarded funding based on a conceptual design, to when they have to have a completed design (3-months) does not leave enough time to do more detailed design studies and performance modelling or to try new things.

- There a need for case studies showcasing technologies and design strategies in general, and some want these to be from local buildings to make sure approaches work in their local environment before trying it themselves.

8.5 Other Sustainability Performance Metrics

When it comes to measuring the performance of affordable housing projects, most of the metrics are related to costs. The main metrics that were mentioned by respondents were energy use and associated utility costs on a per unit or per unit area basis, as well as overall O&M costs. One interviewee commented that a more useful metric would include annualized replacement costs with the O&M costs to provide a more realistic long term cost to the affordable housing provider. Most mentioned implementing water saving measures, but few actually monitored water use, although some housing providers compare water use per unit and flag high users for further investigation. The County of Dufferin likes to use CO_2e to help determine what buildings to target for energy saving retrofits, a metric that they are required to report on due to the Ontario Green Energy Act.

A few mentioned an interest in factoring in other elements of a life-cycle assessment (LCA) such as embodied energy, but did not actually do such an analysis to rate buildings. There is some interest in having design guides and case studies that include LCA elements that they could factor in when making decisions on their future construction projects.

9. Conclusions

Increasing interest in and requirements for improved energy performance of affordable housing buildings coupled with the anticipation of future energy performance requirements has led to the rapid rise of ultra-low energy housing projects in the past few years. Although reaching very high levels of performance requires the use of some mechanical equipment, such as heat (or energy) recovery ventilators, past experience has led many teams towards the use simple and passive approaches to reducing energy use, namely super-insulated and airtight building envelopes with high performance triple glazed windows. The goal is to achieve low energy consumption coupled with reduced operational complexity and maintenance costs.

The beauty of utilising the building envelope to achieve ultra-low energy performance is that it is not that complicated and it has been shown to work. As they are seeing in Pennsylvania, where many affordable housing Passive House projects are being constructed, the biggest change in construction practice is to add roughly 100 mm (4”) of exterior insulation to standard 2x6 walls. This requires some learning on how to properly seal and flash windows, and how best to attach insulation, siding and other finishes. In addition, some learning needs to be done to build transitions that have limited thermal bridging, and on how to install a continuous air-barrier to achieve an airtight building. Given that it is not such a large leap from where they are today, once the design and construction team has gone through one or two projects, they can learn how to effectively apply these new practices. Other changes such as upgrading to triple glazed windows, adding insulation to the roof and slab, and installing an efficient HRV/ERV for ventilation require less of a leap from where we are today.

Whether builders, contractors, and trades are trained through government sponsored programs using a made in Canada approach, or they rely on external third-party training programs like those offered by various organisations, such as the CaGBC and Passive House, accelerating the adoption of ultra-low energy housing will require some training and education. The City of Vancouver indicated that their approach is to ask for Passive House certification for at least the first couple of buildings for a given team, as it is a great way to educate them on how to build it right. The City also helps support Passive House training sessions to build capacity. Of the 129 certified Passive House consultants and designers in Canada[61] at the time of writing this report, roughly half of them are located in Vancouver.

9.1 Potential Future Research

Potential future research could be carried out to help accelerate the adoption of passive low energy designed buildings in Canada. However, sufficient knowledge and technologies currently exist for builders, developers and affordable housing providers to start building affordable low energy and Passive House projects in Canada, as indicated in the references and resources of this report. Numerous case studies of projects that have already been successfully built demonstrate their feasibility. Thus the current research needs are more geared towards accelerating the adoption of these types of projects, as well as to ensure that any potential issues associated with such a shift in building practices are mitigated.

As some high R-value exterior wall assemblies present an increased risk of condensation and mould growth, a hygrothermal analysis is recommended to ensure the long term performance of the selected assemblies. However, builders that opt for prescriptive requirements may also prefer to have a set of pre-qualified wall assemblies available that would perform well for their building type and climate. If builders choose not to perform a hygrothermal analysis, there could be a list of prescriptive design strategies they need to implement based on their selected wall type. Research would need to be carried out to develop these design requirements (or guidelines) for different potential wall and roof assemblies.

Historically, passive solar design has depended on the use of high solar gain windows oriented mainly towards the south. However, super-insulated buildings with minimal heating demand, combined with internal gains from occupants, lighting, electronics and appliances, already provide a large fraction of the required heating energy, and adding large amounts of solar gain can easily push the space above comfortable temperatures. Overheating was observed in many Passive House post-occupancy evaluation studies, and it may be even more of an issue in MURBs that have higher occupant densities, are more difficult to shade, and can experience disproportionate heating on upper floors. More research could help evaluate the true impact of relationships between regional climates, building orientation and window SHGC when coupled with super-insulation with regards to balancing space heating, cooling and thermal comfort factors. This could be coupled with research that identifies architecturally appealing, cost-effective, ventilation and shading strategies for mid- and high-rise MURBs, especially for east and west façades, for a range of Canadian climates.

[61] www.passivhausplaner.eu/mitgliederdatenbank.php

With the potential for building practices to change substantially in a short time frame, there could be unintended consequences in terms of building durability and/or indoor environmental quality (IEQ). Thus there is an ongoing need to perform commissioning and post-occupancy performance evaluations of passive low-energy MURBs to provide important feedback and to help validate hygrothermal building simulation models.

Social and affordable housing providers would benefit from a cost-benefit study that was adapted to their context. As presented in (Synergy Sustainability Institute, 2015), base-case construction costs for affordable housing projects could be lower than that of a typical house, and as such the relative incremental cost of achieving Passive House or other high-performance targets might thus be higher. On the other hand, Schweitzer and Tonn (2003) highlighted a number of non-energy related cost savings that affordable housing providers achieved through the US weatherization assistance program. A study evaluating these non-energy cost benefits for affordable housing providers building ultra-low energy housing could help show an improved cost-effectiveness of building high performance homes. Another aspect that needs to be evaluated is the differences in financing terms that affordable housing providers can have access to. Affordable4 housing projects can be financed through a combination of grants and long term loans that could change the cost-benefit scenarios. Interviewees also highlighted the need to see case studies of high performance high-rise buildings as there are a limited number of such buildings today.

10. Key Resources

Industry Guides

Benesh I., 2009. REMOTE A Manual. A publication of the Cold Climate Housing Research Centre. http://www.cchrc.org/sites/default/files/docs/REMOTE_Manual.pdf

City of Vancouver, 2009. *Passive Design Toolkit – Large Buildings*, http://vancouver.ca/files/cov/passive-design-large-buildings.pdf

FPInnovations, RDH Building Engineering, 2013. *Guide for Designing Energy-Efficient Building Enclosures for Wood-Frame Multi-Unit Residential Buildings in Marine to Cold Climate Zones in North America*. Available for download at www.fpinnovations.ca

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McLeod R., K. Mead, M. Standen, *Passivhaus primer: Designer's guide A guide for the design team and local authorities*. Passivhaus BRE, http://www.passivhaus.org.uk/

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Rickets L., G. Finch, 2015*. Illustrated Guide to R22+ Effective Walls in Wood-Frame Construction in British Columbia*. BC Homeowner Protection Office, https://hpo.bc.ca/r22-effective-walls-wood-frame-in-BC

U.S. Environmental Protection Agency, 2011. *Energy Efficiency in Affordable Housing- A Guide to Developing and Implementing Greenhouse Gas Reduction Programs*. https://www3.epa.gov/statelocalclimate/documents/pdf/affordable_housing.pdf

Resource Centres

Consortium for Advanced Residential Buildings' (CARB): http://www.carb-swa.com/building-america-overview.htm

Led by Steven Winter Associates, CARB provides Profiles, Research, Details, and Guide for projects associated with the U.S. Building America Program:

- Profiles: Highlights focused on integrated whole-house building approaches from our various residential and multifamily projects.
- Research: In-depth explorations of key building components and systems.
- Details: Specialized construction techniques for distinct building components.
- Guides: How-to guides highlighting mechanical system optimization, advanced framing, air sealing, insulation basics, and more.

Building America Solution Centre: https://basc.pnnl.gov/

The Building America Solution Center provides access to expert information on hundreds of high-performance construction topics, including air sealing and insulation, HVAC components, windows, indoor air quality, and much more.

Whole Building Design Guide: www.wbdg.org/

A program of the National institute of Building Sciences, the website provides a gateway of up-to-date information on design techniques and technologies for high performance buildings.

Green Building Advisor: www.GreenBuildingAdvisor.com

Compilation of resources about designing, building, and remodeling energy-efficient, sustainable, and healthy homes, including construction details, in-depth how-to advice, a green-products database, green business strategies, design tools, etc.

Passive House Organisations and Project Databases

There are a number of databases that provide a listing of various Passive House projects, including:

- PHIUS Database: www.phius.org/phius-certification-for-buildings-and-products/certified-projects-database
- PHI Database: www.passivhausprojekte.de/index.php?lang=en
- EU Passive House database: www.passivehousedatabase.eu/
- Canadian Passive House Institute: www.passivehouse.ca/links/
- Passive House Canada - http://www.passivehousecanada.com/projects/

The following are three Canadian organisations providing support for and encouraging the adoption of Passive House construction in Canada:

- Canadian Passive House Institute (CanPHI): http://www.passivehouse.ca/
- Passive House Canada: http://www.passivehousecanada.com/
- Passive Buildings Canada: http://www.passivebuildings.ca/

A database of Certified Passive House professionals from around the world, including 129 in Canada at the time of writing this report, with roughly half of those residing in Vancouver, BC: http://www.passivhausplaner.eu/mitgliederdatenbank.php

Other international Passive House organisations with some relevance:

- Passive House Institute US (PHIUS), http://www.phius.org/home-page
- North American Passive House Network (NAPHN), a cooperative of North American regional Passive House organizations sharing the common mission of promoting the international Passive House Standard to the general public and building industries of North America: http://naphnetwork.org/
- Passive House Institute: http://passiv.de/en/
- International Passive House Association (IPHA), a global network for Passive House knowledge working to promote the Passive House Standard and connect international stakeholders: http://www.passivehouse-international.org/
- PASSIPEDIA, a database of information on the implementation of Passive House: http://passipedia.org/

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Appendix A: Industry Interview Responses

List of people interviewed for project

Organisation	Project	Project Details	Contact
BC Housing	Numerous projects, British Columbia	LEED Gold requirement	Bill MacKinnon, Mgr, Energy Management
Housing Nova Scotia	HNS Passive House pilot, Truro, NS	Passive House duplex built in 2015	Ramzi Kawar, Mgr, Building Design
City of Vancouver	SEFC Net Zero, Vancouver, BC	8-storey, 67 units, built in 2010, 68% energy savings	Sean Pander, Mrg Green Buildings Pgm
Centretown Citizens Ottawa Corporation	Beaver Barracks, Ottawa, On	250 unit mid-rise, 2012, GSHP + energy efficiency	Graeme Hussey, Development Mgr
County of Dufferin	40 Lawrence Avenue, Orangeville, ON	30 unit, 3 storey, GSHP + ICF construction	Steven Piercey, Facilities Mgr
Wood Buffalo Housing & Development Corp.	Stony Mountain Plaza, Fort McMurray, AB	125 unit, 4 storey, prefab, GSHP + energy efficiency	Bryan Lutes, President
Ottawa Community Immigrant Services Organisation	140 Den Haag, Ottawa, ON	64 unit, 8 storey, LEED Silver, R-38 walls	Marie-Josée Houle, Executive Director
Stellar Apartments, St. Vincent de Paul Society	Stellar Apartments, Eugene, Oregon	6 unit, 3-storey Passive House	Nora Cronin, Project Manager
Onion Flats Architecture	Belfield Townhomes, Philadelphia, PA	3-unit Passive House townhouse	Tim McDonald, President & CEO
Habitat for Humanity Canada	Various projects in Canada	Requirements vary by project	Director, Safety & Build Programs

Interview with Bill MacKinnon, BC Housing

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have at BC Housing?

    Bill MacKinnon B.Sc., CEM, LEED AP (BD+C) Manager, Energy Management, Development and Asset Strategies

    b. What has been your involvement in low-energy affordable MURB projects?

    As the energy manager at BC Housing, I have attended and contributed to design team meetings for multiple projects. Most of these projects were or are targeting LEED NC Gold. I'm also involved in procuring incentive funding on new construction projects. Several of our projects have participated in the BC Hydro New Construction Whole Building Design program for which we have received study and incentive funding. I'm also involved in the creation of standards and policies to help achieve energy and sustainability targets on projects.

2. Have you been involved with other affordable multi-unit residential projects that have targeted or implemented passive low-energy and sustainable housing design principles?
    a. If yes, what was the project(s)? Where? Who? Why? Status? Etc.

    Various part nine projects in the City of Edmonton.

    b. Was the project(s) targeting a specific energy savings or other performance goals? What are they (LEED level, Passive House, etc.)?

    LEED for Homes, Built Green, Energuide 80

    c. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets*?*

    We plan to continue to develop and renovate provincially sponsored social housing to meet high standards of environmental sustainability, including low GHG emissions. Certifications for new construction may include LEED, R2000, and Passive House. We are working on designing our first Passive House project currently.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    The initial main driver was the provincial requirement to reduce greenhouse gas emissions and the requirement to build to LEED Gold. Now affordability, comfort, low maintenance, and air quality are also drivers. Some of the buildings we have designed and constructed have ended up being expensive to maintain so we are now focusing more on passive design.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    - *Passive design strategies such as additional insulation, shading, higher efficiency windows have shown the greatest savings and are easy to maintain.*
    - *Low-flow shower heads, energy efficient appliances and lighting have also been low maintenance and quick payback.*

- *In floor radiant heating has caused a lot of problems, mainly due to the complexity of controlling the systems and unwanted heat bleeding into nearby suites (our suites are very small, usually under 500 ft² [46.5 m²]). Sometimes design of the systems is poorly done and makes them very difficult to repair, adjust, and maintain.*
- *Air source heat pumps have been the most problematic piece of equipment in any of our new construction buildings. In general the problem seems to be rooted in poor quality equipment and installation. These systems are tending to cost tens of thousands of dollars more a year to maintain and in some buildings we had to abandon the air-source heat pumps, which cost hundreds of thousands of dollars to install, in favour of the back-up gas heating.*
- *Ground source heat pumps have been less problematic, but require vigilant operators, experienced maintenance contractors and a good understanding of controls and relationship with the controls company.*
- *Solar hot water systems have been problematic as well especially when coupled with complex systems which include heat recovery ventilation, in floor radiant heating, backup heating, and air conditioning. The main problem with solar hot water has been oversizing of the system, lack of emergency cooling or shading for very hot conditions, and lack of adequate storage for these conditions.*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?
    a. What project(s)?

Four LEED measurement and verification projects in the City of Vancouver.

    b. Did the project(s) achieve their performance targets?

The simplest project which had a small ground source heat pump to preheat domestic hot water and makeup air and heat recovery ventilation but relied mainly on building envelope and windows for energy savings performed within expected parameters. Heating was mainly provided by baseboards and heat recovery ventilation is also installed. The second project connected to a district energy system also performed as expected. The other two projects with ground source heat pumps and in floor radiant heating used over 20% more energy than predicted once calibrated for weather and occupancy, including plug loads. Anecdotally most of the projects on which data has been collected are using more energy than expected, somewhere in the range of 20% but this is difficult to quantify without doing a proper measurement and verification study with calibration.

    c. If no, what barriers came in the way of achieving the savings goal?

The main barriers were overly complex design, poor quality equipment and poor installation, insufficient qualifications of operators, lack of maintenance contracts with qualified maintenance providers and controls contractors, and tenant behaviours such as leaving windows open in the winter.

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

All of our passively designed buildings have fairly good air quality as most have heat recovery ventilation with vents direct to suites. If anything, tenants have sometimes complained of too much airflow and some have overridden fuse boxes or covered vents to reduce flow. All of our tenants also

have opening windows so IAQ hasn't been much of an issue (though this is a big energy loss on some of our projects).

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?
    a. Benefits?

    Better air quality. Lower and more predictable energy bills when systems are installed and maintained correctly.

    b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

    Yes, for the cost target that we are trying to build within developers often try to push us towards "LEED like" or just building code. There is definitely a lack of knowledge in the trades about incorporating controls and installing less common equipment such as air source heat pumps.

    c. Concern for risk, liabilities and costs?

    Now that there have been several large projects that are not meeting energy savings targets and that have higher than normal maintenance costs perception of risk on low-energy buildings has increased. Cost is always an issue as we have a very low per square foot cost target framework approximately $200 per square foot or less depending on the region.

    d. Issues of project financing?

    Net present value of energy savings and potential maintenance savings on more passive projects are not included when calculating how much a society can afford to borrow. BC Housing is currently trying to establish a fund to help overcome this barrier.

    e. What would help overcome these issues?

    Demonstrating larger passively designed projects that are actually operating with low energy and maintenance costs. We are in the process of trying our first Passive House pilot projects to this end.

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

    Actual per square foot costs, energy costs, maintenance costs, and tenant feedback from operational passively designed buildings.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

    Will other societies and developers want to build the next project? If the project you build is not operating properly, word will get around and create barriers for people trying to build sustainable housing. Other indicators that are important are of course air quality, water savings, materials including embodied energy, site impact and location. As we reduce actual site energy use, more and more the embodied energy of materials such as concrete and foam will need to be accounted for properly if we are truly going to achieve GHG reduction targets.

10. Do you have any additional thoughts or comments to contribute to this topic?

    I think CMHC or NRCAN could play a greater role in providing information on actual energy savings of different technologies, maintenance costs, and embodied energy of different materials.

Interview with Ramzi Kawar, Housing Nova Scotia (HNS)

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have at Housing Nova Scotia

    Ramzi Kawar, Manager of Building Design.

    b. What has been your involvement in HNS Passive House Pilot project?

    I initiated the project and served as Building Design Manager.

2. Have you been involved with other affordable multi-unit residential projects that have targeted or implemented passive low-energy and sustainable housing design principles?
    a. If yes, what was the project(s)? Where? Who? Why? Status? Etc.

    Before joining HNS in 2014, I worked as the LEED AP at WHW Architects (now Architecture 49). Last project was a long term care facility where I was the LEED AP. Project achieved LEED Silver and utilized ground source heat pumps, ICF, solar thermal.

    b. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets?

    Currently working on two other Passive House projects with HNS, another duplex and a 2-storey-9-unit senior's housing project. We use the climate adjusted Passive House approach developed in the US Passive House institute (PHIUS).

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    When joining HNS, I wanted them to push the envelope in terms of energy efficiency and had learned about Passive House and wanted to try that approach. HNS spends $30-$35 million a year on utilities so they are interested in saving energy. There is also a desire to build affordable housing for those tenants that pay their own utilities, and Passive House is more affordable to them. It is also a more comfortable and quieter building. I want to spread the word to both HNS employees and to the local construction industry that Passive House can be affordable to build, and perform at a higher level. That is why were are monitoring all of our projects to verify performance.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    Hard to comment on a specific technology as houses are just nearing completion, so we don't have occupant feedback or monitoring data. Although I can say that just from visiting the buildings that you can feel a big difference right away as you walk in, they are nice and warm and quiet. Super-insulation and airtightness makes a difference. Other technologies we use are:

    - *Triple glazed windows*
    - *Electric baseboards (instead of our typical boilers)*
    - *75% efficient HRV*
    - *Heat pumps for hot water*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?

   We don't yet have monitoring data, but have equipped our three Passive House projects to learn from these buildings. It would be great if all similar buildings in the region could be monitored so that we could learn and spread the word about what design strategies work best.

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

   N/A

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?
   a. Benefits?

   A nice warm, quite, comfortable living space that is affordable to live in.

   b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

   One of the reasons we wanted to build these projects is to educate the construction industry, as well as our own staff about what works. We want to dispel the idea that this type of construction is too costly and will take too long to build. It's important to move beyond words and show them real projects. There is resistance from people that don't know the approach and say "it's not how you build". We take the time to educate about the passive house approach.

   When discussing with the local home building association, they have a hard time deciding between all the existing building standards in terms of what is the best approach. Also, HNS has been committed to building to LEED and it takes some effort to change approaches.

   c. Concern for risk, liabilities and costs?

   One of the reasons to do this project was to dispel the notion that it would be too expensive. The first duplex was built at around \$130/ft^2, whereas the second duplex had a contract bid at just over \$100/ft^2. This cost is comparable to our other projects.

   d. Issues of project financing?

   It is difficult to apply and get the different rebates available. They have a lot of hoops and loops that we need to jump through to access funding. It often relies on some building modelling. We would like to do more modelling in-house, but it's expensive to buy the tools and to do the training.

   e. What would help overcome these issues?

   N/A

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

   More case studies, including information on cost and performance. Efficiency Nova Scotia did a series of videos based on the HNS Passive House pilot project that will help with the required education. We need to show that it doesn't have to be more costly and too difficult to build.

   There are few Passive House consultants in the area so we end up using the same ones over and over again, which raises questions. There needs to be support given to train more people so that there is more competition within the industry.

   It would be great if we could get support from CMHC or another organisation to help monitor all of the PH projects built in the area to be able to make use of data to show what works, and to derive valuable lessons learned. It needs to be a coordinated approach.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

   In terms of affordable housing, other than energy it would be metrics related to cost (cost of construction and utilities).

10. Do you have any additional thoughts or comments to contribute to this topic?

    N/A

Interview with Bryan Lutes, Wood Buffalo Housing & Development

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have:

    Bryan Lutes, President of Wood Buffalo Housing & Development Corporation

    What has been your involvement?

    Overseeing the Stony Mountain Plaza project.

2. Have you been involved with other affordable multi-unit residential projects that have targeted or implemented passive low-energy and sustainable housing design principles?
    a. If yes, what was the project(s)? Where? Who? Why? Status? Etc.

    Built 93 townhouses with geothermal and other energy efficiency features.

    b. Was the project(s) targeting a specific energy savings or other performance goals? What are they (LEED level, Passive House, etc.)?

    No specific goal; evaluate each project on a case-by-case basis. Opted against LEED to save costs and build more units.

    c. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets?

    Downturn led to 33% vacancy rate in Fort McMurray, so will not see another project soon. Did try a net-zero project, but had issues with the municipality because they didn't want a 5 storey wood frame, so we needed to redesign and those added costs meant no net-zero.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    Main reason is just trying to be "green", but also we are trying to show there is a cost and value to using energy.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    - *Opted for ground-source heat pump (GSHP) at townhouses, for one reason because it also provides cooling. Used individual units of 2-3 tons vs one larger 50 tons for reasons of availability, but also to reduce consequences of a system failure. We can handle it if the heating system fails in one unit, but it would be a challenge if the failure affected all units at the same time. At Stony Mountain, we used hydronic baseboards for the GSHP so it didn't have the benefit of cooling. In both projects, payback of GSHP was acceptable at 7 to 10 years when gas prices were $5 to $7, but prices dropped to $2 making them no longer cost effective.*
    - *We planned to do GSHP for all heating including peak heating at Stony Mountain, but when drilling, we hit oil sands at 180' so we needed to reduce well sizes to 180', which meant adding gas boilers for backup. We had planned to only use the natural gas to top up heating during peak loads, but instead, installer made it so that it switches completely to gas when backup is needed. It reduced system efficiency. However, due to the lower gas prices, it saves money. It would save*

them money to use the boilers for 100%, but we don't as it's not the right thing to do in terms of greenhouse gas emissions.

- *We had a solar thermal system at Stony Mountain to replenish the geothermal field. We found that it gets too cold in winter with not enough sunshine, that we now have to drain the system, and not use it over the winter. We wouldn't redo it again.*
- *We evaluated Photovoltaics (PV) 5 years ago and again last year. Payback was 100 years before and was down to 30 to 40 years. It's hard to compete against their cheap Natural Gas (NG) and electric rates.*
- *Stony Mountain baseline construction is above where the old R2000 was. LEED was too costly administratively, but they are close to LEED gold. We use triple-glazed low-e argon windows, airtight construction with HRVs in each unit. The GSHP in the townhouses have had issues since construction in 2007. We needed to educate the occupants in the time lag of GSHP to limit the use of the back-up electric heater. Tenants would crank up heat, which would turn on back-up unit. Tenants pay for electricity, so they would complain.*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?
    a. What project(s)?

University of Alberta measured performance at Stony Mountain for two years.

    b. Did the project(s) achieve their performance targets?

No.

    c. If no, what barriers came in the way of achieving the savings goal?

Found the control issue with the NG backup, where the GSHP was disabled when backup heat was called for. Also in general, it is hard to get rental tenants to care about how they operate their houses to limit energy consumption.

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

Nice to have the air conditioning for the GSHP in townhomes.

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?
    a. Benefits?
    b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

We had a few experiences where we were trying to innovate (5-storey wood frame, and a waste water treatment plant heat recovery project) which the municipality did not allow, and it required too much proof of concept such as that it had worked 7+ years in other jurisdictions before accepting. Older staff (engineers) that are set in their ways are harder to encourage to adopt new technologies. It's easier with new hires that possibly learned about these new approaches in school.

Need less silos where everyone adds 10% safety margin, on top of each other's designs, leading to projects that are 50% over designed.

c. Concern for risk, liabilities and costs?
d. Issues of project financing?

No. We found that provided we had good debt-coverage ratios (i.e rent covered mortgages), lenders and CMHC didn't care what was in the project or how much it cost. The extra $1M for GSHP at Stony Mountain wasn't an issue in terms of financing.

e. What would help overcome these issues?

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

   Interested in cradle-to-grave concepts. Maybe information or case studies that show an evaluation of cradle-to-grave impacts of different measures.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

   Don't really have other metrics. We implement measures to reduce water consumption but don't monitor. At $0.09/m^3, they are basically giving away water.

10. Do you have any additional thoughts or comments to contribute to this topic?

    Interested in this project and want copies of the report when done.

Interview with Graeme Hussey, Centre Citizens Ottawa Corporation (CCOC)

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role. Graeme Hussey,

    President, Centretown Affordable Housing Development Corporation (CAHDCO),

    b. What has been your involvement in the Beaver Barracks project?

    Project manager starting at the 2nd phase of the project.

2. Have you been involved with other affordable multi-unit residential project that have targeted or implemented passive low-energy and sustainable housing design principles?
    a. If yes, what was the project(s)? Where? Who? Why? Status? Etc.

    CAHDCO is the development company for CCOC and other Ottawa area non-profits. We are the project manager at the Salus Clementine Passive House MURB, as well as other projects at different levels of LEED certification.

    b. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets?

    Project by project as we are dealing with different non-profits; it depends what their goals are.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    - *Non-profits are typically value driven organisations with a long term focus. Reducing energy costs is important to them. We value pursuing various high performance labelling programs as it adds a 3rd party verification and commissioning element to the project. It can also help with getting philanthropists involved and helping to fund projects.*
    - *By their nature, Affordable Housing projects can be achieve LEED Gold levels with little change in design. High performance is looking at going beyond that level of performance.*

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    - *All strategies have worked to a certain degree. They are on a case by case basis depending on the project. Typically we don't include mechanical cooling systems. However, at Beaver Barracks it was right beside a busy highway, and there was a need to include cooling in order to allow tenants to keep windows closed. In that context, Ground Source Heat Pumps (GSHP) that provide heating and cooling made sense.*
    - *Typically we focus on the building envelope (insulation and airtightness). The non-profits don't always have trained building operators, so focusing on reducing load makes sense.*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?

    We are working on Post-Occupancy evaluations at Beaver Barracks and will have the same at Salus Clementine project, but we don't have the results yet.

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

   Tenants love it. It is more comfortable, there is better sound proofing between units, there is better air quality, and more steady utility bills. The GSHP system went down for 3 days in December and many tenants didn't even notice they had no heating.

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?
   a. Benefits?
   b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

   For Passive House projects, there is a lack of trained architects, engineers, consultants, and trades. It was a learning experience for all of them. Many trades that bid on elements of the project didn't accurately account for all of the details of building to Passive House, so they needed more money or did not include some Passive House elements.

   c. Concern for risk, liabilities and costs?

   Although non-profits are value driven and look at projects over a longer term, they still have limited financing, so project capital costs are important.

   d. Issues of project financing?

   Government funding programs offer little advanced warning as to when RFPs will be launched and what will be the priorities in the programs. Therefore can't really plan ahead. But once they do have a program, and funding is awarded, they want construction started right away, so it doesn't allow much time to include high performance elements in the design stage either.

   e. What would help overcome these issues?

   Ideally, there would be a re-design of housing programs to allow more time for planning and including these elements within construction. Even with the limitations imposed by current programming, affordable housing projects tend to be more innovative. Think how good they could be if the programs were designed to support high performance buildings.

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

   Not-sure if more information is needed for housing providers. More training and support is needed for the external team (consultants, architects, engineers, trades) as affordable housing associations will typically rely on them to design their projects.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

   Combination of energy, cost and water. Water is less important right now, but we see it as becoming an increasing priority in the future. The CCOC is also active in tenant engagement initiatives, and do have some metrics that measure tenant involvement.

10. Do you have any additional thoughts or comments to contribute to this topic?

    N/A

Interview with Steven Piercey, County of Dufferin

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have at Dufferin County Community Support Services.

    Steven D. Piercey FMP, Facilities Manager, Building Department, County of Dufferin

    b. What has been your involvement in the 30 unit, 3 storey project at Lawrence Avenue project?

    Involved from the very beginning from specifications to design, and now with Operations and Maintenance (O&M).

2. Have you been involved with other affordable multi-unit residential projects that have targeted or implemented passive low-energy and sustainable housing design principles?
    a. If yes, what was the project(s)? Where? Who? Why? Status? Etc.

    The County is mandated to include energy efficiency measures in all of their projects. They don't actually model energy consumption in the design stage, or target a specific energy use target.

    b. Was the project(s) targeting a specific energy savings or other performance goals? What are they (LEED level, Passive House, etc.)?

    Mandate; no target.

    c. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets?

    Plan on continuing to target energy efficiency in the same manner, as we have not had issues.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    In the past, affordable housing has traditionally been a high energy user. Dufferin County pays for energy as they don't want to sub-meter, therefore they want to reduce their operating costs.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    We have not really had bad experiences, but did need to make some adjustments.

    Geothermal works better in commercial projects, but has worked in this MURB project. They did need to educate tenants in terms of the lag time, as a GSHP is much slower at heating a space. They added micro-switches on windows to turn off heating system when windows are open. Needed to modify control systems to make sure there was some minimum amount of heat in winter to prevent pipe freezing. They used solar thermal preheat on that project, but haven't pursued it again. They used 356 mm (14") thick ICF on the Lawrence Avenue project, and have used ICF in other projects since. All units have an ERV. Initially didn't have education, but added it as there were some issues (such as high relative humidity is some suites). Works well now, and do education when new tenants

arrive. Use LED lights in all of their projects, both because of energy but also due to lower maintenance (re-lamping every 10 years vs 2 years).

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?

   We never model predicted energy use, so they can't verify if buildings are hitting targets. We do track energy use intensity, and energy efficiency projects are more than 50% more efficient than their other buildings. When evaluating technologies or design strategies, we do more simplified modelling to evaluate the benefits of the specific technology.

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

   Other than some of the early issues that were dealt with by adding tenant education, no real issues. We have building automation systems in all of their buildings that allows them to make sure buildings are operating as they should.

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?

   We usually have a total cost target for a project and we implement various energy efficiency measures while staying within that budget. Although, given that the County keeps their buildings for a long time, they are okay with making investments in energy savings that will save them money over time. Other than trying to keep first costs down, there aren't many barriers.

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

   With the green energy act in Ontario making them look at greenhouse gas (GHG) totals per building, this is a good metric to help evaluate potential project retrofits. Like to read guides and case studies to keep up with industry.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

   GHG/unit, water/unit, operating costs/m^2

10. Do you have any additional thoughts or comments to contribute to this topic?

    Overall, we found that Lawrence Ave was a good, successful project. We, and others in the regions, have used it as a benchmark.

Interview with Marie-Josée Houle, Ottawa Community Immigrant Services Organization (OCISO) Non-Profit Housing

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have?

    Marie-Josée Houle, Executive Director, OCISO Non-Profit Housing Corporation.

    b. What has been your involvement in the 64 unit, 8 storey LEED Silver affordable housing project on Den Haag St in Ottawa?

    Started off as a development consultant on the project and now am the executive director at the organisation.

2. Have you been involved with other affordable multi-unit residential projects that have targeted or implemented passive low-energy and sustainable housing design principles?

    Have consulted on other projects. Not sure on exact targets. City of Ottawa projects need to be LEED silver equivalent, but affordable housing providers don't typically go for certification to avoid costs.

    a. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets?

    OCISO would implement approaches that are proven to work.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    Partly requirements. Also, we operate on a shoe-string budget, and reducing energy costs is great. OCISO operates 200 units, but have the most PV of any affordable housing provider in Canada, which is a source of pride.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    - *Tried a two-pipe system for heating and cooling, which means only one system can be on at a time, and it doesn't work. As a result, we need to turn off the cooling tower in winter and start it up again in the spring, with start-up costs of $3,500/yr, which was not factored into the operating budget. Controls system don't work really well. People are opening their windows when heating is on, causing extra energy costs.*
    - *They like PV with the Ontario micro-fit program. Costs of technologies have really come down.*
    - *I like the idea of green roofs, but feel they are underutilized and not well understood. The green roof at Den Haag was added at the last minute, so lack of planning and integration means you can't reap all the potential benefits. For example, with some planning, we could have put the building's air intake close to the green roof, which would have resulted in a lower temperature of the fresh air going into the building, potentially reducing cooling loads.*
    - *Hesitant to adopt Passive House type projects as I have the notion that they won't work if people open windows. Any HVAC design in an affordable housing project needs to take into account that people will open windows.*
    - *I would do passive solar in terms of orientation if it's available at a given site.*
    - *They feel that geothermal is too risky. They would need to see information from it operating well in projects in the area.*

- *Interested in the prospect of mid-rise wood buildings. Would need to demonstrate good price and durability.*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?

   CMHC is doing a project to create a post-occupancy evaluation (POE) plan at Den Haag. Haven't done monitoring on other projects.

   a. What project(s)?
   b. Did the project(s) achieve their performance targets?
   c. If no, what barriers came in the way of achieving the savings goal?

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?

   a.

   They need to build units that tenants will be happy to live in. They don't want high turnover as it costs money.

   b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

   Builders and developers aren't stuck with the building after construction so they are keener on trying new approaches. It's resistance from the Board of Directors and staff, as they are left with the building.

   c. Concern for risk, liabilities and costs?
   d. Issues of project financing?

   Risky to increase financing based on projected reduction in O&M costs. If issues arise, as in unexpected O&M costs at Den Haag, it is hard to make ends meet.

   e. What would help overcome these issues?

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

   The overall process of proposing new affordable housing projects and building them doesn't leave much time for design. They come up with a concept, and if it gets approved, they have only 3 months to have the design completed. Doesn't leave enough time for working together and trying new things.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

   Not really keeping track of much else. We do monitor water use per dwelling, and if there are anomalies they investigate and educate. We also look at tenant turnover, and overall O&M costs.

10. Do you have any additional thoughts or comments to contribute to this topic?

Interview with Sean Pander, City of Vancouver

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have at Vancouver Affordable Housing Agency?

    Sean Pander, Manager, Green Building Programs, City of Vancouver

    b. What has been your involvement in the South East False Creek Net Zero project?

    Was aware of the project, but didn't work on it directly.

2. Have you been involved with other affordable multi-unit residential projects that have targeted or implemented passive low-energy and sustainable housing design principles?

    Currently looking at what standards and policy to adopt to meet Vancouver's goals requiring zero GHG emissions by 2030 or sooner. The City sees affordable housing as a good goal to target for earlier implementation. The focus they are proposing to council is to focus on building envelopes with a de-emphasising of mechanicals. They get bad experiences with buildings that adopt complex mechanicals. Not only in commissioning to get it to work (which can take years of work tweaking controls), but in keeping it working at the desired performance level. Residential building operators typically do not have the skills and sophistication to keep complicated buildings operating.

    Looking to set limits on GHG emissions and heating energy demand to focus on reducing energy requirements. They are targeting Passive House for rezoning policy, as well as new Vancouver Affordable Housing Agency buildings in the future. They are seeing a number of purpose built rental PH MURBs in permitting, which is telling them if they can make it work for profit, it is a good strategy for affordable housing.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    Meeting City of Vancouver's commitment to have zero emissions for all new buildings by 2030 or sooner.

    For the South East False Creek (SEFC) net-zero project, the main driver was the Olympics, which had the goal to be the greenest Olympics ever. Whole SEFC development was to showcase leadership.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    Don't have specific experience to talk about, but heard of a number of anecdotal issues about difficulties with buildings that have implemented complicated mechanical systems to achieve energy savings goals. Whether it be from taking a long time to commission buildings to get them operating as designed, or in high O&M costs, or in building operators not having the skills required to operate more complicated buildings.

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?
    a. What project(s)?
    b. Did the project(s) achieve their performance targets?
    c. If no, what barriers came in the way of achieving the savings goal?

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

   N/A

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?

   a. Benefits?

   Expected reduction in maintenance and call-outs costs is a key benefit.

   b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

   Leadership in industry with a number of new Passive House market rental projects is helping drive the push to adopt Passive House for affordable housing, as if industry can do it for profit, it should also be doable for affordable housing.

   c. Concern for risk, liabilities and costs?

   One of the barriers they see is that of cost, although they see it as manageable in the buildings up to 6-stories (wood construction). Lack of availability in high performance HRVs and windows is a concern to builders, as they don't like having to depend on a single supplier. Internal studies with developers is showing that the incremental costs would be in the range of \$75-\$150/m^2 (\$7-\$14/ft^2). Cost recovery doesn't occur by energy savings alone, but they believe that reduced maintenance and repair costs would tip the scale in favour of Passive House.

   d. Issues of project financing?

   Would like BC government to consider both up front cost and operating cost in deciding financing decisions.

   e. What would help overcome these issues?

   Working with BC Housing to see if it can accept Passive House instead of or as an alternative to LEED Gold.

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

   One of the barriers they see for the adoption of Passive House in high-rise concrete and steel is the lack of examples out there. A couple of demonstration projects showcasing how it works would be good. Heard of a tall high-rise MURB Passive House project planned for Toronto.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

10. Do you have any additional thoughts or comments to contribute to this topic?

    It is important to not just adopt passive design strategies without going through the Passive House certification process. Going through the certification is important (at least for the first few projects) to help really learn what it takes to build a good quality Passive House. Design teams need to fully commit to the Passive House approach of addressing thermal bridges, and providing high quality ventilation systems. With lower quality ventilation systems, occupants tend to turn them off, which wouldn't be good in a Passive House. Also need to ensure airtightness, which you get with certification (important for hygrothermal performance).

Interview with Timothy McDonald, Onion Flats

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have?

    Timothy McDonald, President and CEO of Onion Flats, Lead Architect and Construction Manager.

    b. What has been your involvement in Belfield Homes?

    Built Bellfield Homes triplex in 2012 and found that we could build an affordable ultra-low energy home with a similar budget than other affordable housing projects.

2. Have you been involved with other affordable multi-unit residential project that have targeted or implemented passive low-energy and sustainable housing design principles?

    Didn't know why we weren't seeing more Passive House affordable housing projects. Got together with 25 other stakeholders and went to the Pennsylvania Financing Agency and talked about building all affordable housing projects as net-zero capable by 2030 with Passive House as a tool. Pennsylvania's Tax Credit program to fund affordable housing projects is very competitive, with only 25-30% of proposed projects getting selected. In 2014, added 10 (voluntary) points to their 120 point evaluation grid, which is not negligible. First month, developers complained like crazy that it would be too expensive, but were told it was voluntary so if they couldn't do it, they didn't have to. 38% of projects ended up being Passive House in first year, and over 50% this year, and they believe 100% will be there within 5 years. I'm personally working on 1 of the 8 selected projects, and help with a few others, and can say that costs are remaining as what they were in the proposals, which averaged around 2% more for PH than other projects. Since June 2015, I have been in discussions with 36 other states in the Northern US and there is great interest in replicating this. 9-10 have already adopted something similar. Important element is that it doesn't start as a pilot projects. Pilot projects typically experience higher cost premiums.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    All construction will need to be ultra-high performing low energy buildings within about 10 years. The affordable housing sector is a good market to drive that transformation. Their structured financing and competitive funding structure make it ideal to engage the industry to build Passive Houses at competitive pricing. For wide scale adoption, it is important that we don't rely on demonstrations and pilots. Builders and developers are happy to participate in pilots, but they also will charge a premium. If you include Passive House in the proposal evaluation structure, then builders will compete to win their bid based on competitive pricing. It will help transform the industry since the team of builders, engineers and architects working on the affordable housing projects, also do market housing. After they have built a few PH affordable housing projects, building to Passive House in the market place will give them an edge over their competitors.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    I've been involved in projects in Alaska, Minnesota, Philadelphia, and consulted on various others. All the design solutions are very similar from location to location for multifamily housing:

- *Passive House makes more sense for multi-family buildings as opposed to single family housing.*
- *Wood construction with double-loaded corridors.*
- *2x6 construction with various types of insulation to fill stud cavity and different types of exterior insulation.*
- *Most new projects are using centralized HRV systems. They have lower maintenance costs and fewer penetrations to deal with, although they require more ductwork. Most projects use separate duct work for ventilation. Individual suite HRVs are being used in some projects and also work well. There are pros/cons of both.*
- *Majority of new projects use Variable Refrigerant Flow (VRF) cold-climate air source heat pumps for heating and cooling.*
- *The key is high performance triple glazed windows coupled with airtightness.*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?

   We did extensive monitoring in the Belfield townhomes project. There is a wide range in performance between tenants. The biggest takeaway has been the need to educate and train homeowners on how to benefit from living in these homes. Two of the three townhomes have utilities that are $30/month and the third is $90/month. Many low-income families in Philadelphia don't have washers and dryers. One of the families let friends and families use their laundry facilities - they were doing 140 loads per month. One family had plug-in strip heaters and used those in the bedrooms instead of the air–source heat pump (ASHP) since they had them and were used to them. While monitoring, we can see that as tenants come in from the cold in the winter, they crank up the heat to 90ºF because they think they'll heat up faster. They then get too hot and start opening windows, and put on shorts and t-shirts in the homes in the winter. To get better tenant engagement in reducing their energy use, it is best if they pay their utilities.

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

   Overall tenants love their Passive Houses.

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?
   a. Benefits?

   We have found that the Passive House units are very quiet, and have very good indoor air quality (IAQ).

   b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?
   c. Concern for risk, liabilities and costs?
   d. Issues of project financing?
   e. What would help overcome these issues?

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?
9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

   Used to build LEED Platinum, but stopped because certification process was too much trouble. We don't monitor other elements, but do implement other sustainable design features such as low-flow toilets and fixtures.

10. Do you have any additional thoughts or comments to contribute to this topic?

    Key message is that there is no benefit from moving slowly. It's a proven strategy that doesn't need pilots and demonstrations. In the first year of adding 10 points for Passive House projects to their rating of affordable housing project proposals they had 35% PH proposals, in second year over 50% and they project to have 100% PH within five years. All this in a market that had little knowledge of Passive House. Builders and developers complained in the first month of the new rating scheme, complaining it would drive up costs for nothing, but since it wasn't mandatory they couldn't complain too much. They can either adapt and be competitive, or don't and lose out on projects.

Interview with Nora Cronin, St. Vincent de Paul Society

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a. Can I confirm your name, and what role you have?

    Nora Cronin, Project Manager.

    b. What has been your involvement in Stellar Apartments?
2. Have you been involved with other affordable multi-unit residential project that have targeted or implemented passive low-energy and sustainable housing design principles?
    a. If yes, what was the project(s)?

    State of Oregon requires affordable housing projects to have a green building label. We typically chose Earth Advantages as it's the easiest and most cost effective program. LEED is too expensive to simply get certified. We have done two mid-rise buildings with higher efficiency including ground source heat pumps.

    b. Was the project(s) targeting a specific energy savings or other performance goals? What are they (LEED level, Passive House, etc.)?
    c. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets?

    Wouldn't do Passive House for that same style of building, but would consider it for a mid-rise, as it would be more cost-effective. We did learn a lot from the Stellar Apartments project and are implementing some of the design strategies we learned in PH to other projects, what we call "Passive House informed".

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    The State requirement for some certification is a driver. With Earth Advantage, we have to build 10% over code minimum, and the Code keeps increasing, so we need to continually improve our construction methods. We wanted to try an exterior insulation project before we were forced to do so by code. Also, we want to ensure that our tenants have affordable housing. Our tenants typically pay for utilities, and building energy efficient homes is the only way for us to ensure these units remain affordable into the future.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

    - *In our Passive House informed project, we have added 1" of exterior insulation to reduce thermal bridging and are adopting some of the details.*
    - *HVAC controls are difficult for tenants to understand. Want little to no controls required for buildings to perform.*
    - *Wanted to use 2 central ERV systems, but couldn't find any documentation out there that would guarantee no cross-contamination where smells and air from one unit would transfer to another. So we opted for individual units. We have them in two mechanical rooms, and don't provide any controls for occupants. We let them know that if they feel there isn't enough air, to let us know*

so that we can adjust the airflow. We also adjust airflow when new occupants arrive if there is a large family living in the unit.

- *They have had a lot of issues with super-sophisticated systems.*
- *They had the ceiling drywall as the air barrier, which caused a number of issues. Couldn't have any penetrations, so needed to mount lights, smoke alarms, etc., high on the walls, which isn't great.*
- *The added exterior insulation caused some issues with how doors were swinging outside which required modifications. Doing it over, we would install them to swing indoors.*
- *We didn't go through pre-certification to see if we'd reach Passive House, which costs money, but essentially evaluates your plans in the design stage. We submitted our documents after the fact, and needed to do some modifications, which is more difficult and costly. There was also this uncertainty hanging over the project, over whether we would achieve Passive House or not, which wasn't good. We would go for pre-certification if doing it over again.*
- *There is a push in industry to install ductless heat pumps, but they are reluctant to adopt them, as they fear higher operating and maintenance costs.*
- *Our design called for 5" of exterior insulation, but we couldn't find anything on how we could support our Hardy Siding with that level of insulation. The most we could find was 4", which is what we ended up going with.*
- *Some concern over adopting a really airtight building envelope in the case of an ERV failure, potentially resulting in increased CO_2 levels. Added a CO2 alarm to alleviate those fears.*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?
    a. What project(s)?

Extensive monitoring for 2 years of the Stellar Apartments Passive House vs an Earth Advantage building. We also started (Nov. 2015) monitoring a new "Passive House informed" building (Baskin Village) that is between the two standards. Self-published a book "<u>The Stellar Apartments: The story and data behind the nation's first affordable multi-family passive house</u>" by Professor Kwok at the University in Oregon describes the results of the monitoring.

    b. Did the project(s) achieve their performance targets?

Not quite as high as 90% reduction in space heating as PH claims. Other energy use beyond space heating was similar between buildings. In the shoulder seasons, PH consumed around 70% less energy, and in the colder months, the savings were in the range of 50-55%.

    c. If no, what barriers came in the way of achieving the savings goal?

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

- *Tennant feedback has been mostly good. They like that it is much quieter. Biggest difference is the consistent temperature across the unit; no cold spots by windows.*
- *We didn't include washer/dryer hookups to limit the building envelope penetrations, which tenants don't like. We did have a hookup for condensing dryer, but they are more expensive to buy.*

- *Since we opted for a crank style window, tenants can't add a window air-conditioner, like they can in our other buildings. Some have complained. We have to do tenant education about how to perform night flushing (i.e. when to open and close windows in the summer).*
- *Monitoring revealed Earth Advantage homes kept at roughly 2ºC higher than the Passive House units. We surmise that this is because there is higher mean radiant temperature in PH, and less draughts, which allows people to be more comfortable at lower temperatures.*
- *Some in project team were worried about high relative humidity in units because of airtightness and lower ventilation, but these issues didn't materialize.*

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?
    a. Benefits?

    One of the reasons we wanted to try Passive House was to try to achieve high levels of performance without relying on complicated HVAC systems. We want to keep our Operation and Maintenance (O&M) costs low to keep it affordable.

    b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

    We have been working with the same contractor now for a while and he had some concerns, especially with changing to external insulation. We had to do a lot of research and discussion with our contractor to get him on board. He was worried that extra insulation would rot the walls, and he didn't know how to attach siding.

    c. Concern for risk, liabilities and costs?

    We discussed with the contractor and assured him that we trusted our constants and architects and that if it didn't work, he wouldn't be held responsible for this pilot project.

    d. Issues of project financing?

    There was some concern from investors and financing of potential moisture issues with airtightness and lower ventilation rates. But it was less than I expected. Being that it was just one building, they were less concerned.

    e. What would help overcome these issues?

    We relied on a report from Walsh Construction that discussed the different elements of using exterior insulation which was a useful too. Guidance materials on airtightness and flashing details around windows and doors would be good. In a recent project, we wanted to do 2" exterior insulation, but the details around windows and doors were too complicated to change, so we opted for only 1", which was easier to accommodate.

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

    Guides to specific design features that need to change beyond typical construction. Preferably the guides would show a few different approaches, so that we can adapt what were most comfortable/familiar with.

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

   Being an affordable housing provider, most of our indicators would be financial. We want low operating costs per unit, low overall O&M, low annualized replacement costs (future replacement costs in budget). They want to have realistic costs over the long term. They use 60+ years as their baseline, but essentially want buildings to last indefinitely. This impacts other elements of the material selection and finishing, such as using wood cabinets instead of melamine, which don't last as long.

10. Do you have any additional thoughts or comments to contribute to this topic?

    Would be more cost effective to approach Passive House in a larger mid-rise building. Given our very low baseline cost of $1,195/m^2 ($111/ft^2) for the Earth Advantage building, which has no ventilation system, inexpensive windows and baseboard heating, there is a substantial cost increase to go to Passive House, which cost $1,560/m^2 ($145/ft^2). It is still a reasonable cost, but 30% more than our baseline cost. Costs could have been less, as we only decided to do Passive House after the project was already designed. Even with these high costs, it was a great learning experience for the whole team that will end up improving the performance of our future buildings.

Interview with Terry Petkau, Habitat for Humanity:

1. Before I get into project specifics, I'd like to learn a bit more about who I'm talking with:
    a.

    Terry Petkau, Director, Safety & Build Programs, Affiliate Support & Governance, Habitat for Humanity Canada.

    b. What has been your involvement in low energy housing projects?

    I am not directly involved with specific projects. I am the driving force looking at making Habitat for Humanity buildings more energy efficient through developing incentives for builder affiliates and to build out a program that sponsors can get behind.

2. Have you been involved with affordable multi-unit residential project that have targeted or implemented passive low-energy and sustainable housing design principles?
    a. If yes, what was the project(s)? Where? Who? Why? Status? Etc.

    Habitat for Humanity Canada builds roughly 200-250 housing units a year. Many of these are multi-family buildings with a number of townhouses and three-storey stacked units. We build projects across Canada. Most of our projects implement some passive design strategies, specifically an energy efficient building envelope. We have a partnership with Dow where they provide Cladmate exterior insulation for our buildings. We typically end up with R-26 walls, with R-22 batts and 1-1.5" cladmate. We also use other walls systems such as ICF and SIPS.

    b. Was the project(s) targeting a specific energy savings or other performance goals? What are they (LEED level, Passive House, etc.)?

    To date we have not been aiming for one specific program. We have had buildings target Energy Star, Built Green, R2000 and LEED. Typically our builder affiliates select programs that they are comfortable with in their region, and the popularity of building labels varies from one province to the next.

    c. In future projects, do you intend to include passive design strategies to achieve Passive House, LEED, net-zero energy or other ambitious energy targets?

    For future projects, we are looking to encourage our affiliates to build to Passive House or net-Zero ready.

3. What are the main reasons or drivers for you to pursue low-energy, higher performance affordable housing?

    The first driver is energy savings for the home owners. By reducing their utility bills, they have more funds to help pay down the mortgage faster. To keep the mortgage payments down to 25% of income, it can require long amortization periods of up to 50 years. Energy savings can help lower this. The second reason is to provide healthier living environments. The third reason would be to reduce the impact that the housing has on the environment.

4. Tell me about any experience you have with specific design strategies or technologies that were implemented in a low-energy affordable housing project, both good where you would use it in future projects, or if you had specific issues including overheating, difficulty in operating or maintaining new technologies, unachieved savings, etc?

- *We focus on the building envelope for all of our projects, including insulation, air sealing and durability. It provides our best investment opportunity. Especially since we often get products donated and have volunteers help with construction.*
- *We have a partnership with All Weather Windows which provides good quality windows. Although I would say that there would be room for improvement in the air sealing around the window. There is limited knowledge and skills on how to air seal the window properly.*
- *Different walls systems, with 38 × 140 mm (2 × 6 in.) walls with R22 batts and exterior Cladmate insulation being the most common.*
- *We could do a better job with continuity of insulation from the slab to the attic. Also, party-walls in our townhouse units are challenging to get them being more airtight.*
- *Raised heel trusses are now standard in all our projects to help add more insulation in the attics.*

5. Have you been involved with projects that have verified actual measured energy performance and compared it to their predicted energy savings goals?

   Typically not.

   a. What project(s)?

   There are two 3 unit projects being monitored in the Yukon through a project with Yukon College. I haven't looked at the results.

   b. Did the project(s) achieve their performance targets?

   N/A

   c. If no, what barriers came in the way of achieving the savings goal?

   N/A

6. What feedback have you received or do you know of (positive/negative) from tenants living in housing that had implemented passive design strategies in regards to energy performance and indoor environmental quality?

   We have had some informal tenant feedback, but have not looked at this in detail. It would be interesting to get tenant feedback, and I will look to see if we can get some from a LEED project in Winnipeg.

7. What are the benefits and challenges for your organization to building affordable housing projects that are ultra-low energy or have other sustainable features such as improved IEQ, water conservation etc.?

   a. Benefits?

   See drivers.

   b. Is there resistance to or lack of knowledge of new ideas and construction techniques from builders and developers?

   Resistance comes more from a matter of financing. If there's money associated with energy savings measures, builders are more receptive.

   c. Concern for risk, liabilities and costs?

   Not so much. There are some misconceptions about making buildings too airtight, etc.

d. Issues of project financing?

Typically, this is the major challenge. If there is funding for energy efficiency, it is much easier to implement. The homebuilders affiliated with Habitat for Humanity are independent. The only real influence is when there is money associated with a request.

e. What would help overcome these issues?

Getting recognition for energy efficient projects provides good Public Relations for Habitat for Humanity and the builders. It also develops an expectation of the level of performance that will be achieved in future projects.

8. What tools or information would be useful in your work to develop affordable housing projects that implement passive design strategies to meet ultra-low energy consumption targets and other beneficial environmental features?

- *Generic design features for passive house details would be good.*
- *Opportunities for our builders to participate in workshops and training initiatives to teach building science would be helpful. There is interest but not too many opportunities.*
- *Developing partnerships with product manufactures and other corporations helps. If we could partner with a firm with expertise to help drive a commitment to build all our houses to Passive House or net-zero ready, it would help provide the some of the driving force required.*

9. Beyond energy, what are the main performance indicators that should describe or quantify the sustainability of an affordable multi-unit residential project?

We haven't looked at this in detail. Projects have looked at other indicators but these were typically those associated with the builder performance program the builders were aiming for.

10. Do you have any additional thoughts or comments to contribute to this topic?

Again I would like to stress the importance of partnerships. Our partnerships have helped achieve more energy efficient buildings to date, and new partnerships would help us strive for even more energy efficiency into the future.

Appendix B: Annotated Bibliography

Overview

The following Annotated Bibliography provides the results of a literature review related to passive low-energy affordable housing research, performance, financial data and case studies, with particular attention to multi-unit residential buildings (MURBs). This annotated bibliography serves as the basis of the overall Final Report summarizing the existing literature on the topic.

Note that the Annotated Bibliography is limited to summarizing research reports, guides, articles, and books on the topic. Relevant websites, news articles and other resources are not presented herein. Information from these other resources are included in the overall Final Report.

Each resource was categorized according to its main topic area. Some resources cover a wide range of topics but needed to be placed in a given category. Relevant information from these multi-topic area resources will be distributed throughout the different topic areas in the Final Report.

Resources are listed in alphabetical order of the lead author in each category.

Ranking of Resources

To quickly assess the relevance of the different resources, a ranking system was devised. The following table is presented for each resource, highlighting its key attributes:

AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

<u>Legend of Key Reference Attributes:</u>

AS: Affordable or Social Housing project
PH/LE: Passive House or Low Energy project (planned or certified)
H2O: Water conservation and efficiency measures
IEQ: Indoor Environmental Quality features
SUST: Sustainable Housing features in additional to energy, water and IEQ (e.g. RRR, green infrastructure, transit orientated, renewable energy, etc.)
OCC: Occupant participation or feedback
MURB: Multi-Unit Residential Building
$$: Cost information for project
CA: Canadian reference or example
INT: International reference or example

Resource Titles by Order of Appearance

1. Challenges of responding to sustainability with implications for affordable housing.
2. A comprehensive review on passive design approaches in green building rating tools.
3. Adoption of innovative energy systems in social housing: Lessons from eight large-scale renovation projects in The Netherlands
4. Passive House Certification in Scandinavia

5. NET ZERO ENERGY BUILDINGS Passive House+ Renewables
6. Passivhaus Primer: Airtightness Guide – Airtightness and air pressure testing in accordance with the Passivhaus standard
7. Passivhaus primer: Designer's guide A guide for the design team and local authorities
8. Climate-Specific Passive Building Standards
9. Station Pointe Greens – The Journey to Net Zero Affordable Housing
10. Retrofits for the Future: Affordable Housing and Energy Efficiency Programs in Canada
11. Affordable Multifamily Zero Energy New Homes
12. Design and Evaluation of a Net Zero Energy Low-Income Residential Housing Development in Lafayette Colorado
13. LIVING BUILDING CHALLENGE Framework for Affordable Housing – A Pathway to Overcome Social, Regulatory and Financial Barriers to Achieving Living Building Challenge Certification in Affordable Housing
14. Passive Design Toolkit – Large Buildings
15. Energy Simulations of Strategies to Achieve Low-Energy, Multi-unit Residential Building Designs in Different Regions of Canada
16. Guide for Designing Energy-Efficient Building Enclosures for Wood-Frame Multi-Unit Residential Buildings in Marine to Cold Climate Zones in North America
17. The Passivhaus Designer's Manual – A technical guide to low and zero energy buildings
18. Performance of 8 Passive House Envelopes in Cold Climates
19. Pathways to High-Performance Housing in British Columbia
20. Building Envelope Thermal Bridging Guide, Analysis, Applications & Insights
21. Illustrated Guide to R22+ Effective Walls in Wood-Frame Construction in British Columbia
22. Financing and cost effectiveness of Passive House buildings: experience from Brussels and focus on social housing
23. Are passive houses economically viable? A reality-based, subjectivist approach to cost-benefit analyses
24. Energy Efficient Housing Guidelines for Whitehorse, YT: Cost Optimized House
25. The Business Case for Passive House
26. Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard
27. The Comfort Houses - Measurements and analysis of the indoor environment and energy consumption in 8 passive houses 2008-2011
28. Indoor Air Quality in 24 California Residences Designed as High-Performance Homes
29. Monitoring trends in civil engineering and their effect on indoor radon.
30. Non-energy benefits of the US Weatherization Assistance Program: a summary of their scope and magnitude
31. Towards explaining the health impacts of residential energy efficiency interventions – A realist review. Part 1: Pathways
32. Applying the passive house concept to a social housing project in Austria – evaluation of the indoor environment based on long-term measurements and user surveys

33. Event Report: Getting to Outcome-Based Building Performance Report from a Seattle Summit on Performance Outcomes
34. Analysis of building environment assessment frameworks and their implications for sustainability indicators
35. Indicator based sustainability assessment tool for affordable housing construction technologies

Table 1: Summary of Key Reference Attributes by Order of Appearance

	AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT
1	✓				✓					✓
2		✓								✓
3	✓	✓				✓	✓			✓
4		✓							✓	✓
5	✓	✓					✓		✓	✓
6		✓					✓			✓
7		✓								✓
8		✓							✓	✓
9		✓			✓		✓		✓	
10	✓	✓					✓		✓	
11	✓	✓					✓			✓
12	✓	✓						✓		✓
13	✓	✓	✓	✓	✓		✓			✓
14		✓					✓		✓	
15		✓					✓	✓	✓	
16		✓					✓		✓	✓
17		✓		✓			✓			✓
18		✓			✓					✓
19		✓							✓	
20		✓					✓		✓	
21		✓			✓				✓	
22	✓	✓					✓	✓		✓
23		✓						✓		✓
24		✓						✓	✓	
25	✓	✓					✓	✓	✓	
26		✓					✓			✓
27		✓		✓						✓
28		✓		✓						✓
29		✓		✓						✓
30	✓	✓					✓	✓		✓
31		✓		✓		✓				✓
32	✓	✓		✓			✓			✓
33		✓			✓					✓
34		✓	✓	✓	✓		✓			✓
35	✓				✓					✓

Table of Contents

Energy Efficiency in Affordable Housing

Arman, M., J. Zuo, L. Wilson, G. Zillante, S. Pullen, 2009. *Challenges of responding to sustainability with implications for affordable housing.* Ecological Economics **68** (12). http://library.bsl.org.au/jspui/bitstream/1/1511/1/challenges_of_responding_to_sustainability_with_implications_for_affordable_housing.pdf

✓				✓					✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Summary

Journal article that looks at an Australian project to identify the conceptual challenges of implementing sustainability in affordable housing. The study examined the issue looking at a number of key topic areas, including separating needs from wants, sustainability and consumption, environmental justice, why care about future generations, opportunity costs, and are we locking ourselves into eternal poverty. A number of pragmatic challenges were analysed: appeasing too many interests, global inequality, competitive market, and limited knowledge. The conclusion of the study is that to attain sustainable development, there is a need for debates surrounding the challenges of sustainability, and that since these debates are ongoing, it is an indicator that we are moving towards sustainable development.

Chen X., H. Yang,L. Lu, 2015. *A comprehensive review on passive design approaches in green building rating tools*. Renewable and Sustainable Energy Reviews **50**, 1425–1436. http://www.sciencedirect.com/science/article/pii/S1364032115005730

	✓								✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Summary:

Journal article that performed comparative examinations in respect of the comprehensiveness, effectiveness and accuracy of how passive design was incorporated in five representative building rating systems (BREEAM, LEED, CASBEE, BEAM Plus,GBL-ASGB). Passive design criteria including the building layout, envelope thermos-physics, building geometry, air-tightness and infiltration performance and their effects on building energy consumption are reviewed.

Hoppe, T., 2012. *Adoption of innovative energy systems in social housing: Lessons from eight large-scale renovation projects in The Netherlands*. Energy Policy **51,** www.sciencedirect.com/science/article/pii/S0301421512008014

✓	✓				✓	✓			✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Summary

Journal article describing results of a study that looked at eight social housing retrofit projects in the Netherlands to see what factors influenced the adoption of innovative energy systems (IES) in social housing during retrofits. Key highlights from the study include:

- Despite the intention of the eight projects to adopt IES, only 3 of 8 projects implemented them.
- Many barriers identified: lack of trust between project partners, delay in project progress, financial feasibility considerations, lack of support from tenants, lengthy legal permit procedures, over-ambitious project goals, bad experience in previous projects, IES not considered important by key decision makers.
- Barriers were identified from the perspectives of three main actors (housing associations, tenants, and local authorities).

Passive House Standard

Jacobson R., 2013. *Passive House Certification in Scandinavia*. Annual North American Passive House Conference www.phius.org/NAPHC2013/jacobson.pdf

	✓							✓	✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

This presentation presents how some Scandinavian countries adapted the Passive House standards to address some of the limitation of using the German standard in such a cold climate. The modified standards were designed to move construction industry incrementally towards higher performance. In Sweden, the Forum for Energy Efficient Buildings (FEBY), a publicly funded research group, developed their own "passivhus" standard in 2007, and updated it in 2012. It has the following key attributes:

- Maximum allowable heating loads that vary by climate, between 17 W/m^2 and 19 W/m^2
- Maximum heat load reduced by approximately 11% (2 W/m^2)for buildings larger than 400 m^2
- "Certifikat" awarded during planning, "Verifikat" awarded after 2 years of successful energy monitoring

Norway adopted NS3700 as a national standard for "Passivhus" construction in 2010 with the intent of encouraging low-energy and passivhus construction. It includes an equation that varies maximum heating demand by climate and floor area, as well as including minimum R-value requirements – exterior walls RSI-6.7 (R-38), roof RSI-7.7 (R-44), floor RSI-6.7 (R-38), windows/door USI 0.8 (U-0.14)

Based on their experience, extreme cold temperatures in both Scandinavia and North America result in heat loads that cannot be met using ventilation air alone. Since heating loads cannot be met with ventilation air, a supplemental heating system is still required, and thus there is no "tunnel through the cost barrier", and the cheapest current option for both Scandinavian and North American passive houses is to use supplemental electric resistance heat.

James M., 2015. NET ZERO ENERGY BUILDINGS Passive House+ Renewables, published by Low Carbon Productions. http://naphnetwork.org/NAPHN_NZEB_2015_V2/NAPHN_NZEB_2015.html

✓	✓					✓		✓	✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

A book that presents Passive House and makes a case as to why building to the Passive House standard is a good first step towards building net-zero energy buildings. The book first presents key factors in PH design, then showcases key regions around the world that are leading in Passive House (includes Vancouver), and presents 22 North American projects. Note that this is the North American version of: Passive House Institute, 2014. Defining the Nearly Zero Energy Building Passive House + renewables, http://www.passreg.eu/upload/PassREg_International_EN/Flipbook_Pro.html The five key factors to consider when building to Passive House:

1. An optimal level of thermal insulation.
2. Thermally insulated window frames with high quality glazing and external shading to limit overheating.
3. Careful design to achieve thermal bridge free construction to avoid unnecessary heat loss.
4. An airtight building envelope using an uninterrupted and continuous airtight layer.
5. Mechanical ventilation with heat recovery to ensure continuous supply of filtered fresh air.

McLeod R., et. Al., Passivhaus *Primer: Airtightness Guide – Airtightness and air pressure testing in accordance with the Passivhaus standard*. Passivhaus BRE, www.passivhaus.org.uk

	✓					✓			✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

This primer is an aid to understanding the key principles involved in achieving the airtightness performance required to meet the Passivhaus standard. It explains the Passivhaus certification pressure test requirements and how to prepare the building for the test. It is a general guide that includes some specific information for MURBs:

- If the communal and circulation areas (foyer, corridors and staircases) in a block of flats are all within the thermal envelope (built to Passivhaus standard) then the block will be tested as a whole building.
- For terraced and semi-detached houses, the partitioning walls between units needs to be airtight, and the units must be tested separately.

McLeod R., K. Mead, M. Standen, Passivhaus primer: Designer's guide A guide for the design team and local authorities. Passivhaus BRE, http://www.passivhaus.org.uk/

	✓								✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

Short 10 page guide that provides a basic overview of the Passive House design principles. It's a simple primer that would help someone familiar with building construction, but not with Passive House, to understand the basic design elements required to achieve Passive House.

Wright G., K. Klingenberg, 2015. *Climate-Specific Passive Building Standards*, U.S. DOE, http://www.nrel.gov/docs/fy15osti/64278.pdf

	✓							✓	✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

The U.S. Department of Energy contracted the Passive House Institute – US (PHIUS) to develop a Passive House Standard for the U.S. to address limitations in the German developed International Passive House standard. The limitations included:

- International standard found not to be responsive to the wide diversity of climate and energy market conditions in North America.
- Using European energy metrics for North American climates has forced solar-driven designs that tend to overheat and have very high cost required envelopes.
- Passive House Planning Package's (PHPP's) simplified static calculations under predict cooling and heating loads year round and cannot predict indoor thermal comfort accurately. It cannot be used to size the mechanical system in extreme climates.
- The low PHPP defaults used for electrical loads are grossly unrealistic for North America.

The design targets developed by PHIUS are cost optimized by climate. Cost is a moving target over time and as such, the targets will be revised every 3 to 5 years.

Case Studies

Canadian Projects

Hancock, J., B. Scott, 2013. STATION POINTE GREENS—THE JOURNEY TO NET ZERO AFFORDABLE HOUSING, Journal of Green Building **8** (1), pp. 3-21. http://www.collegepublishing.us/jgb/samples/JGB_V8N1_a01_hancock.pdf

	✓			✓		✓		✓	
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

Journal article describing Station Pointe Greens, a proposed 219-unit residential and commercial Passive House Certified development in Edmonton, Ab. The initial design concept was done in 2009, but the project is still in its research and design phase. The project was part of the CMHC EQuilibrium

Communities demonstration initiative, which helped the team further refine its design concept. A Passive Design path and an Active Design path emerged clearly from the project development charrette:

- Passive Design focused on items like a high-performance envelope and high-performance glazing with the goal of downsizing the mechanical system.
- Active Design still considered envelope and glazing, albeit to a lesser extent, and focused instead on technologies like ground source heat pumps, underground solar thermal energy storage, and a district energy system to achieve the same energy target.

The estimated operation and maintenance costs for the building (including green loan financing) was $346/month for passive design compared to $480/month for conventional construction.

Tsenkova S.,2013. Retrofits for the Future: Affordable Housing and Energy Efficiency Programs in Canada. University of Calgary. Cities, Policy & Planning research series. 80 pp., http://www.ucalgary.ca/cities/files/cities/EnergyRetrofitsTsenkova2013.pdf

✓	✓					✓		✓	
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview: Within the context of this new political commitment to energy efficiency improvements in the social housing sector, this research project focuses on the following objectives:

- To review national and provincial policies and programs to implement energy efficiency retrofits in social housing;
- To identify preferred investment strategies and policy responses by different social housing providers—public, private non-profit and community (cooperative);
- To evaluate the results achieved in several domains: economic/financial, social, technical/technological and environmental through an in-depth analysis of select case studies (Edmonton, Vancouver, Toronto).

International Projects

California Energy Commission, 2012. AFFORDABLE MULTIFAMILY ZERO ENERGY NEW HOMES, Report: Prepared for California Energy Commission by Global Green USA, CEC-500-2012-052, 105 pp., http://www.energy.ca.gov/2012publications/CEC-500-2012-052/CEC-500-2012-052.pdf

✓	✓					✓			✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

Report presenting findings from a pilot that saw Global Green USA partner with a pair of non-profit housing developers to build two Zero Energy Multifamily Affordable housing projects in San Diego County. The first project, Solara, opened in Spring of 2007, and the second project, Los Vecinos, opened in Spring of 2009. Projects set, and met four key criteria:

1. 25% better than Title 24 (2005) California energy code;

2. 70% reduction in electricity costs for the occupants compared to standard housing;
3. Summer peak electrical demand of 1 kW or less per housing unit;
4. Spend less than $5,000 additional dollars per housing unit, after rebates and incentives.

Study had three main conclusions regarding financing, design, analysis, and applicability of zero energy affordable housing in California:

1. Zero energy affordable housing projects are financially viable.
2. Energy cost modeling can be accurate enough to underwrite the additional debt
3. Taller buildings pose a challenge to meet zero energy target since they have less area to install solar photovoltaic (PV) systems in proportion to living area. Residential buildings seeking to achieve net zero electricity goals should set a height limit of three stories using current technology.

Dean, J., O. VanGeet, S. Simkus, M. Eastment, 2012. *Design and Evaluation of a Net Zero Energy Low-Income Residential Housing Development in Lafayette Colorado*. National Renewable Energy Laboratory, NREL/TP-7A40-51450, http://www.nrel.gov/docs/fy12osti/51450.pdf

✓	✓						✓		✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

Report presenting the findings of the Paradigm Pilot Project, which had three residential units, a single family residence and a duplex built to a low energy target. The Paradigm Pilot Project served as a mechanism to revise design strategies and assess the design recommendations for the Josephine Commons low-income housing project (1- and 2-bedroom apartments, including 70 senior's housing units). They used BEOpt to optimize a single family house model to assist with the design, which resulted in a source-energy savings of 37% and reduced the incremental mortgage and utility costs by approximately $166/yr. The total incremental installed cost to implement the energy efficiency upgrades was estimated at $10,680.

International Living Future Institute, 2014. *LIVING BUILDING CHALLENGE Framework for Affordable Housing – A Pathway to Overcome Social, Regulatory and Financial Barriers to Achieving Living Building Challenge Certification in Affordable Housing*. https://living-future.org/sites/default/files/LBC_AffordableHousing.pdf .

✓	✓	✓	✓	✓		✓			✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

This report provides pathways and identifies strategies to assist affordable housing developers in overcoming social, regulatory and financial barriers to achieving Living Building Challenge Certification. Living Buildings are designed to maximize the positive social and environmental potential of the built environment and serve as focal points for inspiration and education in their local communities.

The report looks at critical design requirements (net-positive energy and water, and a number of materials requirements) and provides an Introduction, design solutions, barriers, solutions to barriers, followed by Case Study Examples. The three case study examples are high performance affordable MURB projects built in the U.S. (Minnesota, California and Texas) that studied design requirements to achieve the Living Building Challenge. The Institute is running an affordable housing pilot program from August 1, 2015 to December 31, 2016 where it hopes to have five affordable housing pilot projects built to the Living Building Challenge.

Technologies and Design Practices

City of Vancouver, 2009. *Passive Design Toolkit – Large Buildings*, http://vancouver.ca/files/cov/passive-design-large-buildings.pdf

	✓					✓		✓	
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

A design guide that presents best practices for the application of passive design in large buildings in Vancouver. The toolkit is organized into three main sections: Context, Passive Design Strategies, and Passive Design Elements. Some of the key passive design recommendations for buildings in Vancouver include:

- Design each facade specific to its orientation. Where possible, minimize east and west exposures to avoid unwanted solar gains.
- Limit windows to 50% of the wall area on any facade (for best performance, limit windows to 30%), taking into account other aesthetic and livability criteria.
- Use clear glass with good insulating value (low U-value with low-e coating). Mitigate unwanted solar gains with external shading and allow for passive cooling by natural ventilation.
- Use thermal mass that is exposed to the conditioned space and combine it with other passive elements to achieve its full energy-savings and comfort potential.

CMHC., 2014.*Energy Simulations of Strategies to Achieve Low-Energy, Multi-unit Residential Building Designs in Different Regions of Canada*. Report prepared by EnerSys Analytics Inc. for CMHC., http://www.cmhc.ca/odpub/pdf/68292.pdf

	✓					✓	✓	✓	
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

A report that presents the results of a study that used building energy modelling to examine how energy performance levels approaching Passive House could be achieved in Canadian multi-unit residential buildings, given its cold climate, existing design practices, building codes, and readily available technologies. The study used one building as a reference for the study that consisted of a ten-storey,

concrete-and-steel high-rise with a total floor area of 4,000 m², and did energy simulations in six different Canadian climate zones. A regional economic analysis to achieve passive low-energy MURBs in different Canadian cities is presented. The cost effectiveness of the modelled building, which relied on electric baseboard heating, varied considerably depending on the regional unit cost of electricity compared to natural gas.

FPInnovations, RDH Building Engineering, 2013. *Guide for Designing Energy-Efficient Building Enclosures for Wood-Frame Multi-Unit Residential Buildings in Marine to Cold Climate Zones in North America*. Available for download at www.fpinnovations.ca

	✓					✓		✓	✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

A guide intended to help architects, engineers, designers and builders improve the thermal performance of building enclosures of wood multi-unit residential buildings. It looks at design and construction best practices and material used to ensure durable performance. Its key chapters include: a chapter on moisture, air and thermal control, a chapter that showcases energy-efficient wall and roof assemblies, and a chapter that provides key details to help with implementation.

Hopfe C., R. McLeod, 2015. The Passivhaus Designer's Manual – A technical guide to low and zero energy buildings. Routledge Taylor & Francis Group. 327 pp

	✓		✓			✓			✓
AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

A book written to be a comprehensive technical guide for architects, engineers and construction professionals wishing to build to Passive House and net-zero energy targets. The book includes 12 chapters including: Thermal and occupant comfort; Building physics; Lighting & daylighting; Hygrothermal simulation; Heat and hot water generation; Planning and implementation of ventilation concepts; Renewable energy technologies; Project and site management; Economics; and Passivehaus EnerPHit.

Jacobson R., 2012. *Performance of 8 Passive House Envelopes in Cold Climates*, 7th Annual North American Passive House Conference, Denver CO, www.phius.org/NAPHC2012/Jacobson_ColdClimatePH.pdf

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AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

Conference presentation that looked at 8 passive houses built in cold climates (Scandinavia, EU, and US) with different building envelope systems, to examine the important design elements (calculating R-values, thermal bridges, critical layers for moisture performance, embodied carbon). The building

envelopes examined are TJI with blown-in fiberglass, ICF with exterior EPS, structural engineered panel with exterior EPS, SIP panel, advanced framing with sprayfoam, double-stud wall with blown-in cellulose, advanced 2x6 framing with exterior mineral wool, prefab wall panel with exterior mineral wool, concrete mass wall with exterior mineral wool. Key findings include:

- An analysis comparing the thermal bridging of the different walls found no great differences between envelope types.
- Analysis of mould growth potential shows a significant reduction in the risk of mould growth when the Passive House airtightness target of 0.6 ACH @ 50Pa is achieved.
- To further reduce mould growth, add several inches of permeable exterior insulation or eliminate the critical layer with an assembly (such as ICF) that does not support mold growth and is relatively impervious to moisture.
- Lifecycle assessment presented on the eight walls using Athena show that walls that depend on insulation materials that are made with a blowing agent that is a greenhouse gas performed worse than other wall types.

Mattock C., 2014. Pathways to High-Performance Housing in British Columbia, FPInnovations, SP-56, 232 pp., https://fpinnovations.ca/media/publications/Pages/default.aspx

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AS	PH/LE	H2O	IEQ	SUST	OCC	MURB	$$	CA	INT

Overview

A guide that presents design and construction strategies and detailed measures to improve home energy efficiency in British Columbia. It is intended for designers and builders who are interested in the design and construction of single-family and small multi-family buildings that are substantially more energy efficient and lower in environmental impact than traditionally built homes. Chapters covered include: Design and Construction Strategies, The Integrated Design Process, Building Envelopes, Space Heating, Ventilation, Water Heating, and Photovoltaic Systems.

Morrison Hershfield, 2014. Building Envelope Thermal Bridging Guide, Analysis, Applications & Insights. BC Hydro. https://hpo.bc.ca/building-envelope-thermal-bridging-guide

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Overview

A guide whose primary objective is to address the obstacles currently confronting the building industry, with regard to thermal bridging, by:

1. Providing a catalogue of the thermal performance of common envelope assemblies and interface details.
2. Providing information that makes it easier for industry to comprehensively consider thermal bridging in building codes and bylaws, design, and whole building energy simulations.

3. Examining the costs associated with improving the thermal performance of opaque building envelope assemblies and interface details, and forecasting the energy impact for several building types and BC climates.
4. Evaluating the cost effectiveness of improving the building envelope through more thermally efficient assemblies, interface details, and increasing insulation levels.

Rickets L., G. Finch, 2015. *Illustrated Guide to R22+ Effective Walls in Wood-Frame Construction in British Columbia*. BC Homeowner Protection Office, https://hpo.bc.ca/r22-effective-walls-wood-frame-in-BC

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Overview

A guide developed to assist home designers and builders build walls with RSI-3.9 (R-22) or greater thermal performance. The guide is geared towards low-rise wood frame residential buildings across British Columbia, and would be relevant to other areas in Canada. Introduction covers some background including R-value calculations, cladding attachments, and air barrier systems. Four above grade wall types are presented: split insulated walls, exterior insulated walls, double-stud walls, and deep stud walls with service wall. Two below-grade wall types are presented: exterior insulated and interior insulated walls.

Cost-Benefit Studies

Kondratenko, I., 2014. Financing and cost effectiveness of Passive House buildings: experience from Brussels and focus on social housing. www.passipedia.org/basics/affordability/financing_and_cost_effectiveness_of_passive_house_buildings_-_experience_from_brussels_and_focus_on_social_housing

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Overview

This report presents a brief summary of an information session entitled "Affordability of Passive House social housing" to various key stakeholders in Antwerp. The average extra upfront cost for building to the Passive House Standard as opposed to conventional buildings is 450 €/m² (1563 €/m² versus 1109 €/m²) with a range of results, some examples where the cost of building "passive" was much closer to those of non-passive buildings. The average building costs of the social housing projects in the Exemplary Buildings programme was 1516 €/m², with the lowest being 950 €/m², and most expensive projects cost 2600 €/m². Other non-energy related aspects such as the design layout, the size of the living room, bedrooms and overall building, the choices of appliances, etc. had a much bigger influence on the building costs. Choices in a building project relating to ecological materials, water recuperation systems, green-roofs, etc. also had a strong influence on the building costs.

Galvin, R., 2014. *Are passive houses economically viable? A reality-based, subjectivist approach to cost-benefit analyses.* Energy and Buildings **80**, http://www.sciencedirect.com/science/article/pii/S0378778814004174

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Overview

Journal article summarizing the results of a study that examined the actual versus modelled cost effectiveness of building to Passive House performance levels. The study presents a decision making process for would-be investors to assess the cost-effectiveness of projects. A literature review conducted by the author found no existing transparent cost-benefit study of Passive Houses (PHs) compared to conventional homes (CHs) based on actual consumption of these dwellings. Past studies show that most PH cost 5-15% more to build than CH. A number of studies offer cost-benefit analysis to address this increased cost, setting values for unknowable variables such as future fuel price rise, investor's discount rate and financing costs. Some of the important findings from this study include:

- A German study of 90 low energy buildings found that more complex HVAC systems in the lower energy buildings under-performed, making their actual performance worse than buildings that targeted higher consumption targets.
- Study of 109 PH dwellings found a range of heating consumption from 1 to 48 kWh/m^2 with an average of 20.5 kWh/m^2, or 37% higher than targeted. The study concludes that the average household is likely to consume about 40% more than modelled for both PH and CH.
- Can't rely on cost-benefit studies in literature as they use critical default assumptions: future price of energy and discount rate are choices investor or household has to make rather than fact-based values given correctly by experts.

RDH Building Engineering, 2015. *Energy Efficient Housing Guidelines for Whitehorse, YT: Cost Optimized House*. Natural Resources Canada. 33 pp. http://www.energy.gov.yk.ca/pdf/Energy-Efficient-Northern-Housing-Guide-Cost-Optimized.pdfb

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Overview

BEOpt was used to find the most cost effective energy efficient home for the Yukon considering a combination of incremental costs, and energy savings. The study was based on an archetype 225 m^2 (2400 ft^2), 2-storey wood-frame home with an attached garage. The cost-optimised case has an estimated $6,600 upgrade cost compared to the base case, but achieves overall cost savings of $1,260/yr. Report includes illustrated step-by-step guide to constructing key building envelope assemblies.

Synergy Sustainability Institute, 2015. The Business Case for Passive House, http://canphi.ca/wp-content/uploads/2015/07/Passive-House_BusinessCase_2015.pdf

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Overview

Report that examines the business case from both the builder's, as well as the buyer's, perspective of building to the Passive House standard. The study used three B.C. buildings as a basis for the analysis: Bernhardt Passive House (310 m^2 [3,337 ft^2] two family residence completed in June 2013.), North Park Passive House (6 two-bedroom units ranging in size from 60.8 m^2 to 96.6 m^2 [654 ft^2 to 1,036 ft^2]), and Yukon Affordable Housing (425 m^2 [4,575 ft^2] six-plex built in 2008 as an affordable housing rental project). Some of the findings include:

- Achieving Passive House criteria in projects within the basic building quality spectrum (more typical of affordable housing projects) will have a more significant relative cost increase than projects that are already of medium to high quality (i.e. higher base cost reflects in lower percentage cost increase).
- The Bernhardt Passive House actual energy use was 35% higher than modelled. This was split 39% higher for electricity and 33% higher for natural gas.
- North Park and Bernhardt case studies found increased costs of roughly 4.5% over base case.
- While the business case was stronger (higher ROI and IRR) for the builder than for the buyer (longer payback period), the lack of consumer market demand for the Passive House approach was identified as a key barrier to build Passive Houses according to interviewees.

Non-Monetary Challenges and Benefits

Dodoo, A., L. Gustavsson, R. Sathre, 2010. *Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard*. Resources, Conservation and Recycling **54** (12), http://www.sciencedirect.com/science/article/pii/S0921344910000856

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Overview

Journal article summarizing the results of a study that examined the life-cycle energy of retrofitting wood-frame buildings in Sweden to be more energy efficient. The study found that the heat supply system used in the building has greater impact than the heat reduction measures, with energy reduction in electrically heated buildings having a greater impact than district heated buildings. Primary energy for materials increases with retrofits, but operating energy reductions offset the increase within 4 years. From energy and economic perspectives, a building retrofitted to passive house standard is unlikely to undergo further major energy retrofitting during its lifespan (i.e. it avoids the cost and disruption of doing multiple energy retrofits over the course of the building's life). Doing all of the energy retrofits at one time can result in greater savings over the life of the building.

Larsen, T, R. Jensen, O. Daniels, 2012. *The Comfort Houses - Measurements and analysis of the indoor environment and energy consumption in 8 passive houses 2008-2011*, Aalborg University, ISSN 1901-726X, DCE Technical Report No. 145, http://www.komforthusene.dk/files/KOMFORT%20HUSENE/Vidensdeling/Measurements%20and%20analysis.pdf

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Overview

Report presenting findings of a study that examined the indoor environmental quality (IEQ) of eight different Passive Houses constructed in Denmark. All houses failed to meet the Passive House overheating criteria of having a maximum 100 hours above 26ºC and 25 hours above 27ºC, with 5 out of 8 houses experiencing excessive temperature problems more than 10% of the time. The study found irregular heat distribution between rooms, which underlines the need for analysing a house as a number of different zones.

Most houses operated with a heating set-point temperature of 23ºC, which is 3ºC above what is modelled for Passive House certification, which would increase energy consumption by approximately 6-8 kWh/m² a year over the modelled values. There was a great variation in the measured electricity consumption, with the highest user consuming three times more electricity than the lowest electricity user. Most houses meet the passive house primary energy demand target.

Less, B., M. Nasim, B. Singer, I. Walker, 2015. Indoor Air Quality in 24 California Residences Designed as High-Performance Homes, Science and Technology for the Built Environment **21** (1), 14-24., http://eetd.lbl.gov/publications/indoor-air-quality-in-24-california-r

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Overview

Journal article presenting the results of a research study that used pollutant measurements, home inspections, diagnostic testing and occupant surveys to assess indoor air quality (IAQ) in 24 new or deeply retrofitted homes designed to be high performance green buildings in California. Study found that high performance homes can achieve acceptable and even exceptional IAQ by providing adequate general mechanical ventilation, using low-emitting materials, providing mechanical particle filtration, incorporating well-designed exhaust ventilation for kitchens and bathrooms, and educating occupants to use the kitchen and bath ventilation. Other key findings include:

- Ambient nitrogen dioxide standards were exceeded or nearly so in four homes that either used gas ranges with standing pilots, or gas cooking burners without venting range hoods. Emissions of ultrafine particles (with diameters <100 nm) were dramatically lower on induction electric cooktops, compared with either gas or resistance electric models.
- Homes without active particle filtration had particle count concentrations approximately double those in homes with enhanced filtration.

Ringer, W., 2014. *Monitoring trends in civil engineering and their effect on indoor radon.* Radiation Protection Dosimetry **160** (1-3), http://www.ncbi.nlm.nih.gov/pubmed/24729564

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Overview

Journal article presenting a study that compared radon levels of about 100 low-energy and passive houses compared to conventional new houses. Radon levels were about one-third lower in low-energy houses. Certain features and bad practice can cause high radon in low-energy houses. Low-energy buildings that featured ground-coupled heat exchangers made out of concrete had 1.5 to 2 times more radon compared to those made out of plastic. Study of 163 retrofit buildings found that radon levels increased 26% on average after retrofit, with window replacements causing greatest increase. Ratios vary over a wide range with one-third of all dwellings showing lower radon levels after retrofit.

Schweitzer, M., B. Tonn, 2003. *Non-energy benefits of the US Weatherization Assistance Program: a summary of their scope and magnitude*. Applied Energy **76** (4), http://weatherization.ornl.gov/pdfs/ORNL_CON-484.pdf

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Overview

Journal article summarizing results of literature review looking at non-energy benefits of weatherizing of low income homes. Divided into three major categories and each with subcategories: ratepayer benefits (payment related benefits, service provision benefits), household benefits (associated with affordable housing, and those related to safety, health and comfort), and societal benefits (environmental, social or economic). The study found a lifetime non-energy related benefit of $3346 (2001 dollars) per household, with societal benefits being much larger than ratepayer and household benefit. Non-energy cost-benefits were estimated to be higher than the net-present value of energy savings of $3174. The non-energy cost benefits include:

- Related benefit to ratepayer: avoid rate subsidies, lower bad-debt write-off, reduced carrying cost on arrearages, fewer notices & customer calls, fewer shut-offs & reconnections for delinquency. There is a large range of reported cost-benefit in literature from $38 to $467.
- Ratepayer service provision benefit: fewer emergency gas service calls, transmission and distribution loss reduction, insurance savings. Range $72 to $283.
- Household benefit for affordable housing: water and sewer savings, property value benefits, avoided shut-offs and reconnections, reduced mobility, reduced transaction costs. Range $62 to $8663.

Willand, N., I. Ridley, C. Maller, 2015. *Towards explaining the health impacts of residential energy efficiency interventions – A realist review*. Part 1: Pathways, Social Science & Medicine **133**, http://www.sciencedirect.com/science/article/pii/S027795361500088X

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Overview

Journal article presenting the findings of a literature review of 73 documents from 28 energy efficiency improvement programs to provide a realist review of impacts of residential energy efficiency interventions on householder health. Three key pathways to health improvements were considered: warmth of home, affordability of fuel and psycho-social factors. Study findings include:

- Interventions improved winter warmth and lowered relative humidity leading to cardiovascular and respiratory health improvements.
- Feeling of home as safe haven strengthened householder perceived autonomy and enhanced social status, leading to positive mental health. Financial considerations played a secondary role in improved mental health.
- Evidence for negative impacts is rare, but risk should not be dismissed. There is concern that air tightness can lead to reduced indoor air quality due to lack of ventilation. This was rare, but insufficient natural ventilation was blamed for some incidences of mould and higher carbon monoxide levels.
- Three studies reported educating householders on appropriate ventilation practices, but it seemed that this was not effective in changing householder habits.
- In context of climate changing and rise of ambient temperatures, overheating of homes will present a likely health risk in the near future.

Post-Occupancy Evaluation Studies

Rojasa, G., W. Wagnerb, J. Suschek-Bergerc, R. Pflugera, W. Feist, 2015. *Applying the passive house concept to a social housing project in Austria – evaluation of the indoor environment based on long-term measurements and user surveys.* Advances in Building Energy Research, http://www.tandfonline.com/doi/abs/10.1080/17512549.2015.1040072?journalCode=taer20#.VwbFBI-cFjo

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Overview

Journal article that present the results of a study that analysed the measured indoor environmental data collected during long-term monitoring of a social housing project built to the Passive House (PH) standard. The indoor temperature, CO2 concentration and relative humidity levels were continuously logged in 18 of the 354 apartments. The volatile organic compound concentrations were also measured before the tenants moved in. Furthermore, a survey using questionnaires and interviews was performed to evaluate the occupants' satisfaction levels. For comparison, six dwellings of a similarly constructed low-energy building, but without mechanical ventilation were also measured within this project. In

general, the satisfaction level within the presented social housing complex built to the PH standard was very high. Findings include:

- Average indoor temperature distribution of PH during winter showed a surprisingly large difference compared to the low-energy housing and to other documented PH projects in Germany.
- Overheating during summer seemed to be an issue especially in the top-floor apartments.
- The evaluation of the indoor air quality shows the need for controlled domestic ventilation for non-owner-occupied buildings.

Performance Indicators for Sustainable MURBs

Frankel M., J. Edelson, R. Colker, 2015. *Event Report: Getting to Outcome-Based Building Performance Report from a Seattle Summit on Performance Outcomes*, New Buildings Institute (NBI), 36 pp. http://newbuildings.org/sites/default/files/Performance_Outcomes_Summit_Report_5-15.pdf

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Overview

This report summarizes the key points discussed at a summit of national experts held in Seattle to focus on industry characteristics and needs that will support a move to performance based outcomes. Part of the vision they would like to see is the development of a simple, three-page energy code focused on performance outcome. Some of the key barriers identified to move towards outcome based codes include:

1. Resistance and pushback to creating accountability that lasts into the operational phase of the project.
2. How are energy performance requirements identified, and what are the responsibilities of various parties if buildings do not perform as expected?
3. Low awareness in the industry and the public at large of building energy performance.

Effectively setting building targets and performance metrics will be essential in advancing the application of outcome-based requirements.

Kajikawa, Y., I. Toshihiro, G. Thong, Goh, 2011. *Analysis of building environment assessment frameworks and their implications for sustainability indicators.* Sustainability Science **6** (2), http://link.springer.com/article/10.1007%2Fs11625-011-0131-7

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Overview

Journal article presenting the results of a study that aimed to provide an overview of the current status of building environmental assessment (BEA) tools, illustrate possibility and limitations, and discuss roles and limitations, with a focus on BREEAM (UK), LEED (US), GBTool (Canada), and CASBEE (Japan). Striking a balance between completeness of coverage and simplicity of use is one of the challenges in developing an effective and efficient environment BEA tool. There is a need to expand BEA to different areas in increasing order of inclusiveness and breadth (product level, building level, building and supporting infrastructure level, community level, and building stock level). There is also a need to expand the scope to a wider context including community building, urban planning, city and regional development.

Wallbaum, H., Y. Ostermeyer, C. Salzer, E. Zea Escamilla, 2012. *Indicator based sustainability assessment tool for affordable housing construction technologies*. Ecological Indicators **18**, http://www.sciencedirect.com/science/article/pii/S1470160X11004079

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Overview

The study presents a new sustainability assessment tool geared towards affordable housing construction technologies. Ten sustainability indicators were developed (initial costs, durability, economies of scale & mass production, time schedule & degree of prefabrication, requirements of production and construction processes, maintenance costs, modularization & flexibility, local value creation, interface to basic services, recycling and demolition ability) with a grading from 0 to 10. Forty-six technologies were analysed with the assessment tool. . No one technology emerged as a solution to sustainable affordable housing, but combining multiple top-ranking technologies can provide an optimized solution. Most promising technologies are closely connected to local production of materials.

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