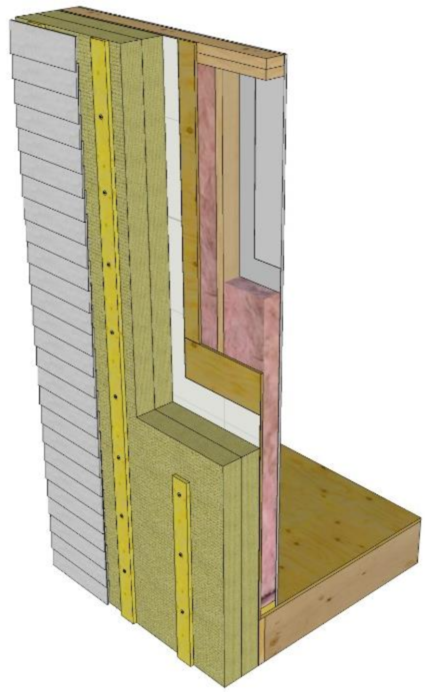
The Economics of Passive House | Project 4229.070

Costing Study on Passive House for Single Family Homes in Vancouver



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Executive Summary

This study was completed to assess the costs and economics of Passive House single family homes in the City of Vancouver to help owners, designers, and builders compare the costs of "Passive House" construction for a variety of different assemblies and systems to minimum VBBL requirements for energy performance.

Costing and energy analysis was performed for two prototypical single family houses with RS-1 zoning, which covers about 70% of residential land in Vancouver. The results were used to assess the life cycle economics of Passive House, single family dwellings in Vancouver. An intermediate energy performance target between the VBBL and Passive House was also studied.

Comparing the Energy Performance of VBBL, Passive, and 30 kWh/m²

The 2014 VBBL improved the energy performance of the building enclosure over previous versions, exceeding the BC Building Code standards (s9.36 of NBC, with BC revisions). When evaluated in Passive House Planning Package (PHPP) software, the Passive House designs in this study that are constructed using VBBL assemblies and components may produce a house with a space heating demand as low as 86 kWh/m²/yr[1]. Other designs may be higher. The associated heating energy savings and corresponding GHG reductions were approximately 75% compared to the VBBL.

Achieving Passive House performance requires a 'House-as-a-System' design approach. No single component or assembly is solely responsible for the 15 kWh/m²/yr result. Likewise, any policy that relies heavily on a short list of upgrades may not deliver this performance across the wide variety of house designs.

High-performance windows are pivotal to achieving high-performance enclosures. The findings in this study suggest it will be difficult to achieve even an intermediate target of 30 kWh/m²/yr without Passive House level windows, and experience suggests that the substitution of lower-grade windows may require distribution of heat below the windows, reducing mechanical cost savings. However, few Passive House certified windows are available in BC at this time. Some North American (NFRC certified) products achieve near-Passive House performance but are not certified following the Passive House procedures.[2]

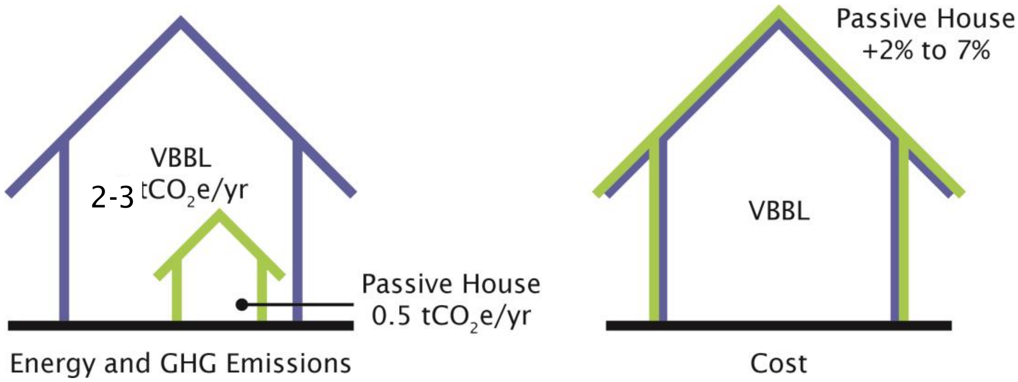
Similarly, ventilation energy efficiency improvements require better HRVs. There is presently a lack of HRVs in the 85%-plus sensible heat recovery efficiency range. BC based manufacturers can achieve 70%, or even as high as 83% for double core systems. It may be advisable to signal an intent to adopt HRVs with 85-95% heat recovery efficiency, and to set a firm target, so that industry has time to adapt.

Comparing the Economics of VBBL and Passive House

For the two houses studied in this project, building enclosure costs are 15% to 20% higher for Passive House; however, mechanical cost savings of 30% to 40% are also realized. This

[1] Based on PHPP simulation results and Treated Floor Area (TFA)
[2] See *International Window Standards Final Report*, April 2014, https://hpo.bc.ca/files/download/Report/International-Window-Standards.pdf

leads to an overall total construction cost premium of approximately 2% to 7% as compared to VBBL construction based on typical construction prices in Vancouver.



The cost premium for Passive House (enclosure and mechanical costs) was $20,000 to $25,000 based on the two designs investigated in this study. Houses with less compact designs or non-standard assemblies and systems may see higher cost premiums.

Improved airtightness and reduced thermal bridging represent the most cost-effective improvement options modelled in this study. These upgrades are more dependent on knowledge, construction practices, and detailing than materials; while they may require additional training and learning as these practices are new to the building community, they should not add cost for experienced teams.

Total annual energy bill savings 20% - 25% for a Passive House, compared to a VBBL house. At current and projected energy costs, the life cycle economics for Passive House yield long payback periods and a negative net present value for savings beyond the relatively high standard in the 2014 VBBL. However, the total incremental cost for Passive House is low, compared to land and construction costs in Vancouver.

If an intermediate target of 30 kWh/m^2 is to be considered, including Passive House windows, HRVs, airtightness, and an intermediate wall R-value (between Passive House and VBBL) appears to be the most cost effective path. In other words, keeping Passive House performance level and relaxing the opaque building enclosure R-values (e.g. walls, roof, below grade) compared to Passive House standard. This approach would also allow the market for Passive House level components (windows and HRVs) to develop. However, a concern is that reduced opaque enclosure performance could make it difficult to achieve cost-effective airtightness and thermal bridging savings, and mechanical designs may not deliver modelled performance.

It is also important to recognize the many non-energy benefits to Passive House that are not captured in the life cycle economic analysis performed for this report that provide additional value for a Passive House. Benefits like comfort, acoustics, and durability may well be the primary selling points for home owners.

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1 Introduction

Passive House construction is growing in popularity in North America following the extensive momentum established in Europe. The Passive House standard includes an ultra-low energy consumption target that is achieved through passive design measures such as a well-insulated, airtight building enclosure with minimal thermal bridging, passive solar heating, heat recovery ventilation, and seasonal shading.

The City of Vancouver has announced a commitment to be a 100% renewable energy city by 2050. As part of this goal, the City is focused on encouraging ultra-low energy buildings. Given that approximately two thirds of Vancouver's buildable land is zoned for One-Family Dwelling (RS-1), single family dwellings are an important building sector.

A number of single-family homes being built in Vancouver have already opted to pursue the Passive House standard. Owners and builders often cite high costs as a barrier to Passive House construction, while Passive House advocates maintain the standard is cost effective considering lifecycle economics.

The Passive House standard consists of the following requirements, which are assessed through the Passive House Planning Package (PHPP). All of these requirements must be fulfilled in order for a building to attain certification.

→ Annual heating demand less than 15 kWh/m^2/yr, or peak heating load less than 10 W/m^2 (similar requirements for cooling demand/load apply if the building has cooling).

→ Total primary (source) energy consumption less than 120 kWh/m^2 per year.

→ Airtightness less than 0.6 air changes per hour (ACH) when tested at a pressure difference of ±50 Pa.

→ Additional requirements related to overheating (temperatures over 25°C less than 10% of the year), thermal comfort and hygiene.

The economic case for building Passive Houses is easily understood in concept; invest in a high performance building enclosure during construction and accrue savings from energy bills over the life of the building. Improvements in durability and thermal comfort are also likely to contribute financial value. However, this investment requires an incremental capital cost compared to code-minimum construction that may be viewed as a barrier for some homeowners or developers.

1.1 Objective

The goal of this study is to assess the capital costs of the building enclosure and mechanical systems, and the lifecycle energy savings, compared to the minimum requirements of the 2014 Vancouver Building By-Law (VBBL) in order to understand the economics for Passive House construction in Vancouver.

1.2 Scope

This study evaluates the capital costs required to build code minimum and Passive House single family homes in Vancouver. Plans for two houses were used for areas and geometries, both Passive House projects in design or construction at the time of this study. Both houses are being constructed on RS-1 lots in the City of Vancouver. The plans for each house were used as a guideline for geometry only; building assemblies and mechanical systems were developed specifically for the purpose of this study based on common construction practices in Vancouver.

For each of the two houses, energy models were prepared using HOT2000 for a VBBL-compliant house and PHPP for a Passive House. Lifecycle costing (LCC) was performed for each house using a 30-year service life assumption and utility energy pricing current as of September 2015.

Costing for each house was completed for the building enclosure assemblies (walls, windows, roof, below grade) and primary HVAC systems (heating and ventilation). An option for electric heat and hot water in the Passive House case was considered. Complete costing is beyond the scope of this study (eg. electrical, finishes, permitting, design, etc.). Passive House certification costs were also not included in the analysis.

As an extension to the economic study, additional analysis was completed to investigate an intermediate heating demand target of 30 kWh/m^2, a possible less stringent requirement than the Passive House target of 15 kWh/m^2.

1.3 Approach

In order to quantitatively compare the cost of constructing a Passive House with the cost of a VBBL house, the following research approach was used:

→ Complete quantity takeoffs of two homes currently under construction in Vancouver, each being built to the Passive House standard. Itemize two lists of enclosure and mechanical components required to construct the homes. One list was developed to describe all components necessary to comply with the Passive House Standard. A second list was developed that describes all components necessary to comply with the 2014 VBBL. Both lists include multiple options for certain assemblies appropriate in order to reflect common practices.

→ Assess two scenarios of energy performance for both houses, one reflecting the houses constructed to meet the Passive House standard (modelled using PHPP), and a second reflecting the houses constructed to meet the VBBL (modelled using PHPP and HOT2000[3]).

→ Evaluate the life cycle cost effectiveness of constructing the case study houses to the Passive House standard, as compared to complying with the 2014 VBBL.

[3] HOT2000 and PHPP simulated in significantly different values for heating demand for the same VBBL house. PHPP was used for the economic comparison in this study in order to compare houses across the same simulation tool. This is explained further in Section 3, and Appendix B shows the analysis when HOT2000 is used to model the VBBL house.

2 Case Study Houses

Plans for two Passive House projects were used for quantity takeoffs. Both houses typify common Passive House design practices with respect to their enclosure geometries, glazing ratios, and layouts. These houses were in design and/or construction in Vancouver at the time of this study.

2.1 Case Study House 1

Case Study House 1 is a two-storey house with a small third-storey mezzanine. First and second floor plans for this house are shown in Figure 2.1. The house has a conditioned basement and a predominantly low-slope roof, with a vaulted roof above the third floor mezzanine.

→ Gross Floor Area (GFA): 300 m^2 (3,215 sf)

→ Treated Floor Area (TFA): 217 m^2 (2,335 sf)[4]

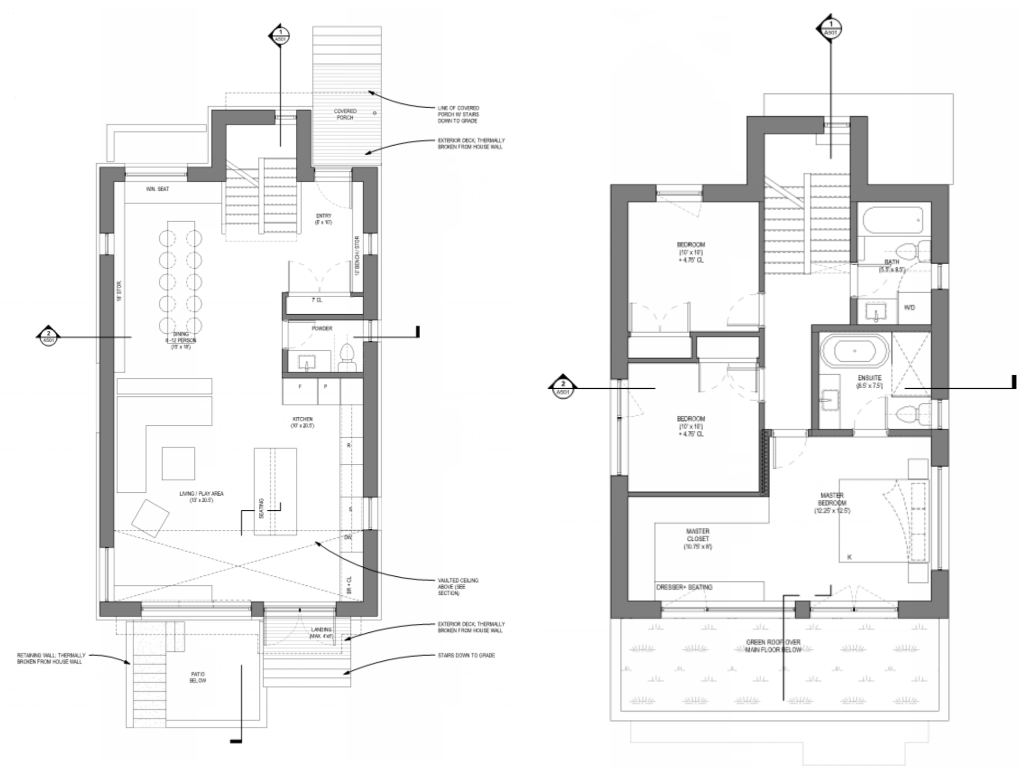


Figure 2.1 First (left) and second (right) floor plans of Case Study House 1.

[4] Appendix B provides additional details on GFA and TFA. North American costing and energy studies typically reference GFA, while Passive House energy demand targets are based on TFA. The two values can be significantly different as TFA excludes several areas. This study uses GFA for all costing ($/sf) and TFA for all energy intensities (kWh/m^2 and W/m^2). This was done to allow builders to compare costing values to their typical costs, while keeping energy demand numbers in line with Passive House requirements.

2.2 Case Study House 2

Case Study House 2 is also a two-storey house with a small third-storey mezzanine. First and second floor plans of Case Study House 2 are shown in Figure 2.2. Similar to Case Study House 1, the house has a conditioned basement and a predominantly low-slope roof, with a vaulted roof above the third floor mezzanine.

→ Gross Floor Area (GFA): 235 m^2 (2,500 sf)

→ Treated Floor Area (TFA): 171 m^2 (1,840 sf)

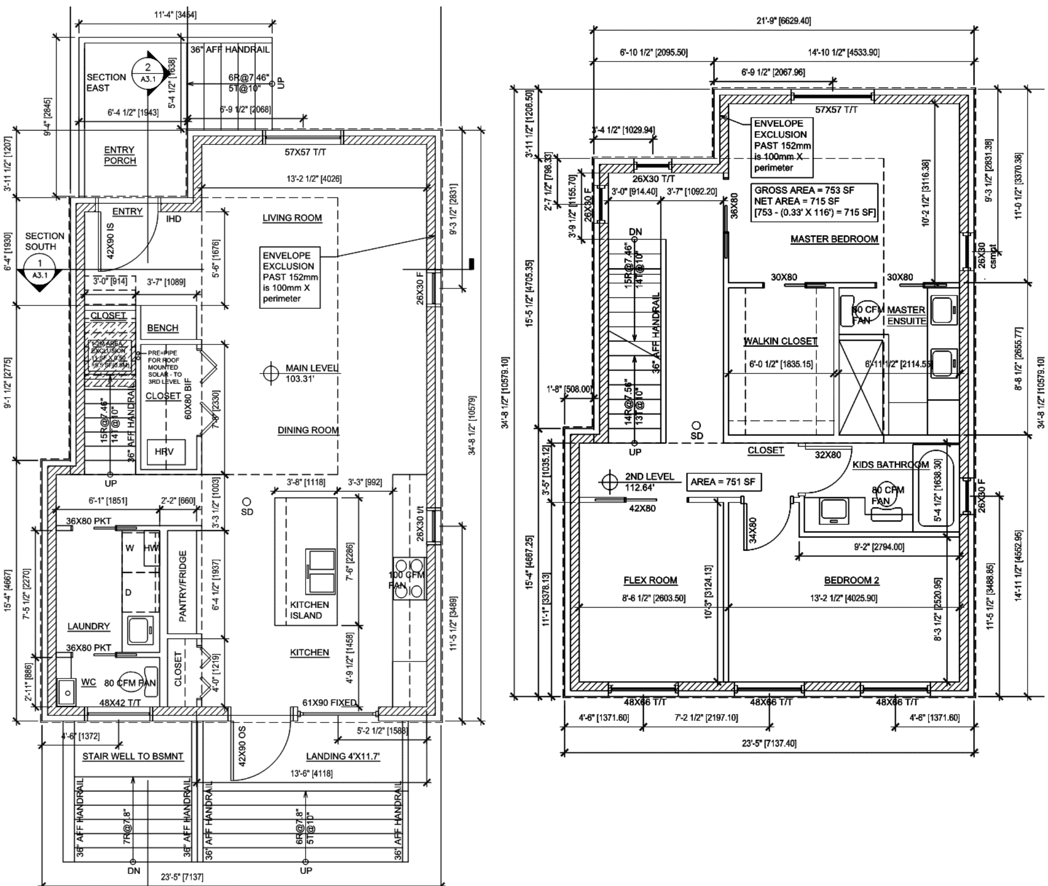


Figure 2.2 First (left) and second (right) floor plans of Case Study House 2.

3 Energy Analysis

A series of energy models were prepared based on two house designs. The two house designs selected as the basis of this study were chosen because they are actual Passive House projects on typical 33-foot-wide lots in the City of Vancouver. In order to standardize construction costs, the assemblies and components in the modelled designs are different from those in the actual houses. This was done to base the study on that are common in Vancouver.

Each design was modelled twice, first to the VBBL standard, and again to the Passive House (PH) standard. This resulted in a total of four variations to be studied: House1 to VBBL, House 1 to PH, House 2 to VBBL, and House 2 to PH.

The first and third of these variations (the VBBL compliance models) were initially modelled in HOT2000 (Version 10.51) using standards and practices establishes by Natural Resources Canada and the City of Vancouver. Each of these HOT2000 models was prepared by an active Certified Energy Advisor and reviewed by a second active Certified Energy Advisor. No advanced modelling techniques were employed; rather, these models were prepared much as any other HOT2000 model would be prepared for compliance with City of Vancouver requirements.

The results of these HOT2000 models provide a rough “baseline” that shows how the EnerGuide for New Houses system would rate these two designs if constructed to the VBBL using the selected assemblies. House 1 achieved a rating of EnerGuide 81, House 2 achieved a rating of EnerGuide 84.

When compared to other new houses built to the City of Vancouver code, both of these designs fall on the higher end of the EnerGuide Rating spectrum. House 2, for example, achieves EnerGuide 84 without the addition of a heat pump, drain water heat recovery, or other above-code components. This is likely a result of the fact that these designs were developed by project teams aiming for the Passive House standard: Both have lower than normal ratio of floor area to envelope area, and both have optimized window placement to maximize wintertime solar gains while limiting summertime overheating.

The energy efficiency of the VBBL versions of these designs, both those modelled in HOT2000 and those modelled in the Passive House Planning Package, is likely superior to the efficiency of many new single-family homes in Vancouver. So while the designs are similar in gross shape and size to the overwhelming majority of new developments on 33-foot-wide RS-1 lots, this two-house sample must not be misconstrued as representative of how all RS-1 designs will perform.

3.1 HOT2000 vs PHPP

All four variations (both the PH and VBBL models for both designs) were modelled in the Passive House Planning Package (version 9.3) using standards and practices established by the Passive House Institute (PHI). Each of these PHPP models was prepared by an active Certified Passive House Consultant, and reviewed by a second Certified Passive House Consultant. No atypical modelling techniques were employed; the PHPP models were prepared as simply as possible.

Wherever practical, the HOT2000 and PHPP inputs were standardized. Ventilation rates, for example, are set at the Passive House flow rates in each model.

In numerous instances, however, it was not possible to standardize the inputs within the scope of this limited study. The two energy modelling systems employ different boundary conditions (i.e., different design temperatures and climate data), different takeoff practices (i.e., inside vs. outside measurements), and different usage assumptions (i.e., occupancy and plug load). These are just three of many examples.

The most significant difference between the two modelling regimes is likely the way each system assesses thermal bridging. HOT2000 incorporates assumptions about repeating and geometric thermal bridges through assembly calculations and by counting corners on exterior walls. The estimated "Psi Values" that drive these calculations are not readily visible to the modeller, and Certified Energy Advisors are not trained either to assess or input results of structural thermal bridging.

Due to these many differences between systems, the project team cautions against drawing direct comparisons between results from HOT2000 and PHPP. Experience working with both systems suggests that "Peak Heat Load" may be the most directly comparable metric between the two systems because "Peak Heat Load" is not as significantly affected by variations in climate files, heating system efficiency, usage assumptions, and annual energy calculation algorithms.

TABLE 3.1 VBBL PEAK HEATING

	HOT2000	PHPP
House 1 peak heat load	8,397 W	7,638 W
House 2 peak heat load	5,864 W	5,623 W

3.2 VBBL vs Passive House

Having compared the PHPP results for the VBBL assemblies to the more widely used HOT2000 results for the same design and assemblies, PHPP was used to compare the VBBL assembles to the Passive House assembles for the two house designs. This approach was used in order to compare study results with the same simulation tool. Appendix B presents further results using HOT2000 for the VBBL baseline.

Passive House is often described as a standard that results in buildings that require 85 percent to 90 percent less heating energy than code-minimum construction. This claim is based on comparing Passive House heat demand with historical heat demand data, typically aggregated on a national level. For example, Natural Resources Canada data shows that "average" Canadian homes consume in the range of 150 kilowatt hours of energy for each one square meter of floor space heated over the course of a year. Because a Passive House is, by definition, a building that limits heating demand to 15 $kWh/m^2/yr$, on can reasonably describe the Passive House as a 90% reduction of heating energy.

The City of Vancouver adopted a new and more stringent building envelope standard for one- and two-family residences in 2014. The Vancouver Building By-Law (VBBL) requires R-22 effective walls, U_{SI}-1.4 windows, and airtightness of 3.5 air changes per hour at ±50 Pascals, among other requirements.

The findings below appear to support the conclusion that the 2014 VBBL requirements for enclosure improvements are capable of significantly improving building energy performance. When modelled to the VBBL requirements, the two homes in this small study achieve a modelled annual heating demand of approximately 86 kWh/m²/yr. Appendix B presents additional VBBL versus Passive House results.

TABLE 3.2 VBBL VS. PASSIVE HOUSE RESULTS		
	VBBL	**Passive House**
House 1		
Peak heating, W	7,638 W	2,430 W
Peak heating, W/m² (TFA)	35.2 W/m²	11.2 W/m²
Annual Space Heating , kWh/m² (TFA)	87 kWh/m²/yr	15 kWh/m²/yr
Primary Energy, kWh/m² (TFA)	154 kWh/m²/yr	68 kWh/m²/yr
House 2		
Peak heating, W	5,623 W	1,606 W
Peak heating, W/m² (TFA)	32.9 W/m²	9.4 W/m²
Annual Space Heating, kWh/m² (TFA)	86 kWh/m²/yr	12 kWh/m²/yr
Primary Energy, kWh/m² (TFA)	166 kWh/m²/yr	80 kWh/m²/yr

This limited study suggests that for compact single-family homes in the City of Vancouver, the difference between 2014 VBBL and Passive House is closer to 80 percent.

Please note again that both of the designs on which these models were based were optimised for Passive House performance. Typical RS-1 designs might be expected to perform slightly worse, whether constructed using either the VBBL or Passive House assemblies.

4 Economic Analysis

4.1 Capital Costs

In order to compare the capital costs and the operating costs of a Passive House, the capital costs of the building enclosure and primary mechanical systems were measured using construction estimation techniques. Pricing was obtained using published data including RSMeans and informed by project experience. RSMeans is a construction cost estimation database and the industry standard tool for estimating material and labor costs. Because the costs of construction can vary greatly between geographical areas, RSMeans uses a 'location factor' to reflect pricing between different locations; Vancouver pricing was used for this study. All costing reflects pricing obtained in summer 2015; pricing can vary significantly over time, which would have an impact on the relative costs of Passive House construction. All costs were reviewed by a third-party cost consultant (PQS).

The costing analysis completed for this study excluded costs for Passive House certification, as the study seeks to understand the economics of performance exclusive of certification costs.

It is important to highlight several factors in this study that may impact the cost of Passive House, but are considered learning costs rather than hard material and construction costs. These factors were also not included in costing, in order to understand the long-term economics of a market with trained and experienced designers, professionals, and trades. However, these factors remain important considerations in achieving the high standards required for Passive House performance.

→ Design and engineering costs
  There may be a learning curve for design, engineering and construction for things like simple form factors, highly insulated enclosure assemblies (split insulation, thicker assemblies), HRV layout, etc. as the industry gains experience with Passive House techniques.

→ Air sealing
  The high airtightness target required for Passive House is likely to increase costs in the short term for extra airtightness testing and sealing work, which may include costs for repair work following initial testing that does not meet the Passive House standard. However, it is anticipated that as airtight construction and testing practices become standard, the material and labour costs to deliver an airtight house should not be higher than the air barrier costs carried for a current VBBL house.

→ Thermal bridging reduction
  Greater attention to detail will be required to reduce thermal bridging, however this is anticipated to be a learning curve that should not add costs to a project in the long term as designers and contractors become used to these practices.

Table 4.1 provides a summary of the assemblies and mechanical systems used for the VBBL and Passive House cost comparison. A complete summary of costing is provided in Appendix A, with rationale behind the assemblies and systems selected for the cost comparison.

TABLE 4.1 ASSEMBLIES USED FOR ECONOMIC ANALYSIS		
Assembly	**VBBL**	**Passive House**
Slab-On-Grade	2” XPS under-slab insulation with 2” XPS slab-edge protection	Super-insulated raft slab with 6” XPS under-slab insulation and 6” XPS slab-edge protection
Below-Grade Walls	Insulated concrete form (ICF) with 2.25” continuous EPS insulation on interior and outer face of 7.75” concrete core	Insulated concrete form (ICF) with 4.25” continuous EPS insulation on interior and exterior face of a 7.75” concrete core
Above-Grade Walls	Split-insulated 2x6 wood framing (24” o.c.) with 1.5” continuous exterior mineral wool	Split-insulated 2x4 wood framing (24” o.c.) with 8” continuous exterior mineral wool
Windows	Double glazed, vinyl frame, surface 4 low-e (USI < 1.4)	Triple glazed, vinyl frame, Passive House window (USI < 0.8)
Roof	2x10 low-slope, 10” batt insulated roof with 2-ply SBS membrane	18” low-slope parallel chord truss, with 18” mineral wool batt insulation and 2-ply SBS membrane
HRV	65% efficient unit with trunk and branch distribution system	85% efficient unit with home run, flexible plastic distribution system
Space Heating	High efficiency condensing boiler combination system with in-floor radiant distribution	High-efficiency condensing boiler combination system with radiant panel distribution (one panel per floor)

Table 4.2 provides a breakdown of the capital costs required to construct the enclosure and mechanical components for a Passive House and a VBBL house based on the average costs of the two buildings studied. It is important to note that these houses include compact shape factors to minimize enclosure area; costs for a house with larger enclosure to volume ratio would likely see higher incremental costs for Passive House construction.

TABLE 4.2 COST BREAKDOWN FOR PASSIVE HOUSE AND VBBL ASSEMBLIES				
Assembly	**VBBL Cost**	**Passive House Cost**	**Incremental Cost for Passive House**	**Percent Increase for Passive House**
Enclosure Costs	*$/sf assembly*	*$/sf assembly*	*$/sf assembly*	*%*
Slab-On-Grade	$16.93	$20.44	$3.51	21%
Below-Grade Walls	$35.93	$37.25	$1.32	4%
Above-Grade Walls	$17.33	$21.25	$3.92	23%
Windows	$51.35	$59.05	$7.70	15%
Roof	$22.24	$25.91	$3.67	17%
Total Enclosure	$53/sf GFA	$62/sf GFA	$9/sf GFA	18%
Mechanical Costs	*$*	*$*	*$*	*%*
HRV	$1,701 (dist.) + $1,453 (unit)	$2,500 (dist.) + $3,557 (unit)	$2,900	92%
Space Heating[5]	$4.00/sf (dist.) + $4,000 (unit)	$1,950 (dist.) + $4,000 (unit)	-$9,480	-61%
Total Mechanical	$18,600	$12,000	-$6,580	-35%
Total Costs[6]				
$/sf floor area	$59/sf GFA	$66/sf GFA	$7/sf GFA	12%
Average Total Cost	$170,000	$190,000	$20,000	

4.2 Life Cycle Cost Assessment

A Life Cycle Cost assessment (LCC) was performed for each of the two case study houses to compare the energy cost savings attributable to Passive House design practices with the incremental costs of constructing the homes to Passive House. The LCC assessment is an economic analysis that looks at cash flow projections to consider increased capital costs versus energy savings over the life of the house and the time value of money. A 30 year window was selected for this analysis as a reasonable timeframe for the study; the building enclosure components are likely to have a longer lifespan, while mechanical equipment is likely to have a shorter lifespan.

For the LCC, a number of assumptions were made regarding critical inputs for the analysis, shown in Table 4.3.

[5] Because space heating distribution for the VBBL house is based on floor area of the building, the average floor area for House 1 and House 2 is used in this comparison.
[6] "Total Construction Cost" in the context of this study reflects enclosure and mechanical systems, and does not include items such as interior finishes and cost of land, among other things.

TABLE 4.3 PARAMETERS USED FOR LIFE CYCLE COST ASSESSMENT	
Natural gas rate	\$9.00 / GJ [7]
Electricity rate	\$0.08 / kWh [8]
Natural gas rate increase	2% per year
Discount rate (real 2015 \$)	6%
CPI	1.10%
Natural gas emission factor	49.99 kg CO_2e/GJ [9]
Electricity emission factor	14 tCO_2e/GWh [9]

Table 4.4 summarizes the LCC economics of Passive House construction as an upgrade over the VBBL for the two houses studied. This comparison is based on heating energy savings modelled using PHPP for both the VBBL and Passive House scenarios; refer to Appendix B for additional details and a comparison using HOT2000 simulation results.

TABLE 4.4 HOUSE 1 & 2 LCC SUMMARY[10]		
	House 1	**House 2**
Total Incremental Cost	\$23,700	\$16,300
Incremental Cost per SF GFA	\$7.50/sf	\$6.50/sf
Annual Energy Cost Savings	\$550	\$510
Annual GHG Savings	3,000 kg CO_2e	2,400 kg CO_2e
Net Present Value (NPV)	(\$13,300)	(\$7,900)
Internal Rate of Return (IRR)	0%	1%
Discounted Payback	30 years	26 years

4.3 Discussion

The energy analysis performed for this study indicates that substantial energy savings may be realized by upgrading to Passive House construction practices. As a result of these energy savings, substantial GHG savings are also realized (in the order of 50-75% annually), which is attributable to less natural gas combustion for heating.

An average incremental cost of \$20,000 was estimated for constructing the homes to Passive House levels based on the two prototype houses studied. This cost premium is driven by the increased thermal performance required for the building enclosure, but is reduced by lower mechanical system costs. For instance, in-floor radiant heating was not required for the Passive House homes; instead a single radiant panel was used on each floor of the Passive House. When viewed as a percentage of the total construction costs for the homes, these added costs represent a cost premium of 2-7% (depending on the total cost of construction, see Table 4.5). This result is in line with several previous studies, as summarized in Figure 4.1.

[7] Fortis BC rates as of September 2015 plus carbon tax (\$1.50/GJ).
[8] Blend of BC Hydro Step 1 and Step 2 rates.
[9] 2013 B.C. Best Practices Methodology for Quantifying Greenhouse Gas Emissions, http://www.toolkit.bc.ca/sites/default/files/BC-Best-Practices-Methodology-for-Quantifying-Greenhouse-Gas-Emissions.pdf
[10] Table 4.4 results are based on energy modeling done in PHPP, both for the VBBL baseline and Passive House models. A similar comparison using HOT2000 for modeling the VBBL house and PHPP for modeling the Passive House is provided in Appendix B. The HOT2000 simulation resulted in far lower annual heating demand than the PHPP simulation, and so the economics are worse when compared using results from HOT2000 for the VBBL case.

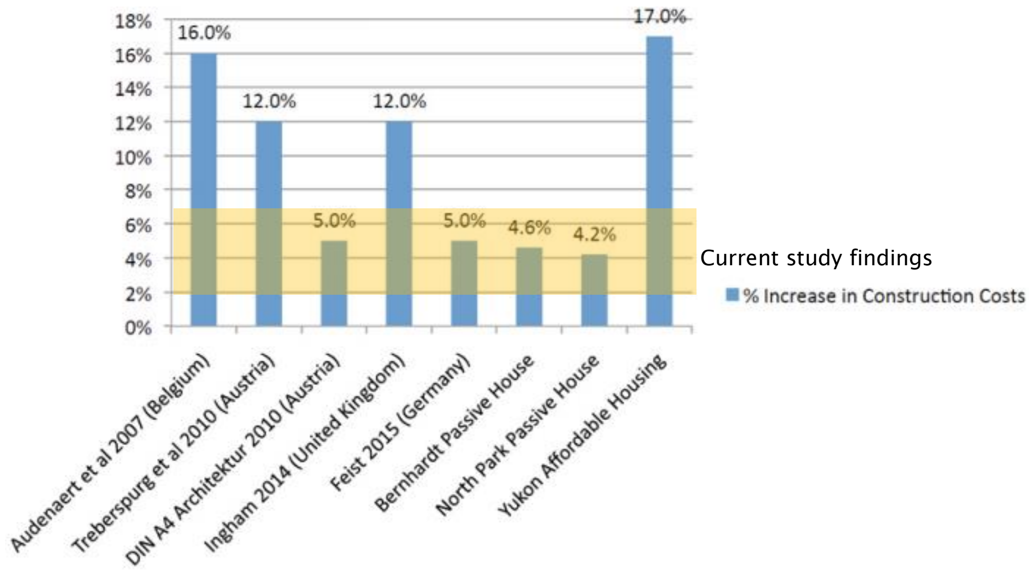


Figure 4.1 Summary of incremenetal construction costs of Passive House construction as determined in recent studies.[11]

While the results from this report are in some ways comparable with the other research projects summarized in Figure 4.1, projects across the world are subject to different building codes and costs of construction. Furthermore, there are methodological differences between the studies in Figure 4.1, such as the inclusion of consultant fees and Passive House certification fees, which were not included in this work.

Figure 4.2 shows the incremental costs for Passive House estimated through this study compared to a typical construction costs in Vancouver. Incremental Passive House costs represent a relatively low proportion of costs considering typical construction costs in Vancouver.

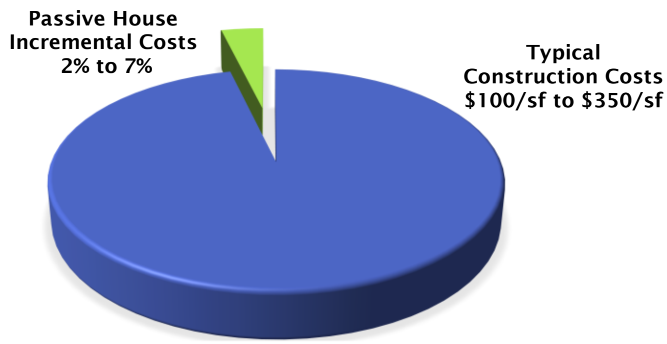


Figure 4.2 Incremental costs for Passive House as a percentage of typical construction costs in Vancouver.

An important consideration in the analysis of incremental costs is the increase over the total project cost, including land value. The mean land value for an RS-1 lot in Vancouver is $1,025,000, based on the City of Vancouver's Open Data Catalogue 2014 survey. A summary of the range of percentage price premiums for Passive House construction in Vancouver, calculated based on total construction costs as well as the cost of land, is presented in Table 4.5. When land is factored into the costing analysis, Passive House construction represents less than 2% of the cost.

[11] Synergy Sustainability Institute. *The Business Case for Passive House*. May 27, 2015

TABLE 4.5 INCREMENTAL COST FOR PASSIVE HOUSE AS A PERCENT OF TOTAL CONSTRUCTION COSTS

Total Construction Costs ($/ft^2)	Passive House Price Premium (%, excluding land)	Passive House Price Premium (%, including land)
$100	7% - 8%	<2%
$150	4% - 5%	<2%
$200	3% - 4%	<2%
$250	2% - 3%	<2%

5 Electric Baseboard Heating

The previous analysis was completed for a hydronic heating system, with a gas-fired boiler and radiant heating (in-floor for the VBBL house and wall mounted panels for the Passive House). This work was updated to compare economics with electric baseboard heating in the Passive House case (keeping radiant floor heating in the VBBL scenario).

Table 5.1 shows the cost breakdown comparing the VBBL baseline (same as previous) to a Passive House with electric heat and hot water. Incremental costs are lower for this scenario due to capital cost savings associated with the electric system versus a hydronic boiler in the VBBL baseline.

TABLE 5.1 COST BREAKDOWN FOR PASSIVE HOUSE AND VBBL, ELECTRIC HEATING IN PASSIVE HOUSE CASE

Assembly	VBBL Cost	Passive House Cost	Incremental Cost for Passive House	Percent Increase for Passive House
Enclosure Costs	*$/sf assembly*	*$/sf assembly*	*$/sf assembly*	*%*
Slab-On-Grade	$16.93	$20.44	$3.51	21%
Below-Grade Walls	$35.93	$37.25	$1.32	4%
Above-Grade Walls	$17.33	$21.25	$3.92	23%
Windows	$51.35	$59.05	$7.70	15%
Roof	$22.24	$25.91	$3.67	17%
Total Enclosure	$53/sf GFA	$62/sf GFA	$9/sf GFA	18%
Mechanical Costs	*$*	*$*	*$*	*%*
HRV	$1,701 (dist.) + $1,453 (unit)	$2,500 (dist.) + $3,557 (unit)	$2,900	92%
Space Heating[12]	$4.00/sf (dist.) + $4,000 (unit)	$1,000 (bb's) + $1,000 (DHW)[13]	-$9,480	-61%
Total Mechanical	$18,600	$8,000	-$10,600	-56%
Total Costs[14]				
$/sf floor area	$59/sf GFA	$65/sf GFA	$6/sf GFA	10%
Average Total Cost	$170,000	$186,000	$16,000	

Table 5.2 shows a breakdown of the life cycle costs of Passive House construction as an upgrade over the VBBL with electric baseboard heating and an electric water heater in the Passive House case. GHG savings are higher due to fuel switching from gas to electric heating (DHW emissions savings are not considered in this analysis), but annual energy

[12] Because space heating distribution for the VBBL house is based on floor area of the building, the average floor area for House 1 and House 2 is used in this comparison.
[13] The cost of an electric storage tank water heater is included; although DHW is not within the scope of this study, the baseline VBBL house includes a combination heat and hot water boiler, and so the cost of an electric water heater should be included here for comparison.
[14] "Total Construction Cost" in the context of this study reflects enclosure and mechanical systems, and does not include items such as interior finishes and cost of land, among other things.

cost savings are lower due to the higher price of electricity. Overall economics are better than the previous (gas-gas) comparison due to the lower capital cost for Passive House.

TABLE 5.2 HOUSE 1 LCC SUMMARY, PHPP FOR VBBL BASELINE		
	House 1	**House 2**
Total Incremental Cost	$19,900	$12,100
Incremental Cost per SF GFA	$6.20/sf	$4.90/sf
Annual Energy Cost Savings	$340	$300
Annual GHG Savings	3,600 kg CO_2e	2,900 kg CO_2e
Net Present Value (NPV)	($12,200)	($5,600)
Internal Rate of Return (IRR)	0%	2%
Discounted Payback	>30 years	25 years

6 Intermediate Target: 30 kWh/m²

In addition to the Passive House costing analysis, a similar analysis was performed to evaluate an intermediate target of 30 kWh/m² annual space heating energy consumption. This 30 kWh/m² is intended to represent an intermediate level of energy efficiency, in between Passive House and VBBL.

6.1 Components to Reach 30 kWh/m²

In order to reach the intermediate target of 30 kWh/m²/yr, a combination of building enclosure components and mechanical systems were selected from the VBBL and Passive Houses and modeled using PHPP for both House 1 and House 2. The combination of building components that was selected for evaluation is summarized in Table 6.1. Several additional combinations of measures were investigated in PHPP in determining the best set of measures; additional results for these simulations are shown in Appendix B.

TABLE 6.1 ASSEMBLIES USED FOR ECONOMIC ANALYSIS

Assembly	**30 kWh/m² House**
Slab-On-Grade **VBBL**	2" XPS under-slab insulation with 2" XPS slab-edge protection
Below-Grade Walls **VBBL**	Insulated concrete form (ICF) with 2.25" continuous EPS insulation on interior and outer face of 7.75" concrete core
Above-Grade Walls **Intermediate**	Split-insulated 2x4 wood framing (24" o.c.) with 4" continuous exterior mineral wool
Windows **PH**	Triple glazed, vinyl frame, Passive House window (USI < 0.8)
Roof **VBBL**	2x10 low-slope, 10" batt insulated roof with 2-ply SBS membrane
HRV **PH**	85% efficient unit with home run, flexible plastic distribution system
Space Heating	High-efficiency condensing boiler combination system with radiant panel distribution (amount of panels calculated to meet load)

These assemblies were selected from the VBBL and Passive House as follows:

→ **VBBL** Slab, foundation walls, and roof assemblies

→ **Intermediate** Above grade walls

→ **PH** windows, ventilation, airtightness, and thermal bridging

The capital cost of each of these assemblies was calculated using a quantity takeoff (QTO) approach as described previously in order to determine the incremental costs above VBBL that would be required for reaching this intermediate target. Table 6.2 shows the costs associated with the 30 kWh/m² case compared to the VBBL baseline.

TABLE 6.2 COST BREAKDOWN FOR PASSIVE HOUSE AND VBBL, 30 KWH/M2				
Assembly	**VBBL Cost**	**30 kWh/m² Cost**	**Incremental Cost for 30 kWh/m²**	**Percent Increase for 30 kWh/m²**
Enclosure Costs	*$/sf assembly*	*$/sf assembly*	*$/sf assembly*	*%*
Slab-On-Grade	$16.93	$16.93	-	-
Below-Grade Walls	$35.93	$35.93	-	-
Above-Grade Walls	$17.33	$21.25	$3.92	23%
Windows	$51.35	$59.05	$7.70	15%
Roof	$22.24	$22.24	-	-
Total Enclosure	$53/sf GFA	$58/sf GFA	$5/sf GFA	10%
Mechanical Costs	*$*	*$*	*$*	*%*
HRV	$1,701 (dist.) + $1,453 (unit)	$2,500 (dist.) + $3,557 (unit)	$2,900	92%
Space Heating[15]	$4.00/sf (dist.) + $4,000 (unit)	$6,500 (dist.) + $4,000 (unit)	-$2,000	-11%
Total Mechanical	$18,600	$16,600	-$2,000	-11%
Total Costs[16]				
$/sf floor area	$59/sf GFA	$64/sf GFA	$5/sf GFA	8%
Average Total Cost	$170,000	$184,000	$14,000	

6.2 Life Cycle Cost Assessment

After updating the capital costs, a Life Cycle Cost assessment (LCC) was performed for each of the two case study houses to compare the energy cost savings attributable to a performance of 30 kWh/m²/yr heating with the incremental costs of constructing the homes to this intermediate performance level.

For this LCC, the same assumptions that were made regarding critical inputs for the analysis (Table 4.3) were used here. The results of this LCC are summarized in Table 6.3.

TABLE 6.3 HOUSE 1 AND 2 30 KWH/M2 LCC SUMMARY		
	House 1	**House 2**
Total Incremental Cost	$16,900	$10,900
Incremental Cost per SF GFA	$5.30/sf	$4.40/sf
Annual Energy Cost Savings	$430	$350
Annual GHG Savings	2,400 kg CO_2e	1,900 kg CO_2e
Net Present Value (NPV)	($8,600)	($4,200)
Internal Rate of Return (IRR)	1%	2%
Discounted Payback	27 years	23 years

[15] Because space heating distribution for the VBBL house is based on floor area of the building, the average floor area for House 1 and House 2 is used in this comparison.
[16] "Total Construction Cost" in the context of this study reflects enclosure and mechanical systems, and does not include items such as interior finishes and cost of land, among other things.

6.3 Discussion

This analysis suggests that the intermediate target of 30 kWh/m^2 of annual space heating energy can save over 2,000 kg CO_2e annually (as compared to the VBBL baseline) with approximately 30% less capital investment than the Passive House standard. This contributes to a less negative NPV for the intermediate target house as compared to the Passive House, a positive IRR, and a payback period below 30 years.

It is important to note that at the intermediate target of 30 $kWh/m^2/yr$ it is possible that certain assumptions applicable to Passive House levels of efficiencies no longer hold true. For instance, Passive Houses are able to achieve comfortable indoor environments by minimizing the difference between surface temperatures and air temperatures in the building, reducing the need for perimeter heating. If the performance of certain components are lowered, and depending on the design of the house, additional heating capacity may be required despite a low simulated annual demand.

Additionally, it is important to note that some of the critical Passive House attributes, in particular thermal bridge-free design and air tightness, may be more challenging to achieve in practice without using Passive House assemblies. This could further erode the energy savings of the 30 $kWh/m^2/yr$ intermediate target. Finally, the components found to yield 30 $kWh/m^2/yr$ in the simulations performed for this study are for an optimally designed house, with a low form factor and ideal window placement. This same package of measures may not yield 30 $kWh/m^2/yr$ for a house with more traditional, less optimal plans.

Further research is recommended to determine whether the enclosure R-values and mechanical system performance identified in this exercise consistently yield energy consumption of 30 $kWh/m^2/yr$, particularly in houses that are not optimized for Passive House (higher form factors, non-optimal window placement). This could be valuable in establishing prescriptive requirements for building enclosure and mechanical system components for low energy buildings moving forward.

7 Summary and Conclusions

This study was completed to assess the costs and economics of Passive House single family homes in the City of Vancouver to help owners, designers, and builders compare the costs of Passive House construction for a variety of different assemblies and systems to minimum VBBL requirements.

Costing and energy analysis was performed for two prototypical single family homes with RS-1 zoning which covers about 70% of residential land in Vancouver. The following analysis was performed:

- → Cost estimates for several VBBL and Passive House building enclosure designs, including incremental capital costs for the more insulated Passive House enclosure.
- → Cost estimates of typical heating and ventilation systems.
- → Modelled energy consumption using two energy simulation programs: Canadian (HOT2000) and Passive House (PHPP).
- → Life cycle cost analysis of Passive House in Vancouver.
- → Additional scope to consider Passive Houses with electric baseboard heating.
- → Additional scope to consider the economics of a 30 kWh/m^2 target.

This work led to several key findings, and identified additional research needs.

7.1 Comparing the Energy Performance of VBBL, Passive House, and 30 kWh/m^2

The 2014 VBBL produces a better than average enclosure. When evaluated in PHPP, a Passive House design constructed using VBBL assemblies and components may produce a structure with a space heating demand as low as 86 kWh/m^2/yr (evaluated with PHPP). Other designs may be higher. Still, heating energy savings and corresponding GHG reductions of 75% over the VBBL can be achieved by constructing to the Passive House standard.

Passive House performance requires a 'House-as-a-System' approach. No single component or assembly produces the 15 kWh/m^2/yr result. Likewise, any policy that relies heavily on a short list of upgrades is unlikely to succeed across a variety of building types.

High performance windows are pivotal to achieving high performance envelopes. The findings suggest it will be difficult to achieve even 30 kWh/m^2/yr without Passive House-grade windows, and experience suggests that the substitution of lower-grade windows may require distribution of heat below the windows, reducing mechanical cost savings. Given the difficulty the local industry has experienced in producing U-1.4 windows, it may be advisable to signal an intent to adopt USI-0.8 (PH-grade) windows as early as possible, and set a firm target, so that industry has time to adapt. At the same time, it may be advisable to communicate the global market available to such windows.

Similarly, ventilation improvements require better HRVs. There is presently a relative shortage of ventilation equipment capable of producing heat recovery in the 85%-plus range in the Vancouver market. It may be advisable to signal an intent to adopt HRVs with

85-95% heat recovery efficiency, and to set a firm target, so that industry has time to adapt.

If an intermediate target of 30 kWh/m² is to be considered, relaxing opaque building enclosure R-values (e.g. walls, roof, below grade) compared to Passive House standards appears to be the most cost effective path. This approach would also allow the market for Passive House level components (windows and HRVs) to develop. However, a concern is that reduced opaque enclosure performance could make it difficult to achieve cost-effective airtightness and thermal bridging savings, and mechanical designs may not deliver modelled performance.

7.2 Comparing the Economics of VBBL and Passive House

For the two houses studied in this project, building enclosure costs are 15% to 20% higher for Passive House; however, mechanical cost savings of 30% to 40% are realized. This leads to an overall total construction cost premium of approximately 2% to 7% as compared to VBBL construction based on typical construction prices in Vancouver.

The cost premium for Passive House (enclosure and mechanical costs) was $20,000 to $25,000 based on the two designs investigated in this study. Houses with less compact designs or non-standard assemblies and systems may see higher cost premiums.

Improved airtightness and reduced thermal bridging represent the most cost-effective improvement options modelled in this study. These upgrades are more dependent on knowledge than materials; while they may require additional training and learning as these practices are new to the building community, they should not add cost for experienced teams. It may be advisable to commence a sustained period of training for architects and builders, with the intent of upgrading industry knowledge base over a five-year period (also preparing the industry for higher-performance windows and HRVs).

Overall annual energy bills are up to 20% to 25% lower in a Passive House than a comparable VBBL house. However, the life cycle economics for Passive House still yield high payback periods and negative net present value due to the low cost of energy in Vancouver and the relatively high standard in the 2014 VBBL. Despite the life cycle economics, the total incremental cost for Passive House is low compared to land and construction costs in Vancouver. There are also many non-energy benefits to Passive House that are not captured in the economic analysis performed for this study that provide additional value for a Passive House home.

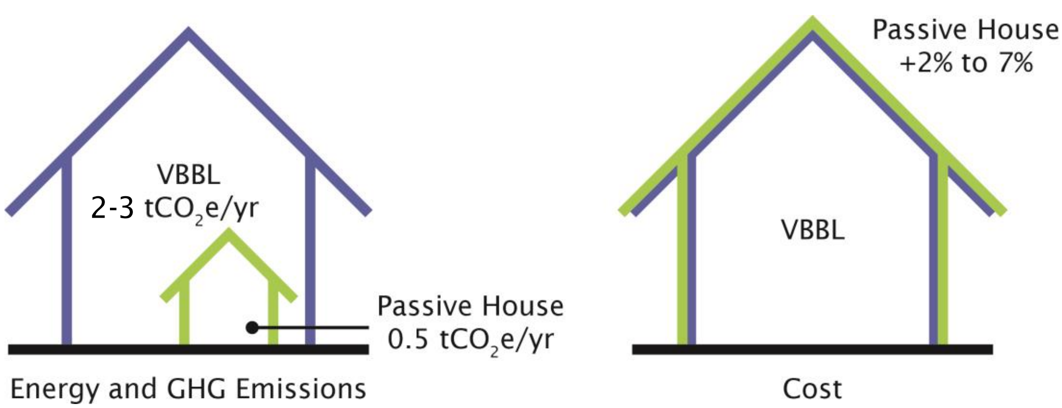


Figure 7.1 Comparison of the GHG emissions and cost of Passive House and VBBL construction.

7.3 Recommendations for Future Work

Several areas for additional study were identified through this project.

- → Significant discrepancies in heating energy were noted between the same VBBL-compliant house modelled using HOT2000 and PHPP. Further investigation should be completed to better understand the reasons for the difference in simulated heating energy to ensure decisions are based on appropriate simulation results. This study included a comparison of the VBBL house simulated in both HOT2000 and PHPP; a follow-up study should include the simulation of the Passive House in HOT2000.
- → A better understanding of thermal bridging in VBBL houses is needed to understand real, effective heat loss in VBBL and 30 kWh/m^2 houses. If a 30 kWh/m^2 target is to be assessed using the program HOT2000, guidance is needed on appropriately addressing thermal bridging in this program.
- → This study was based on two homes designed to follow the Passive House standard, with compact form factors, low enclosure to volume, and optimal window configurations. While this study has identified packages of measures that result in 30 kWh/m^2, it is important to note that these same packages of measures may not yield this performance target when applied to a house with a more standard design, including traditional plans and non-optimal window placement. A follow-up study is recommended to investigate whether or how the 30 kWh/m^2 target can be achieved using more common plans for houses in Vancouver.
- → The 30 kWh/m^2 target may allow for some capital cost savings through a less stringent enclosure, however concerns over comfort could lead to over-designed systems that do not realize the same level of savings that the Passive House standard would deliver. For example, a lower performing window may necessitate perimeter heating, despite low annual energy loads. This should be investigated further if an intermediate 30 kWh/m^2 target is pursued.
- → Being a European standard, Passive House relies on several different methods and standards than traditionally used in North America, including product certification and testing standards for windows and HRVs. Also, Passive House uses references Treated Floor Area (TFA) for energy intensities, while Gross Floor Area (GFA) is used for costing and most North American energy studies. Any standards or requirements must be careful to reference appropriate values or certifications. Guidance should be provided to assist designers and builders in navigating the various standards and metrics.
- → High solar heat gain coefficient (SHGC) glazing is key to achieving Passive House performance targets, but there is currently no standard for SHGC in the VBBL. Further, the Passive House standard includes criteria to ensure appropriate airflow and/or shading is provided to prevent overheating. North American glazing manufacturers typically recommend low solar gain products due to overheating concerns. Designing optimal glazing and shading to maximize solar gains and prevent overheating is an area that requires further study in the Vancouver climate, with common Vancouver designs and construction practices.

Appendix A

Itemized Costing

Itemized Assembly Costing

Itemized pricing for each assembly that was costed is provided in this Appendix. VBBL assemblies are highlighted in blue and Passive House assemblies are highlighted in green.

Where multiple assemblies were costed, the rationale behind selection of the assembly used in the final costing analysis for this study is provided.

Slab

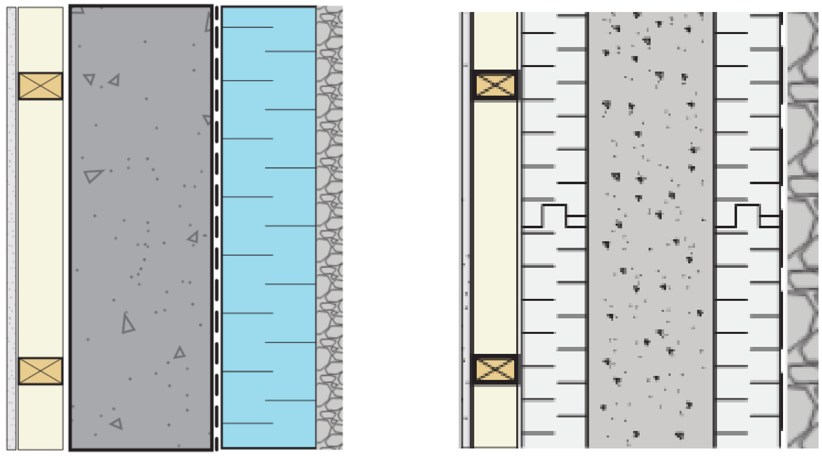
For costing purposes, 2" XPS insulation under the entire slab with 2" XPS slab edge protection was selected for the VBBL assembly to reflect common, code compliant construction practices. A super-insulated raft slab with 6" XPS was selected as the Passive House assembly for its cost-competitiveness. An insulated concrete footing with 6" of high density EPS under the footings was also priced, and was found to be 27% more expensive than the raft slab option.

Slab	$\$/ft^2$
VBBL: 2" XPS Insulation (R12)	
Finished flooring - laminate	6.25
Finished flooring - underlayment	2.90
150mm (6") reinforced concrete slab	5.50
15 mil polyethylene vapour/radon barrier	0.28
50mm (2") XPS insulation	2.00
Total Cost	16.93
PH: Superinsulated raft slab (R32)	
Finished flooring - laminate	6.25
Finished flooring - underlayment	2.90
150mm (6") reinforced concrete slab	5.50
15 mil polyethylene vapour/radon barrier	0.28
150mm (6") XPS insulation	5.51
Total Cost	20.44
PH: Insulated concrete footings (R32)	
Finished flooring - laminate	6.25
Finished flooring - underlayment	2.90
Reinforced concrete slab	5.50
15 mil polyethylene vapour/radon barrier	0.28
150mm (6") XPS insulation	5.51
Poured concrete footings	0.00
150mm (6") high density EPS insulation under footings	5.51
Total Cost	25.95

Below Grade Walls

Both a cast-in-place and an ICF option were priced for VBBL and Passive House construction standards. ICF pricing was used in the costing analysis because of its lower cost; however, it should be noted that some builders might prefer aspects of cast-in-place construction despite the relatively higher cost of construction.

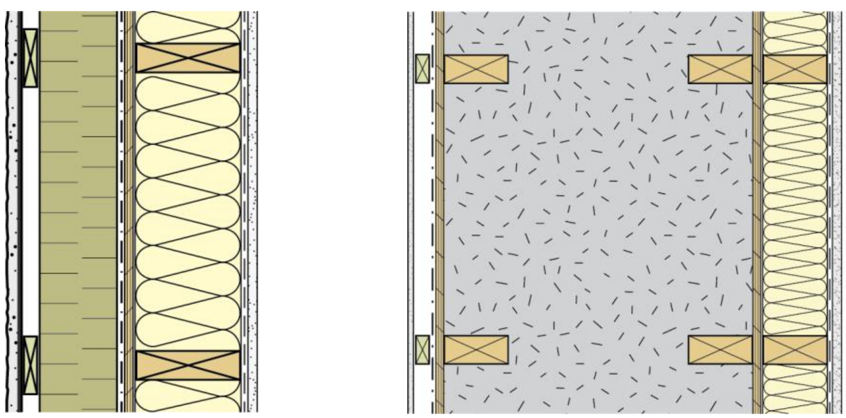
Below Grade Walls		$/ft^2
VBBL: Exterior 4" XPS		
	Interior painting	1.00
	13mm (1/2") gypsum wallboard	1.65
	38mm x 89mm (2x4) framed service wall	2.21
	Pressure treated horizontal 19mm x 38mm (1x2) strapping, fastened to foundatior	2.98
	Poured concrete foundation wall	21.00
	Self adhered waterproofing membrane	2.87
	Dimplemat non-capillary drainage layer	1.13
	100mm (4") XPS board insulation fastened to exterior of foundation wall	3.51
	300mm (12") free-draining backfill	1.85
	Clay soil drainage cap	0.16
	Total Cost	38.36
VBBL: ICF (R22)		
	Interior Painting	1.00
	13mm (1/2") gypsum wallboard	1.65
	38mm x 89mm (2x4) framed service wall	2.21
	ICF Joist hanger	0.38
	57mm (2 1/4") EPS board insulation	1.84
	197mm (7 3/4") concrete	21.00
	57mm (2 1/4") EPS board insulation	1.84
	Self adhered waterproofing membrane	2.87
	Dimplemat non-capillary drainage layer	1.13
	300mm (12") free-draining backfill	1.85
	Clay soil drainage cap	0.16
	Total Cost	35.93
PH: Exterior 8" XPS		
	Interior painting	1.00
	13mm (1/2") gypsum wallboard	1.65
	38mm x 89mm (2x4) framed service wall	2.21
	Pressure treated horizontal 19mm x 38mm (1x2) strapping, fastened to foundatior	2.98
	Poured concrete foundation wall	21.00
	Self adhered waterproofing membrane	2.87
	Dimplemat non-capillary drainage layer	1.13
	200mm (8") XPS board insulation fastened to exterior of foundation wall	7.10
	300mm (12") free-draining backfill	1.85
	Clay soil drainage cap	0.16
	Total Cost	41.95
PH: ICF (R38)		
	Interior Painting	1.00
	13mm (1/2") gypsum wallboard	1.65
	38mm x 89mm (2x4) framed service wall	2.21
	ICF Joist hanger	0.38
	108mm (4 1/4") EPS board insulation	2.50
	197mm (7 3/4") concrete	21.00
	108mm (4 1/4") EPS board insulation	2.50
	Self adhered waterproofing membrane	2.87
	Dimpleboard drain mat	1.13
	300mm (12") free-draining backfill	1.85
	Clay soil drainage cap	0.16
	Total Cost	37.25



Graphical representation of exterior insulated (XPS) cast in place foundation wall (left) and insulated concrete form foundation wall (right)

Above Grade Walls

Multiple above grade wall options were priced for both VBBL and Passive House construction standards to reflect the fact that multiple wall options are commonly used throughout the industry. For the purposes of this costing analysis, split-insulated assemblies with continuous mineral wool insulation were used for both VBBL and Passive House construction standards, adjusting the thickness of exterior insulation as required for each performance target. This assembly was chosen because of the durability benefits associated with split-insulated assemblies, as well as their similarity to standard wood frame construction in Vancouver.



Graphical representation of split insulated above grade wall assembly (left) and double stud above grade wall assembly (right)

Above Grade Walls	$/ft^2
VBBL: 2x8 Wood framing with batt insulation	
Interior painting	1.00
12.7mm (1/2") gypsum wallboard	1.65
6 mil polyethylene vapour retarder	0.17
38mm x 190mm (2x8) framing @ 600mm (24") o.c.	4.03
190mm (7 1/2") high density batt insulation in stud cavity (R4/inch)	1.35
13mm (1/2") plywood sheathing	2.15
Vapour permeable air and water barrier membrane	0.30
Membrane tape	0.00
6mm (1/4") x 87.5mm (3.5") long metal screw fasteners	0.00
Vertical Strapping 19mm x 64mm (1x3) @ 600mm (24") o.c.	1.70
Rainscreen drainage cavity	0.00
Exterior cladding - cement board	4.27
Total Cost	16.62
VBBL: 2x4 Wood framing with 3" exterior mineral wool insulation	
Interior painting	1.00
12.7mm (1/2") gypsum wallboard	1.65
6 mil polyethylene vapour retarder	0.17
38mm x 89mm (2x4) framing @ 600mm (24") o.c.	2.21
89mm (3 1/2") high density batt insulation in stud cavity (R4/inch)	0.94
13mm (1/2") plywood sheathing	2.15
Vapour permeable air and water barrier membrane	0.30
Membrane tape	0.00
75mm (3") high density mineral wool insulation	2.75
6mm (1/4") x 125mm (5") long metal screw fasteners	0.00
Vertical Strapping 19mm x 64mm (1x3) @ 600mm (24") o.c.	1.70
Rainscreen drainage cavity	0.00
Exterior cladding - cement board	4.27
Total Cost	17.14
VBBL: 2x6 Wood framing with 1.5" exterior mineral wool	
Interior painting	1.00
12.7mm (1/2") gypsum wallboard	1.65
6 mil polyethylene vapour retarder	0.17
38mm x 140mm (2x6) framing @ 600mm (24") o.c.	3.22
140mm (5 1/2") high density batt insulation in stud cavity (R4/inch)	1.26
13mm (1/2") plywood sheathing	2.15
Vapour permeable air and water barrier membrane	0.30
Membrane tape	0.00
38mm (1.5") high density mineral wool insulation	1.61
6mm (1/4") x 87.5mm (3.5") long metal screw fasteners	0.00
Vertical Strapping 19mm x 64mm (1x3) @ 600mm (24") o.c.	1.70
Rainscreen drainage cavity	0.00
Exterior cladding - cement board	4.27
Total Cost	17.33

PH: Double stud wall with 12" cellulose insulation		
	Interior painting	1.00
	12.7mm (1/2") gypsum wallboard	1.65
	6 mil polyethylene vapour retarder	0.17
	38mm x 89mm (2x4) framing @ 600mm (24") o.c.	2.21
	Bag for insulation filling	0.25
	125mm (5") gap between stud walls	0.00
	38mm x 89mm (2x4) framing @ 600mm (24") o.c.	2.21
	300mm (12") dense pack cellulose insulation	2.01
	13mm (1/2") plywood sheathing	2.15
	Vapour permeable air and water barrier membrane	0.30
	Membrane tape	0.00
	Vertical Strapping 19mm x 64mm (1x3) @ 600mm (24") o.c.	1.70
	Rainscreen drainage cavity	0.00
	Exterior cladding - cement board	4.27
	Total Cost	17.92
PH: 8" Exterior mineral wool insulation		
	Interior painting	1.00
	12.7mm (1/2") gypsum wallboard	1.65
	38mm x 89mm (2x4) framing @ 600mm (24") o.c.	2.21
	89mm (3 1/2") high density batt insulation in stud cavity (R4/inch)	0.94
	13mm (1/2") plywood sheathing	2.15
	Vapour permeable air and water barrier membrane	0.30
	Air barrier tape	0.00
	200mm (8") high density board stock mineral wool insulation	7.03
	6mm (1/4") x 280mm (11") long metal screw fasteners	0.00
	Vertical Strapping 19mm x 64mm (1x3) @ 600mm (24") o.c.	1.70
	Rainscreen drainage cavity	0.00
	Exterior cladding - cement board	4.27
	Total Cost	21.25
PH: 2x10 Framing with batt insulation and 2x4 service wall		
	Interior painting	1.00
	12.7mm (1/2") gypsum wallboard	1.65
	38mm x 89mm (2x4) framing @ 400mm (16") o.c.	2.21
	89mm (3 1/2") fiberglass batt insulation in stud cavity	0.94
	12.7mm (1/2") plywood sheathing	2.15
	Tape plywood sheathing joints	0.00
	38mm x 235mm (2x10) framing @ 600mm (24") o.c.	5.08
	235mm (9.25") high density fiberglass batt insulation in stud cavity (R4/inch)	1.41
	12.7mm (1/2") plywood sheathing	2.15
	Vapour permeable air and water barrier membrane	0.30
	Membrane tape	0.00
	Vertical Strapping 19mm x 64mm (1x3) @ 600mm (24") o.c.	1.70
	Rainscreen drainage cavity	0.00
	Exterior cladding - cement board	4.27
	Total Cost	22.86

Windows

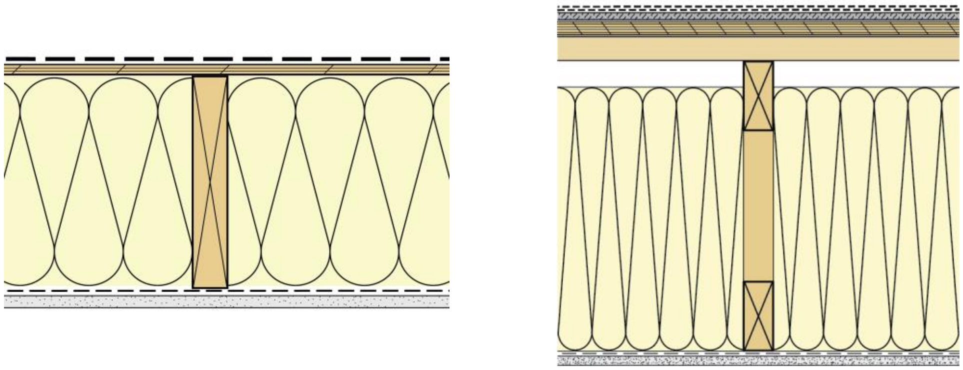
Vinyl-frame windows were chosen for both VBBL and Passive House construction. Pricing for each option was obtained from two manufacturers, and is based on recent quotes for local projects. Pricing for windows has historically varied widely depending on the local demand at the time of procurement. The prices shown in this analysis were obtained in August 2015.

Windows	$/ft^2
VBBL: Double glazed, vinyl frame, surface 4 low-e (USI<1.4)	
Seal gypsum wallboard to rough opening with foam gasket	1.80
37.5mm x 37.5mm (1 1/2" x 1 1/2") metal angle at sill & jambs	2.65
Peel & stick waterproofing membrane at sill	0.69
Perimeter seal at interior window frame	1.73
Interior wood trim at rough opening	3.81
Perimeter seal at exterior window frame	2.45
Metal flashing at head & sill	1.70
Window - vinyl double-glazed	34.19
Window rough opening	2.32
Total Cost	51.35
PH: Triple glazed, vinyl frame Passive House window (USI<0.8)	
Seal gypsum wallboard to rough opening with foam gasket	1.80
37.5mm x 37.5mm (1 1/2" x 1 1/2") metal angle at sill & jambs	2.65
Peel & stick waterproofing membrane at sill	0.69
Perimeter seal at interior window frame	1.73
Interior wood trim at rough opening	3.81
Perimeter seal at exterior window frame	2.45
Metal flashing at head & sill	1.70
Window - vinyl triple-glazed	41.90
Window rough opening	2.32
Total Cost	59.05

Roof

Low-slope roof assemblies were chosen for both VBBL and Passive House construction to reflect Case Study Houses 1 and 2. An unvented, wood-framed assembly with a 2-ply SBS membrane was chosen for the VBBL assembly to reflect common construction practices that perform well in Vancouver's climate. A parallel chord truss assembly with a 2-ply SBS membrane was chosen for the Passive House assembly to reflect economical Passive House construction practices that perform well in Vancouver.

Roof	$/ft^2
VBBL: 2x10 low-slope roof (R28)	
Interior painting	1.93
12.7mm (1/2") gypsum wallboard on ceiling	1.65
Polyethylene vapour barrier	0.76
38mm x 235mm (2x10) roof joists	1.46
235mm (10") high density batt insulation (R4/inch)	1.41
16mm (5/8") plywood sheathing	2.37
2 layers of 3/16" asphaltic protection board, mechanically fastened	1.32
2-ply SBS membrane, torch applied	6.00
450mm (18") fiber cement fascia board	3.82
127mm (5") aluminum gutter	1.01
Metal drip flashing at roof edge	0.51
Total Cost	22.24
PH: 18" low-slope paralell chord truss with 16" mineral wool batt	
Interior painting	1.93
12.7mm (1/2") gypsum wallboard on ceiling	1.65
Polyethylene vapour barrier	0.76
Paralell chord truss system - 450mm (18") deep	3.27
38mm x 38mm (2x2) wood flanges	0.00
10mm (3/8") plywood web	0.00
450mm (18") loose fill and/or high density batt insulation (R4/inch)	3.27
16mm (5/8") plywood sheathing	2.37
2 layers of 3/16" asphaltic protection board, mechanically fastened	1.32
2-ply SBS membrane, torch applied	6.00
450mm (18") fiber cement fascia board	3.82
127mm (5") aluminum gutter	1.01
Metal drip flashing at roof edge	0.51
Total Cost	25.91



Graphical representation of 2x10 low slope roof (left) and low slope truss roof (right)

Ventilation

Heat recovery ventilators (HRVs) were selected as the ventilation system for both VBBL and Passive House construction. For VBBL construction, a 65% efficient HRV with a traditional trunk and branch distribution system was selected. For Passive House construction, an 85% efficient HRV with a flexible plastic home run distribution system was selected.

HRV		**$/ft^2**
VBBL: 65% efficient HRV, trunk and branch system		
	HRV unit	1452.54
	Supply diffusers	560.62
	Return air diffusers	340.00
	Metal ductwork	800.00
	Total Cost	3153.16
PH: 85% efficient HRV, home run system (90% efficient)		
	HRV unit	3557.07
	Supply/return diffusers, zender pipe (flexible plastic ductwork)	2500.00
	Total Cost	6057.07

Space Heating

A condensing boiler combination heat and hot water system was selected for space heating in both VBBL and Passive House construction. For VBBL construction, an in-floor radiant distribution system was selected as it is a common system in new construction in Vancouver. For Passive House construction, radiant panels were chosen as the distribution system, with one panel required per floor of the house.

Heating		**$/ft^2**
VBBL: High efficiency condensing boiler combi system, in-floor radiant distribution		
	Boiler unit	1.40
	In-floor radiant distribution	4.00
	Total Cost	5.40
PH: High efficiency condensing boiler combi system, radiant panel distribution		
	Boiler unit	1.40
	Radiant panel distribution	0.68
	Total Cost	2.08

Appendix B

Additional Energy Analysis

Additional Energy Analysis

Bundles In Between VBBL and Passive House

As part of the exercise to investigate a 30 kWh/m²/yr target, several combinations of measures were simulated. This section shows the annual heating demand simulated in PHPP for various combinations of assemblies and systems drawing from VBBL and Passive House components.

No Single Upgrade Achieves Passive House

Having compiled PHPP models for identical designs to both VBBL and Passive House alternatives, a range of variables were tested to identify which, if any, Passive House strategies offered the most significant improvement over VBBL practice.

Below is an overview of some of the variations that were modelled. In each case, the house design was modelled entirely to the VBBL standard, with only the named variation converted to the Passive House standard. Figures shown indicate the annual heating demand that results from the variation.

Variation	House 2	House 1
VBBL alone:	86 kWh/m²/yr	87 kWh/m²/yr
w/ PH assemblies:	62 kWh/m²/yr	63 kWh/m²/yr
w/ PH windows & install:	65 kWh/m²/yr	57 kWh/m²/yr
w/ PH ventilation:	76 kWh/m²/yr	79 kWh/m²/yr
w/ PH airtightness:	78 kWh/m²/yr	80 kWh/m²/yr
w/ PH thermal bridging:	66 kWh/m²/yr	76 kWh/m²/yr

This data merits further discussion. If subsequent studies were to find similar results among a more representative sample of home designs, potential policy implications may include the following:

→ The addition of triple-paned windows and thick walls, by themselves, do not produce the desired degree of energy savings. This raises questions about the practice of referring to such buildings as “passive design” or similar. Rather, overall performance is achieved through rigorous design and a House-as-a-System approach to energy efficiency.

→ The combined effects of exemplary airtightness, minimal thermal bridging, and highly efficiency heat recovery ventilation account for savings of between 26 kWh/m²/yr (House 1) and 37 kWh/m²/yr (House 2). Given that implementation of these strategies is significantly less expensive than thick walls and triple-paned windows, sustained efforts to educate Vancouver architects and builders on these low-cost strategies may represent a cost-effective interim step between the current VBBL and Passive House.

30 kWh/m²

A short list of viable paths to a lesser standard were also identified. In particular, the City of Vancouver requested options for the specific target of 30 kWh/m²/yr.

Several downgrade scenarios under which individual VBBL components or assemblies are substituted for Passive House components or assemblies were investigated. The following is a summary; see Appendix C for complete results.

Variation	House 2	House 1
Passive House alone:	12 kWh/m²/yr	15 kWh/m²/yr
w/ VBBL assemblies:	31 kWh/m²/yr	34 kWh/m²/yr
w/ VBBL windows:	28 kWh/m²/yr	34 kWh/m²/yr
w/ VBBL ventilation:	20 kWh/m²/yr	20 kWh/m²/yr
w/ VBBL airtightness:	18 kWh/m²/yr	20 kWh/m²/yr

Please note again that these are well-designed homes. Less compact designs, or designs with less attention to solar heat gains, might achieve lower overall performance under these scenarios.

These variations should be viewed solely as modelling exercises intended to frame future discussion. There is no reason to expect that anyone with the knowledge and ability to detail a Passive House would bother to build such a structure, only to degrade just one component.

The Passive House heating demand target of 15 kWh/m²/yr is viewed as valuable because it correlates to the energy reduction threshold at which most buildings no longer require an active furnace or boiler. This allows builders to offset the additional cost of triple-paned windows and additional insulation with savings from not needing to install furnaces, ducts, or radiant floors. Similarly, the Passive House standard for windows minimizes the drafts that result from air falling along cool glass surfaces, and therefore eliminates the need to place radiators or radiant flooring at the foot of every large window. As a result of these and similar factors, there may not be construction cost savings from construction of a residence to 30 kWh/m²/yr versus a lower heating demand.

Note on the Models

The different PHPP and HOT2000 models used in this study have been created using standard modeling techniques for City of Vancouver when using PHPP Version 9.3 and HOT2000 Version 10.51-EGH. Both PHPP and HOT2000 were configured to use their approved and respective climate data sets for Vancouver, BC. The sites elevations were being estimated using Google Earth Pro Version 7.1.5. HOT2000 results were generated using the Energuide rating (New Houses) mode. PHPP reports were generated using the Passive House Classic energy standard mode for New Building (Standard Dwelling) with standard occupancy for residential buildings.

Each house shares the same PHPP core data for all PH and VBBL models so that potential errors and/or omissions apply to both models and do not influence the study results.

Thermal Envelope and TFA: It is to be noted that the total building thermal envelope area in PHPP and in HOT2000 are slightly different. In PHPP, the building element exterior dimensions are used for modeling. In HOT2000, interior dimensions are used. The PHPP building envelope area has been chosen for all models. Furthermore, HOT2000 does not use the concept of Treated Floor Area (TFA). The study refers to the PHPP TFA for all models and energy intensity values. The TFA is based on a German standard called WoflV for residential buildings. In its simplest form, it relates to all the useful floor areas within the thermal envelope of the building. The TFA includes some areas at 100% of their area, others at a lesser percentage, and some areas cannot be included at all.

U-Values: Cladding is not modelled as per PHi and CoV modelling conventions.

Windows: Passive House certified Euroline 4700 Thermo+ with Cardinal 360 glass windows with PH high performance installation details have been chosen for Passive House models. Standard City of Vancouver USI-1.4 vinyl windows with typical installation details have been chosen for VBBL models and modeled using HOT2000 custom codes. Such windows include the Oasis 6000 series or the Euroline 1400 series (chosen for the VBBL models). PH and VBBL window frames are assumed to be same dimensions.

Shading: The PHPP models assume no horizon type shading due to structures or vegetation.

Ventilation: To obtain a meaningful comparison, the ventilation flow rates in HOT2000 (BCBC 9.32) and PHPP must be the same. The PHPP ventilation flow rates were chosen and used in HOT2000.

DHW and Space Heating: The DHW system was modelled as an NRCan “combi” system.

HRVs: Venmar ConstructoE10 SP, 65% ER efficiency situated towards the center of the building footprint (6m supply and exhaust runs with no insulation) is used for the VBBL models. Zendher ComfoAir 550, 85% ER efficiency 92with 2.5 supply and exhaust runs with 5” reflective insulation is used for the Passive House models.

Thermal bridges: Window and door thermal bridges include door sills and windows sills when the window is installed and on or very near the wall bottom plate. Note that the thermal bridge due to the window or door installation detail performance is reflected by the psi (install) value of the window. Non window and door thermal bridges include thermal bridges at junctions such as wall corners, wall to roof corners, slab to foundation wall corners, foundation walls to exterior wall junctions, etc.

It is to be noted that the psi value for the thermal bridges used in House 1 and House 2 were not accurately modeled using tools such as THERM or Flixo, but were approximated based on similar junctions found in the “Building Envelope Thermal Bridging Guide”[17], the Scottish Government Accredited Construction Details Guide, and in Passive House Institute and Passive House Academy documentation.

Economic Results Using HOT2000 Baseline

The VBBL baseline house was simulated using HOT2000 and PHPP to compare the heating demand from both programs. While the programs produced similar results for peak heating loads, annual heating demand was significantly different in the two programs. The analysis presented in this study uses results from PHPP only so that both the VBBL and Passive House cases are compared using the same software. However, this section presents results of the LCC analysis if VBBL heating modelled in HOT2000 is compared to Passive House heating modelled in PHPP. This is an area that requires further work to better understand the differences between the two programs.

[17] https://www.bchydro.com/powersmart/business/programs/new-construction.html - thermal

The results in Table B.1 compare the costs of upgrading to Passive House using energy cost savings simulated with HOT2000 for the VBBL case and PHPP for the Passive House case. The results with both cases modelled in PHPP are shown in Table B.2 below for reference (repeated from Section 4.2). The economics appear far less favourable when the baseline is modelled in HOT2000 since this program simulates lower annual heating energy than PHPP for the VBBL house, and therefore annual savings are lower.

TABLE B.1 HOUSE 1 AND 2 LCC SUMMARY, VBBL IN HOT2000 AND PASSIVE HOUSE IN PHPP

	House 1	**House 2**
Total Incremental Cost	$23,700	$16,300
Incremental Cost per SF GFA	$7.50/sf	$6.50/sf
Annual Energy Cost Savings	$270	$100
Annual GHG Savings	1,500 kg CO_2e	560 kg CO_2e
Net Present Value (NPV)	(-$18,600)	($-14,400)
Internal Rate of Return (IRR)	(-4%)	(-6%)
Discounted Payback	>30 years	>30 years

TABLE B.2 HOUSE 1 & 2 LCC SUMMARY, BOTH MODELS IN PHPP

	House 1	**House 2**
Total Incremental Cost	$23,700	$16,300
Incremental Cost per SF GFA	$7.50/sf	$6.50/sf
Annual Energy Cost Savings	$550	$510
Annual GHG Savings	3,000 kg CO_2e	2,400 kg CO_2e
Net Present Value (NPV)	($13,300)	($7,900)
Internal Rate of Return (IRR)	0%	1%
Discounted Payback	30 years	26 years

Appendix C

Packages for 30 kWh/m^2

PHPP results of Passive House 2 with VBBL components

TFA (m2): **170.9**

Building Envelope Surface Area (m2): **479.5**

	VBBL Base	Passive House	*Option A* VBBL Slab, Foundation walls, Walls, Roofs PH Windows with PH Install PH Ventilation PH ACH PH Thermal Bridges	**Option Selected for Study** *Option A to 30kWh/m2a* VBBL Slab, Foundation walls, Roofs Walls Reff=26 (2x4 24oc Batt + 4" Ext Rockwool) PH Windows with PH Install PH Ventilation PH ACH PH Thermal Bridges	*Option A to 30kWh/m2a* VBBL Foundation walls, Walls, Roofs Slab R=24 (4" XPS) PH Windows with PH Install PH Ventilation PH ACH PH Thermal Bridges	*Option B* PH Slab, Foundation walls, Walls, Roofs VBBL Windows with PH Install PH Ventilation PH ACH PH Thermal Bridges	*Option C* PH Slab, Foundation walls, Walls, Roofs PH Windows with PH Install VBBL Ventilation PH ACH PH Thermal Bridges	*Option D* PH Slab, Foundation walls, Walls, Roofs PH Windows with PH Install PH Ventilation VBBL ACH PH Thermal Bridges	*Option E* PH Slab, Foundation walls, Walls, Roofs PH Windows with PH Install PH Ventilation PH ACH VBBL Thermal Bridges	*Option F* PH Slab, Foundation walls, Walls, Roofs PH Windows with PH Install VBBL Ventilation VBBL ACH VBBL Thermal Bridges
Average Windows u-value (W/m2K):	1.4	**0.79**	**0.79**	**0.79**	**0.79**	**1.4**	**0.79**	**0.79**	**0.79**	**0.79**
Average Thermal Envelope u-value (W/m2K):	0.509	**0.194**	**0.328**	**0.311**	**0.296**	**0.245**	**0.194**	**0.194**	**0.309**	**0.309**
Average Thermal Envelope Reff:	11.2	**29.3**	**17.3**	**18.3**	**19.2**	**23.2**	**29.3**	**29.3**	**18.4**	**18.4**
Annual Heating Demand (kWh/a):	14,664	**2102**	**5,292**	**4,747**	**4,703**	**4,214**	**3,395**	**3,063**	**4,602**	**7,311**
Total Energy Demand for DHW (kWh/a):	1,617	**1617**	**1,617**	**1,617**	**1,617**	**1,617**	**1,617**	**1,617**	**1,617**	**1,617**
Heat Load x TFA (W):	5,623	**1,606**	**2,666**	**2,478**	**2,512**	**2,222**	**2,102**	**2,529**	**2,410**	**3,794**
CO2eq Emmissions (kg/(m2a)):	39.2	***19.2***	*23.6*	*22.8*	*22.7*	*21.8*	*22.5*	*20.4*	*22.5*	*28.2*
Space Heating Demand (kWh/(m2a)):	85.8	***12.3***	**31.0**	**27.8**	**27.5**	**24.7**	**19.9**	**17.9**	**26.9**	**42.8**
			18.7	***15.5***	***15.2***	***12.4***	***7.6***	***5.6***	***14.6***	***30.5***
Heat Load (W/m2):	32.9	***9.4***	**15.6**	**14.5**	**14.7**	**13.0**	**12.3**	**14.8**	**14.1**	**22.2**
Airtightness (1/h):	3.5	***0.6***	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**3.5**	**0.6**	**3.5**
PE Demand (kWh/(m2a)):	166	***80***	**99**	**95**	**95**	**91**	**94**	**85**	**94**	**118**
PER Demand (kWh/(m2a)):	190	***61***	**90**	**85**	**85**	**79**	**75**	**69**	**83**	**114**
*Better than **VBBL Base** by (%):*			**63.9%**	**67.6%**	**67.9%**	**71.2%**	**76.8%**	**79.1%**	**68.6%**	**50.1%**