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04.
COMPARING AND ADAPTING PITT RIVER SCHOOL TO THE PASSIVE HOUSE STANDARD

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ABSTRACT
This article presents a study of a Pitt River Middle School (built in 2013) and, analyzes how close the project comes to achieving the International Passive House standard and what changes would need to be made to achieve the standard. The article reviews the target metrics associated with the Passive House Standard and processes involved in successful implementation. These processes include overlap of BIM and the Passive House energy modelling process, the impact of thermal bridging and review of specifications for building envelope components. The study finds that the project was designed to achieve annual Energy Use Intensity (EUI) for heating of 48 kwh/m^2 (15.3 kBtu/ft^2), a 40 percent improvement over a baseline according to ASHRAE standard of 82 kwh/m^2 (25.99 kBtu/ft^2). The Passive House standard limits this value to 15 kwh/m^2 (4.8 kBtu/ft^2) an 82 percent improvement over the baseline. Improving the building envelope specification would decrease EUI to 23 kWh/m^2 (7.4 kBtu/ft^2). To achieve the Passive House standard, several design considerations would require a revisit, specifically form factor (compactness), orientation glazing ratio, etc. These criteria need to be considered early in the design process and analyzed in conjunction with other project goals and architectural requirements.

KEYWORDS: Passivhaus; energy efficiency; high performance building; energy modelling; thermal bridging

1.0 INTRODUCTION
1.1 Objectives and Case Study Overview
This article investigates the application of the Passive House standard and how it might be better integrated into the design process. Using a recently built project by the Perkins+Will Vancouver office, Pitt River Middle School (completed in 2013), the research had three aims:

- To establish a project benchmark to see how the project performs relative to the International Passive House standard. This research was conducted after the building was designed and completed (i.e. the building was not designed or built to achieve Passive House standards). The aim of this research was to apply the Passive House lens in retrospect to understand what changes would be necessary for meeting the standard.
- To provide feedback in terms of impact on the design process for projects aiming to achieve the standard, specifically understanding the potential impact on project schedule, and by association potential impact on fee proposals.
- To provide feedback in terms of further training required for design professionals.

Figure 1: Pitt River Middle School.

Pitt River Middle School is a two-story educational facility, located at Port Coquitlam, British Columba, with 5580 m² (62,000 ft²) of conditioned space (Figure 1). It has two wings: an academic wing and an athletic wing. The academic wing consists of classrooms, administrative offices, a library and a workshop. The athletic wing includes a gym, a fitness room, a multipurpose room, a music room and offices.

The project has been recognized for its design excellence, winning a Lieutenant Governor of British Columbia Award in Architecture from the Architectural Institute of British Columbia (AIBC), and a Design Citation Award within the wider Perkins+Will community. It is important to note that any potential recommendations in meeting the Passive House standard would have an impact (positive or negative, depending on how they are treated) on the design and aesthetics of a project, such as thicker walls, eliminated thermal bridges, potentially reduced window areas and reduced north facing clerestory lighting (good for daylighting within the space, but negatively affecting heat loss). All of these factors would have an impact on the design aesthetic in addition to thermal performance.

1.2 Why the Passive House Standard

Commercial, institutional, and residential buildings are responsible for about a third of carbon pollution in the U.S., and about a fifth of carbon pollution in Canada, constituting the largest source of emissions in North America[1,2,3]. Worldwide, buildings account for about a third of energy related emissions, and continue to grow[4]. Over 80 billion square meters (900 billion square feet) will be built and rebuilt in urban areas by 2030, an area roughly equal to 60 percent of the current global building stock[5]. Once these developments are built, their performance is locked in and cannot be improved without costly renovation. The Passive House standard, as suggested by its name, takes a passive approach to improve the thermal performance of the building. Major areas of consideration focus on the building envelope, increased insulation and airtightness of walls, roof and windows, as opposed to active systems that require a constant supply of conditioned air by HVAC systems. This results in a reduction of emissions from buildings under consideration at a low cost, while also improving durability, comfort, and resilience.

This study focuses on the international Passive House (or Passivhaus) standard, as administered by the Passive House Institute in Germany. There are various affiliates in North America that promote, educate and advocate for the standard on a local level (e.g. Passive House Canada, the North American Passive House Network, New York Passive House, etc.). The Passive House Institute US (PHIUS) operates in the U.S. Originally an affiliate of PHI and the international standard to standard, PHIUS has split off in recent years to formulate separate PHIUS+ standards based on U.S. climate zones. This can be confusing for design teams and clients, so it is important to be clear which standard applies.

The Passive House Standard is internationally recognized, performance-based energy standard for both new build and renovation construction projects. It was developed by German and Swedish building scientists and physicists, building on previous energy efficiency concepts in North America and Europe. The focus is on energy conservation and improvement of building envelope. The aim of the rating system is to assist with designing a building in which a comfortable interior climate can be maintained without active heating and cooling systems. It results in buildings that consume roughly 80 percent less heating and cooling energy than conventional buildings while ensuring occupant comfort.

Designing and building a project according to the Passive House standard demands a rigorous methodology. There is an increased focus on the building envelope with the core principles being:

1. Reducing demand
    - Reducing heat loss or gain though superinsulation, reducing air Infiltration and thermal bridges
    - Limiting the overall energy use through a primary energy limit
2. Maximizing gains
    - Capitalizing on solar heat gain and internal gains
3. Ensuring occupant comfort
    - Controlling gains and overheating in the summer
    - Providing fresh air and using a heat/energy recovery ventilator to recover waste heat.
    - Ensuring all thermal comfort criteria are met[6].

Many municipalities are looking into the ways to combat climate change and reduce carbon emissions. For example, the City of Vancouver adopted a Zero Emissions for New Buildings Policy, which came into affect May 2017 for all rezonings. This policy aims to achieve zero emissions for all new buildings by 2030, with stepped

Green House Gas (GHG) and thermal energy demand targets. This policy references the International Passive House standard as a performance benchmark[7].

1.3 Summary of the International Passive House Standard

There are five performance metrics that need to be met for a project to be certified according to the Passive House Standard, as defined by PHI, which are outlined in Table 1[8]. For the purposes of this study, the main focus is on the certification criteria of 15 kWh/m^2a (4.75kBtu/ft^2 yr) limit to the annual heating energy per area of the building. The same limit is applied for cooling, but there is an additional allowance for cooling depending on the context. The resulting focus of this study is narrow, mainly on the build-ing envelope components. In reality, there are wider issues to be considered when designing to achieve the Passive House standard, including airtightness detailing, mechanical systems design and electrical appliance specifications, accurate measuring of internal gains, all which would all have an impact on achieving the standard.

Table 1: Performance criteria for the internationally recognized Passive House (Passivhaus) Standard, as certified by the Passive House Institute (PHI).

	Performance Metric	**Comment**
Space Heating & Cooling Demand	15 kWh/m^2 a (4.8 kBtu/ft^2)	A limit to the annual energy consumption per area for heating and cooling the building. For comparison, ASHRAE 90.1-2010 has space heating demand requirement of 85.4 kWh/m^2 a (27 kBtu/ft^2 a) for Education Buildings in Vancouver[9]. The cooling demand limit has an additional, climate-dependent allowance for dehumidification.
Max Heat/Cooling Load	10 W/m^2	Alternative means of compliance to the Thermal Demand figure. This is a limit on the peak power output of system on the coldest day of the year. Compliance can allow the small heat load to be supplied via the fresh air ventilation system – reducing heating distribution system required.
Primary Energy Demand [Site Energy]	120 kWh/m^2 a (38.1 kBtu/ft^2) [30-60 kWh/m^2 a] (9.5 - 19 kBtu/ft^2)	A conversion/generation factor is applied to the total site energy (including heating, HW, plug loads etc.) to give an overall primary energy demand limit. This limit was set at 120 kWh/m^2 a (38.1 kBtu/ft^2). These limits are being recalibrated with 3 new stepped certification targets to allow for a renewable energy generation – making it easier to achieve in BC where 97 percent of energy comes from renewable sources. The reality is that this limits the EUI of the building to 30-60 kWh/m^2 a (9.5-19 kBtu/ft^2), depending on fuel source. Architecture 2030 Challenge Targets for K12 buildings[10]. 2015 ~ 73 kWh/m^2 a (23.1 kBtu/ft^2) 2020 ~ 37 kWh/m^{2}a (11.7 kBtu/ft^2
Airtightness	0.6 ACH@50Pa	The City of Vancouver residential code calls for 3.5 ACH@50Pa. The Zero Emissions Plan (active as of May 2017) requires 2.0 L/s*m² @75 Pa if not complying through achieving Passive House. The average airtightness for large buildings in Canada is approximately 2.15 L/s*m² @75 Pa[11]. Note that there are two differing metrics for airtightness testing: - Relative to volume of air in the building - dividing the airflow by the volume of the building. This gives a result as air changes per hour (ACH or h^{-1}), and results are usually reported at 50Pascals. This is roughly equivalent to a 20mph wind on the four sides of the building. The test report is in ACH (or h^{-1})@50Pa. This is the usual testing protocol for residential and smaller scaled buildings. - Relative to the area of the building envelope - dividing the airflow (V75) by the area of the building enclosure. This gives a result of flow per unit area (L/s·m^2 or cfm/ft$^{2)}$. Results are reported at 75Pascals (0.3 inch water column (wc)). This higher pressure can be more difficult to achieve (requiring more equipment, etc.). The test result is reported is in L/s·m^2@75Pa or cfm/ft^2@0.3 in wc. This is typically the testing protocol of commercial or larger scale buildings. For larger buildings (over 1500 m^2 / 16145 ft^2), both values must be reported for facilities seeking certification. The airtightness metric is verified with an onsite pressure test in both pressurized and depressurized states for Passive House certification. Most regulatory airtightness testing require testing in one direction only.
Overheating frequency	(over 25°C) ≤ 10 percent of year	Ensuring minimum overheating due to summer sun and internal heat gains. Must be met for all living areas year-round.

2.0 SUMMARY OF PREDICTED ENERGY PERFORMANCE OF PITT RIVER MIDDLE SCHOOL

Two energy models were developed during the design of the project, which gave an insight into the predicted performance of Pitt River Middle School. These models were examined to determine whether any further energy reduction would be possible by pursuing building envelope performance requirements of the Passive House standard.

2.1 BC Hydro Incentives (August 2011)

The BC Hydro New Construction Program offers funding, resources and technical assistance for projects who use an approved energy study to achieve savings of over 50,000 kWh/a, compared to a baseline case[12]. This is an absolute number (without regard to building area) so the project type and size will determine how easy this is to achieve.

Pitt River Middle school applied for this program, comparing the proposed design and energy conservation measured with a baseline based on ASHRAE 90.1 2004. Under the BC Hydro program, the Design Team proposed a series of Energy Conservation Measures (ECMs), resulted in a 39 percent reduction of energy consumption. From the associated energy study, it was clear that space heating is the most dominant energy end use even after the proposed energy conservation measures are implemented (42 percent of total consumption, as shown in Figure 2). This makes it a viable case for the Passive House approach, which targets space heating reductions by focusing on a high quality thermal envelope.

The result of the proposed ECMs on the space heating demand is outlined in Table 2. The Passive House certification target of 15Wh/m²a would require an overall maximum space heating demand of 83,700kWh, with an annual cost of $9,039.60 (energy costs of CAD $0.108/kWh were used in the modeling process). Typical ASHRAE compliance level for education buildings in Vancouver is approximately 85 kWh/m²a.

Table 3 demonstrates proposed ECMs, focusing on the building envelope and their comparable Passive House recommendations, giving an idea where further reductions may be achieved through improvement of the building envelope elements.

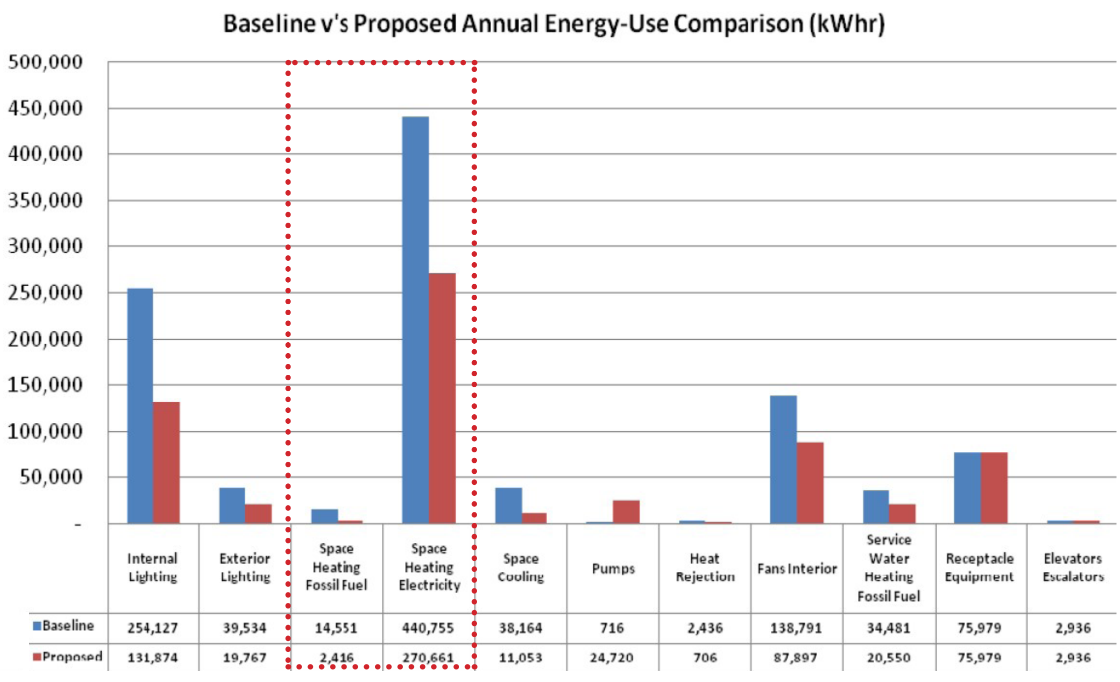


Figure 2: Pitt River Middle School Replacement Project BC Hydro new construction program schematic energy study, indicating space heating as the predominant energy usage.

Table 2: BC Hydro Incentive results compared with Passive House values.

BC Hydro	Baseline	Proposed via BC Hydro	Passive House
Annual Heating Demand	455,306 kWh/a	-273,077 kWh/a	83,700kWh/a
Specific Space Heating Demand	82 kWh/m²a	-49 kWh/m²a	-15 kWh/m²a
Cost (@ CAD $0.108/kWh)	$47,601.54	-$29,231.39	-$9,039.60

Table 3: Assembly performance values of the baseline case (as per ASHRAE90.1 2004), compared to the proposed BC Hydro Incentives and Passive House values. .

BC Hydro	Baseline per ASHRAE 90.1 2004	Proposed	Passive House (recommended)
Roof U-value W/m²K (Btu/h-ft²-°F)	0.360 *(R16)*	0.139 *(R41)*	0.09-0.15 *(R35-R70)*
Wall U-value W/m²K (Btu/h-ft²-°F)	0.475 *(R12)*	0.272 *(R21)*	0.1-0.15 *(R35-R50)*
Floor U-value W/m²K (Btu/h-ft²-°F)	0.296 *(R19)*	0.296 *(R19)*	0.15-0.175 *(R30-R40)*
Overall glazing U-value W/m²K (Btu/h-ft²-°F)	3.24 *(R1.5)*	3.24 *(R1.5)*	0.85 *(R6-8)* (installed including thermal bridges)
Thermal Bridging ψ value (W/mK)	Not accounted for	Not Accounted for	Thermal Bridge Free 0.01
Glazing g-value (SHGC)	0.39 (S,E,W) 0.49 (N)	0.39 (S,E,W) 0.49 (N)	0.5-0.6
Glazing Percentage	40 percent	57 percent	Generally 40-60 percent, varies depending on project. South exposure and solar gain to be optimized while avoiding summer overheat-ing

2.2 LEED Energy Compliance Model (November 2013)

An IES energy model and report was prepared for the purposes of LEED certification in November 2013. This compared the proposed building design with ASHRAE 90.1.2004 to determine energy points earned under LEED Canada NC V1.0. The report was prepared for LEED certification (not to predict actual energy use or costs). The report indicated that the energy use of proposed building design was reduced by 41 percent when compared to the ASHRAE 90.1-2004 baseline building. The combination of energy efficiency measures of this facility results in 38 percent regulated energy cost savings and earns 5 points in the LEED Canada NC V1.0 Energy and Atmosphere Credit 1.

As per the BC Hydro study, space heating offered the highest potential for saving and was the highest energy use both for the baseline and proposed case, as seen in Table 4. The order of magnitude of energy use for heating is the same as for the BC Hydro study.

Important ECMs identified for achieving the proposed savings were:

- Exterior roof with overall 62 percent U-value improvement when compared to baseline case
- Exterior wall with overall 56 percent U-value improvement when compared to baseline case
- High efficiency glazing with overall 49 percent U-value improvement when compared to baseline case
- Reduction of lighting power density when compared with the baseline case
- Occupancy sensors
- Exhaust air heat recovery system
- Variable speed drives on pumps and fans
- Hydronic heating system fed by a central heating plant consisting of three water-source heat pumps with 3.3 COP, versus the baseline case's air source heat pump at 3.20 COP
- Hydronic heating system fed by a central heating plant consisting of two natural gas condensing boilers with 95.3 percent efficiency, versus the baseline case's natural gas boiler at 80 percent efficiency
- Domestic gas-fired condensing boiler with 95.3 percent efficiency, versus the baseline case's gas-fired domestic hot water boiler at 80 percent efficiency
- Demand control ventilation
- Low flow fixtures providing 40 percent service water reduction when compared to the baseline[13].

As a result of these measures, the project would achieve the following LEED NC V1.0 v3 credits:

- Energy & Atmosphere Cr1 – Optimize Energy Performance 5 out of 10 possible
- Energy & Atmosphere Pr2 – Prerequisite gained (reduce cost by 18 percent compared to ASHRAE).

There are synergies in how Passive House can help achieve points under LEED Energy and Atmosphere and Indoor Envoironmental Quality categories. The first Passivhaus public school in North America, the Center for Energy Efficient Design (CEED) in Rocky Mount, Virginia received 33 points, representing 41percent of the total points required for LEED Platinum certification. These points have been rewarded for the energy efficiency and indoor air quality benefits, achieved using the Passive Haus Certification Strategy[14].

The proposed ECMs focus on improvements to the building envelope, as well as an optimized and more efficient mechanical system. Implementing these strategies to recommended Passive House performance levels would give an opportunity for further energy savings, as is examined in the next section.

Post-occupancy energy evaluation was undertaken for the first 18 months, subsequent to the project opening. However, sub data sets of space heating were not available for comparison purposes.

Table 4: LEED baseline and proposed savings compared with Passive House values.

LEED	Baseline	Proposed via LEED	Passive House
Annual Heating Demand	474,455 kWh	251,070 kWh	86,400kWh
Specific Space Heating Demand	82.3 kWh/m²	43.6 kWh/m²	15 kWh/m²
Cost (@ $0.108/kWh)	$51,241.14	$27,115.56	$9,331.20

3.0 TAKING PITT RIVER SCHOOL TO THE PASSIVE HOUSE STANDARD

Passive House projects use an excel based energy modelling software, Passive House Planning Package (PHPP), both as a design tool and submission for third party verification under the certification process. Completing this energy model is time consuming and requires experience.

Part of this research was to explore the use of DesignPH, a SketchUp plugin, as a 3d environment that design team can work in and also understand Passive House metrics. The plugin gives initial results for the specific heating demand metric, and can automatically calculate the shading inputs required for PHPP (which otherwise can be a time consuming manual process). The DesignPH model will not give the final results for certification, it still needs to be exported to PHPP for further inputs and calibration.

This study looked to analyze SketchUp as an interface to connect Revit to PHPP, as shown in Figure 3. However, a potential area of future study is the interface between Revit and PHPP directly. Given that PHPP is an Excel-based tool and Revit has the ability to export and link to Excel (for example, using the spreadsheet link), this might improve interoperability between different software platforms.

The following steps outline the process for Revit – SketchUp (DesignPH) – PHPP data exchange:

1. Open Revit model and delete/purge all elements and worksets that are not required. For the purposes of DesignPH and PHPP, all outside surfaces of the thermal envelope are required, along with any elements that cause shading on windows, e.g. columns outside the thermal envelope, surrounding buildings, etc. Also, internal floor areas are required (without internal walls) to calculate the Treated Floor Area (TFA).
2. Export as .dwg (ACIS solids) for import into SketchUp.
3. SketchUp requires the Design PH Plugin to be installed. Depending on the cleanliness of the model, imported geometry can either be used without further modifications or remodeling over the imported geometry is necessary to create the thermal envelope. This can be achieved by working with groups and layers within SketchUp to separate walls, roofs, glazing, etc. in component parts. Each element is assigned an element grouping (Wall Ambient, Roof, etc.), and assigned U-value. Design PH has a glazing component tool, which can be used to create windows and assign thermal properties to frames and glazing.
4. DesignPH allows export to PHPP (v8 and v9). With larger projects, the SketchUp file ends up with a large number (500+) of surfaces for walls, window frames, etc., which is a problem for PHPP to handle. This requires editing PHPP to add more rows in Excel (not recommended) or simplifying the model further to reduce the number of surfaces.

Figure 3: Modelling processes with the Passive House standard.

There is an opportunity for an improved workflow from Revit (or other BIM platforms used by architects, such as ArchiCad) to PHPP. There is potentially a computational design interface using Dynamo within Revit that could serve to communicate with PHPP directly to streamline the process, especially when it comes to early design stage iterations. It is vital for the success of a Passive House project that the PHPP be used as a design tool and not as a spot check once a design has been finalized.

Figures 4 and 5 show the energy balance of the Pitt River Middle School, as modelled in Design PH (similar to the energy balance graph formulated typically in PHPP). These figures compare the losses to gains, and the remaining segment is the heating demand.

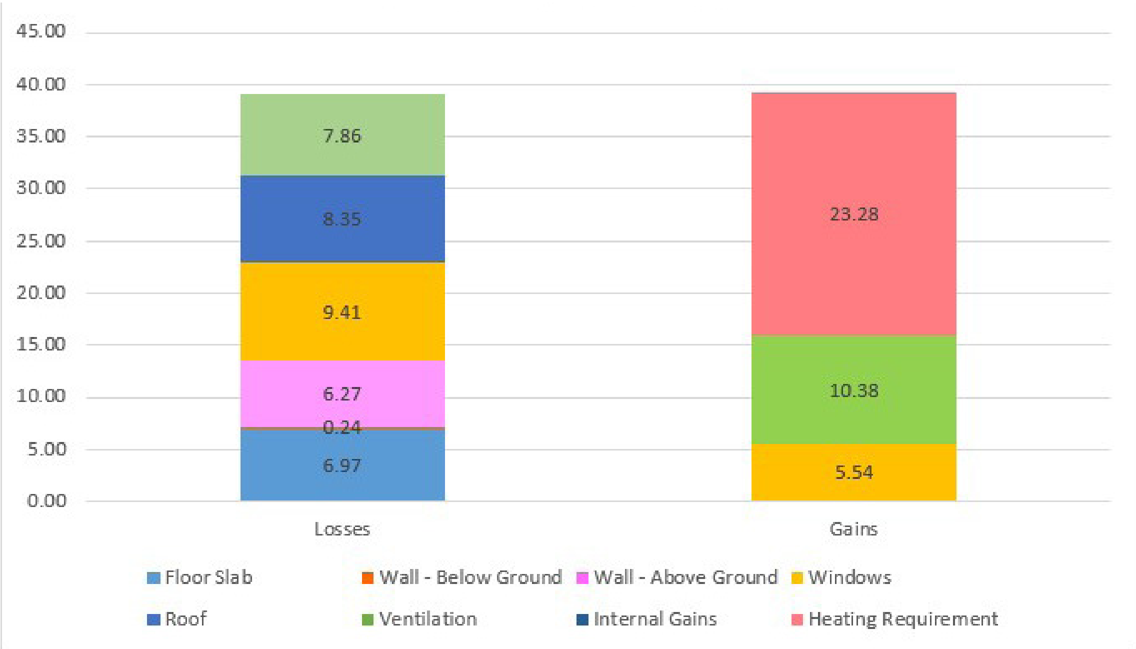
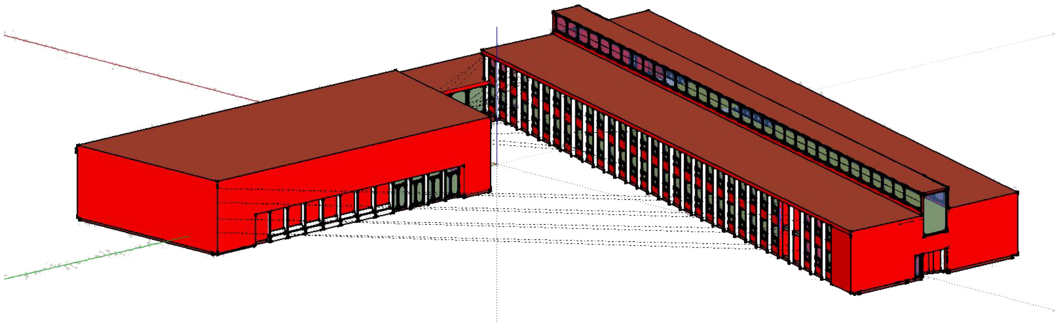


Figure 4: Result of DesignPH modelling – energy balance graph.

CLIMATE: Vancouver
Qh 23 kWh/m²a
TFA 5688 m² (User-defined)
Heat Loss Form Factor 1.91



Losses (kWh/a)		**Gains (kWh/a)** (Utilization factor: 0.99		**Heating Demand (kWh/a)** (Q_H)
Transmission (Q_T)	Ventilation (Q_V)	Solar (Q_S)	Internal (Q_I)	
177721.57	44681.50	31524.90	59053.19	132429.32
Specific Annual Heat Demand (q_H) = Q_H /TFA = **23.28 kWh/m²a**				

Figure 5: Energy balance of Pitt River Middle School, as modelled in DesignPH.

Using a TFA of 5687.8 m² (61,223 ft²), as exported from the Revit model, the specific annual heating demand for Pitt River School was calculated as 23.28 kWh/m²a (7.4 kBtu/ft²), compared to the Passive House certification standard of 15 kWh/m²a (4.8 kBtu/ft²), as shown in Figure 6.

While the results indicate that the project lies outside the certification target, with further refinement achieving the standard could potentially be possible. The results, like any other modelling effort, are only as good as the inputs. Potential areas that would negatively affect the calculation include:

- The TFA calculation, on which the Passive House certification standard is based, would require further study. While it compares to the areas used for the BC Hydro and LEED modeling efforts, the area used was imported from Revit without any further verification per Passive House parameters (e.g. all internal walls discounted, stairways not double counted, etc.). As a result, there is a high likelihood the actual TFA is a smaller area, which could increase the specific heat demand.
- Thermal bridging was assumed to follow Passive House best practices (without thermal bridging), therefore having negligible effect on the resulting heat loss. In reality, the details as proposed have a PSI value of greater than 0.01W/mK (0.006 kBtu/hr-ft-F).and therefore would need to be accounted for in the energy model, as discussed in more detail in the later section. This can be assigned within DesignPH. Thermal bridging was not factored into either of the BC Hydro or LEED energy models, and can be a source of considerable heat loss if not taken into consideration. This is explored further in the next section.
- The inputs assumed that the airtightness target of $0.6h^{-1}$ is met and the HRV is at least 75 percent efficient, as measured to the Passive House standard protocol (HRV units tested to the North America protocols are typically found to be less efficient when tested to International Passive House protocols, mainly due to more stringent requirements on the recirculation of air within the unit and limits on electric fan power).
- No surrounding context was modelled, which

could have a large impact on shading and solar gains. This, however, is not likely to be a major issue as there are no significant shading elements to the south of the project.

- Internal gains are modelled using the PHPP default value of 2.1 W/m². In the UK, Passive House school projects have found that this default is too low[15]. In reality, correct internal gains would have to be modelled based on occupancy, usage patterns, equipment and lighting to determine more accurate internal gains.
- Altitude of the project can have an effect on the results and would need to be correctly entered in PHPP.

The 15 kWh/m²a certification target is based on the TFA as calculated per PHPP protocols. Defining this value correctly, along with setting the correct climate data, is one of the first steps when using PHPP to model a Passive House project. For the purposes of this study, the value used was that imported from Revit of 5688 m². This falls between the values used for the BC Hydro energy study (5580 m²) and LEED (5760 m²). Using either of these values gives a q_H value of 21 and 24 kWh/m²a, respectively. The overall heating demand value is still relevant, at 132,429 kWh/a it is still more than 50 percent smaller than that of the optimized BC Hydro and LEED models (273,077 kWh/a and 251,070 kWh/a, respectively). In this study, this was achieved without

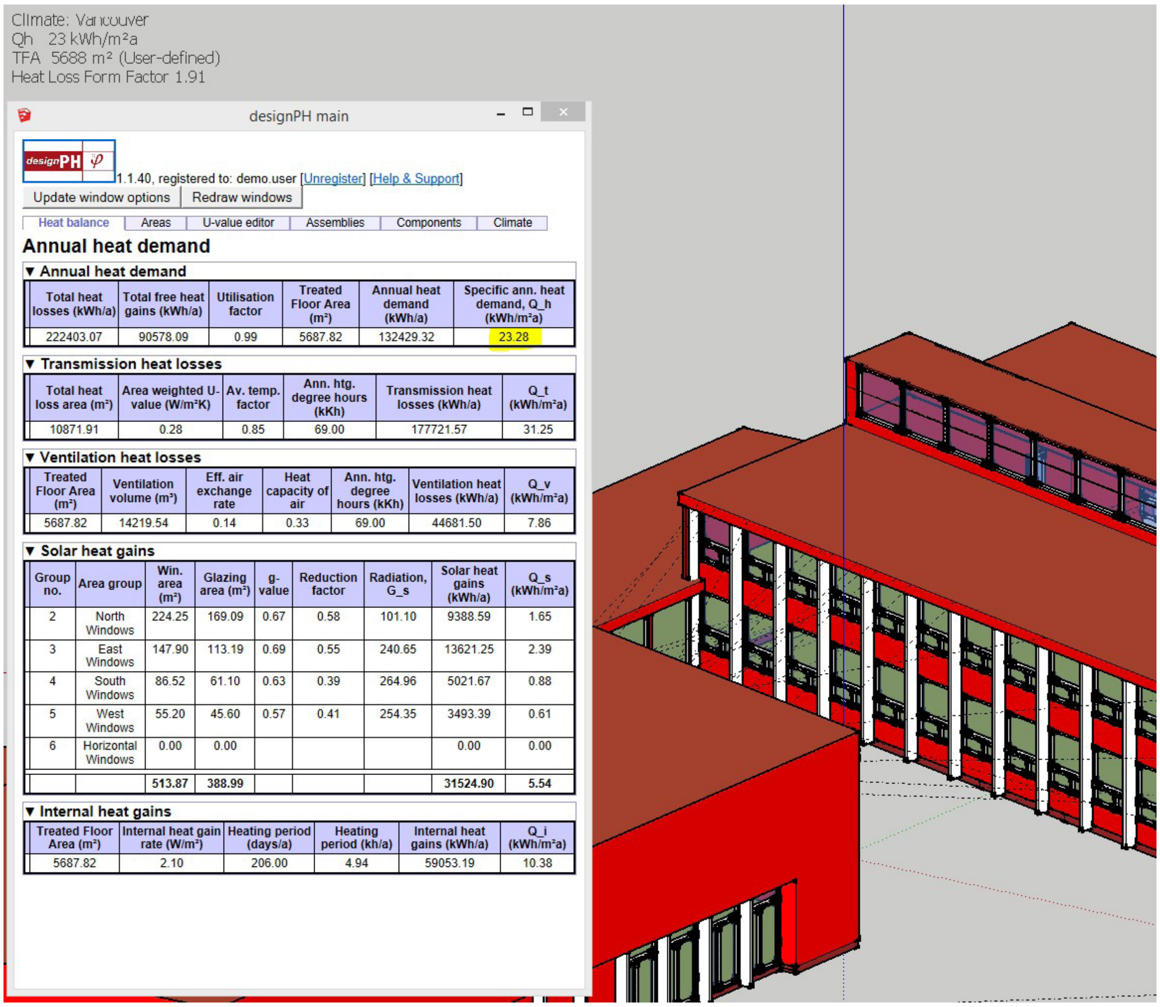


Figure 6: Energy balance of Pitt River Middle School as modelled in DesignPH.

any change to the design, just be assuming a Passive House level of performance for the building envelope elements.

To achieve the additional heat loss savings required (~8 kWh/m²a), these elements would have to be examined in detail and there may also need to be changes in the design (more compact form, glazing ratios, and examination of window energy balance revisited). This is where it is important to seek performance improvements without compromising the architectural design and integrity of the project. Whether these final improvements of 8 kWh/m²a, the most difficult to achieve, are worth any compromise on the design is something for the design team to consider. This can become a source of conflicting ideals if the standard is not considered from the outset. However, having the target established from the start and having everyone on the design team, client and if possible contractor on board and engaged, ensures that it is a shared goal and ambition as opposed to a source of conflict with project aims.

4.0 ANALYSIS OF THE BUILDING ENVELOPE

4.1 Form Factor

Passive House Form Factor quantifies the relationship between the living area of the building and the total amount of surface area. The form factor is calculated by dividing the total heat loss area by the floor area.

The form factor is related to the amount of required insulation in building envelope. If the building form is compact, this reduces surface area and subsequently heat loss, reducing the amount of needed insulation to obtain improved thermal performance. For Pitt River Middle School, the form factor is 1.91. This does not tell us much without comparing it to other similar sized projects. However, this would be an area that could be revisited to see if the design be made more compact to achieve the additional ~8kWh/m²a savings.

While designing the most compact form possible is not always the most architecturally desirable solution for a given project, the effect of creating a less compact form should still be understood by the design team.

4.2 Opaque Elements

Table 5 outlines the properties of opaque elements of the building envelope, and improvement strategies.

Table 5: Properties of opaque elements and improvement strategies.

Element	As Specified / Built	As modelled	Comment
Walls: U-Value (W/m²K)	0.272	0.15	This could have been modelled at a higher level (some Passive House projects achieve 0.1 W/m²K)
Roof: U-Value (W/m²K)	0.139	0.14	The roof as specified and built was within Passive House levels at 0.139
Floor: U-Value (W/m²K)	0.8	0.25	There was 2” of insulation under the ground floor slab. There is scope for improvement here. The U-Value modelled is conservative, 0.25 equates to ~160mm of EPS (λ= 0.04W/mK / R3.6 per inch). The insulation provided in the project was not continuous at perimeter footings, which would result in a thermal bridge (discussed in the next section).

4.3 Glazing

Table 6 lists U-value of the windows in the project. When specifying windows, it is also important to note that generally manufacturers provide only center of glass U-value for a fixed size unit. It is also necessary to obtain and specify a frame U-value, spacer thermal bridge value and if possible the thermal bridge of the installation detail (discussed more in the next section). Individual windows within a project will have different U-values if the sizes vary (this is calculated in PHPP for each window and factored in). PHPP is available in both metric and Imperial units, and care needs to be taken when specifying units to use consistent method. The best performing Passive House windows are generally 0.59-0.75 W/m²K with the recommended install U-value (accounting for the thermal bridge of the connection to the wall) being 0.75 -0.85 W/m²K (0.13-0.15 Btu/hr-sf-°F).

Table 6: U-value of windows.

Element	As Specified / Built	As modelled
Windows: U-value (W/m²K)	1.53 Fixed 1.76 Operable	0.92 (Installed)

Windows were modelled with a Psi install (thermal bridge value as discussed below) of 0.04W/mK. This is a default PHPP value that indicates a thought-out detail, but it can be improved with further attention to fully eliminate thermal bridge (≤ 0.01 W/mK). Left unattended, this thermal bridge at window installation can result in sizeable heat loss (as modelled below). The install U-value modelled in this study (accounting for glass, frame, spacer and installation) is 0.92 W/m²K. This in itself is conservative, typically 0.85 W/m²K is recommended, but there are not as many Passive House level windows available in North America. This higher performance requirement for windows is to ensure heat loss is minimized but also to ensure comfort and hygienic requirements are met. The average temperature internal surface of the glazing and minimum surface temperature is limited to avoid unpleasant cold air descent, radiant heat deprivation and eliminate the risk of condensation and mold growth (PHPP will issue a warning glazing elements are close to or above these thresholds).

There is a large amount of glazing in the project, in particular oriented north. This is good from a daylighting point of view and in Pitt River Middle School results in a very successful corridor spaces lit via north facing clerestory windows, as seen in Figure 1. However, it is not desirable from a heat loss perspective, and the north facing windows results in losses of approximately 24,000 kWh/a (or 4.2 kWh/m²a). Overall, there are 53,550 kWh/a losses (or 9.4 kWh/m²a) compared to 31,525 kWh/a gains (or 5.5 kWh/m²a). Generally, Passive House projects seek to minimize losses and maximize gains. Glazing elements are less efficient than opaque surfaces but are also the only building envelope element which can serve as a source of free heat and result in a net gain contributor.

4.4 Thermal Bridging

Thermal bridges, sometimes referred to as “cold bridges”, occur in the building envelope when a material of relatively high conductivity interrupts or penetrates the insulation layer. They provide a path of least resistance for heat to bypass the insulation layer and have a measurable impact on energy efficiency and thermal comfort. As buildings become more insulated, the relative effect of thermal bridging becomes more pronounced.

In addition to being a source of heat loss, the primary reason to avoid thermal bridging is the durability of the building envelope and indoor air quality. Thermal bridging can result in colder surface temperatures on the internal surface of the building envelope. This in turn can lead to warm moist air, hitting a colder surface, with a risk of condensation and mold. In order to ensure human comfort that Passive House requires, internal surface temperatures should be maintained above 17°C (62.6°F). Critical areas (e.g. door thresholds, window frames, etc.) should be kept “condensation risk free” above 12.6°C (54.7°F) the temperature where dew point is likely, by eliminating thermal bridging.

There are a number of different types of thermal bridges, which are outlined below. Typically, the approach in Passive House buildings is to avoid/eliminate thermal bridging by ensuring continuity of insulation. While this takes a bit of consideration in the design stage, it is a simpler and in the long run more cost-effective, in terms of energy loss and building detailing.

Thermal bridges are often unavoidable, particularly where there are other multiple issues to be resolved at a junction (e.g. structure, fire safety). Where they cannot be eliminated, they should be minimized and accounted for in the PHPP energy model.
Thermal bridges can be categorized in a number of ways, but there are two main groups:

- Geometrical thermal bridges occur due to the building form. It may be due to shape alone where the thermal envelope changes shape, such as an external wall corner.
- Construction thermal bridges occur where there is a penetration or gap in the insulation due to the construction.

There are a number of other sub-categories of thermal bridges that are often referenced:

- Repeating thermal bridges are construction-based and follow a regular pattern and are evenly distributed over an area of the building envelope, such as studwork in a wall assembly, cladding attachments, masonry wall ties, etc. These are the only thermal bridges accounted for in ASHRAE 90.1, whereby the R-values of the assemblies are degraded from nominal R-values to effective R-values[16]. This is allowed in

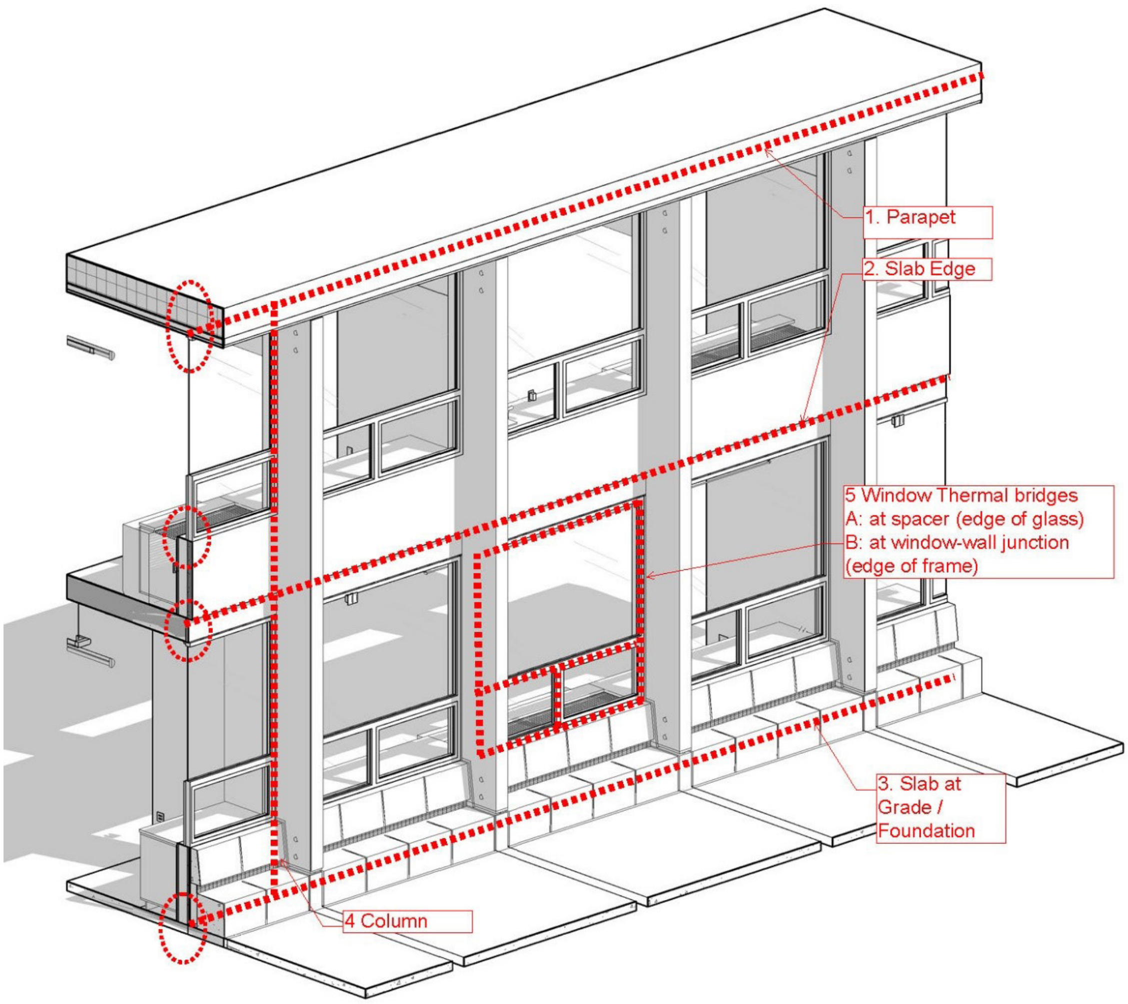


Figure 7: Potential areas of (linear) thermal bridging.

PHPP modelling. Repeating thermal bridges can have a significant effect on heat loss.
- Non-repeating are intermittent and occur at a specific point in the construction. These may be linear thermal bridges or point thermal bridges, as described below.

There are also a number of thermal bridges that may come as a surprise to the design team and may need to be modelled in PHPP, such as curtain wall anchors, rainwater liters and sanitary pipes if uninsulated and penetrating the envelope, any direct venting (e.g. a kitchen extract hood, dryer exhaust), etc.

Figure 7 shows potential thermal bridges for this project. In the instance of the balcony detail thermal bridging was recognized as a potential issue by the design team and was highlighted in the project specifications and detail drawings. Excerpts from specifications are included below:
- Provide thermal isolation where components penetrate or disrupt building insulation. Install gap-filling insulation in shim spaces at perimeter of assembly to maintain continuity of thermal barrier
- Structural Performance: Provide structural thermal break assemblies capable of withstanding the design loads within limits and under conditions indicated.

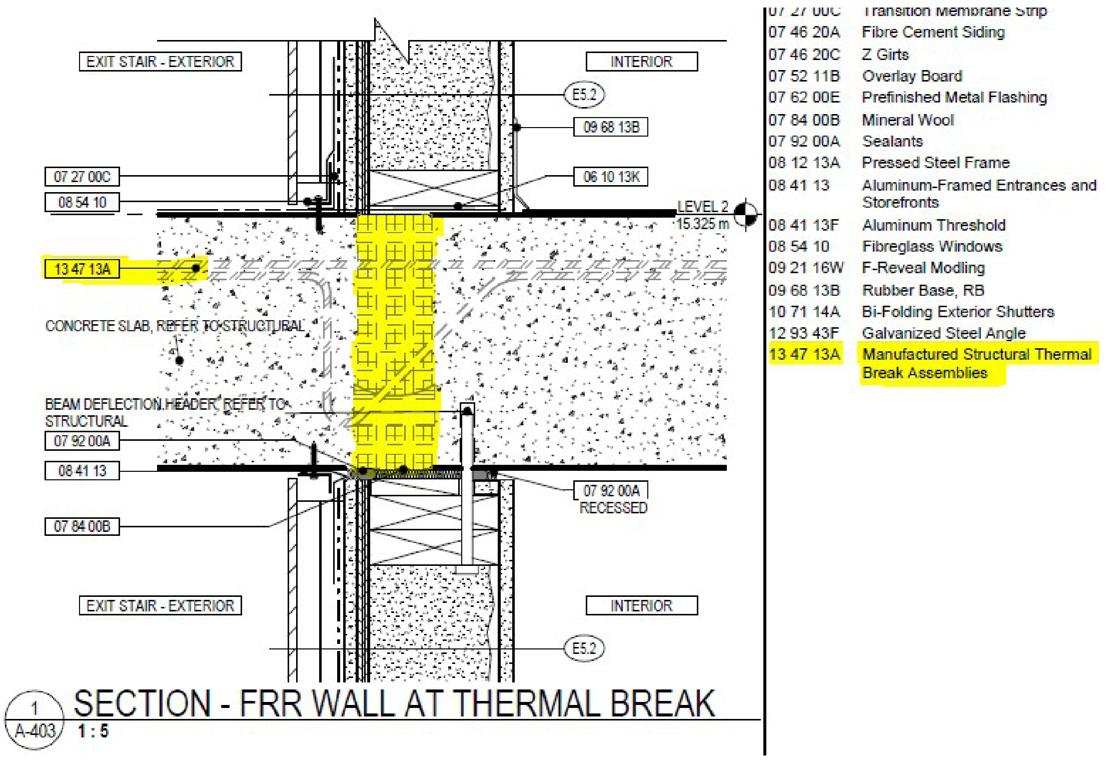


Figure 8: Detail drawing.

- Expanded-Polystyrene Foam Insulation: Manufacturer's standard high density foam with graphite; minimum thermal transmittance (U-factor) of 0.78 W/sq. m x K per 25 mm thickness.

Of note are structural thermal breaks installed at floor slabs, penetrating the envelope to become a balcony slab. Typically, balcony slabs are constructed without the thermal break, and dramatically decrease the effectiveness of assembly. It is important that these measures are not only specified, but also installed correctly. Passive House certification process requires photographic evidence of the thermal break correctly installed to achieve certification. In a Passive House project, all potential thermal bridges need to be identified and calculated and the specification would need to indicate required Psi (ψ) values (described below), and mitigation measures.

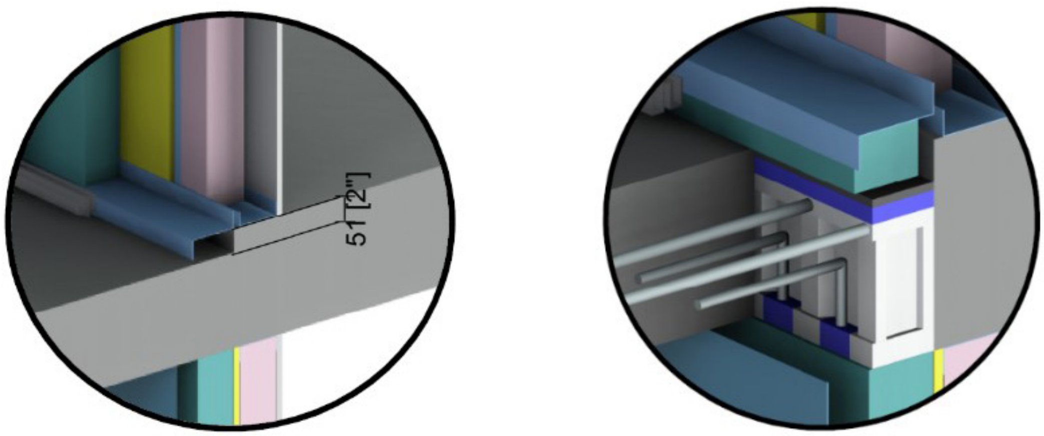
Thermal bridging can have a dramatic effect on the thermal performance of building envelopes[17]. In the example illustrated in Figure 9, the nominal R-value of R-29 (Btu/hr-ft^2-F) wall becomes an effective R-value of R-8.6 due to the thermal bridging of a concrete slab. Installing a thermal break does not completely mitigate the problem and render the detail thermal bridge free, but can restore some of the effectiveness of the insulation, in this example to R-13.6.

In terms of energy loss through thermal bridges, this is assigned a coefficient known as the Psi (ψ) value for linear thermal bridges and a Chi (χ) value for point thermal bridges. Similar to a U-value for elements such as walls, this value indicates the rate of heat flow through the thermal bridge. For a Passive House project to be thermal bridge free, these values should be less than or equal to 0.01W/mK (0.006 kBtu/hr-ft-F). This is achieved through detail design, providing adequate continuous insulation and specifying materials of adequate thermal performance.

The heat loss effect of a thermal bridge is given by multiplying ψ value by the linear length of the thermal bridge, such as a balcony running around the perimeter of a building. Table 7 illustrates the comparative effect of the potential heat losses of a thermal bridge 200 m long the

Table 7: Comparison of heat losses for different climates, in relation to thermal bridging. This given by is the heating degree hours by the climate data files within PHPP, given in kilo-Kelvin hours per annum (kKh/a). This is 69kKh/a for Vancouver and 93kKh/a for Toronto.

	No thermal break	Thermal break	Passive House
ψ (W/mK)	1.059	0.327	0.01
Heat loss (W/K) = ψ x L	211.8	65.4	2
Annual Demand in Vancouver* HL x 69 (kWh/a)	14,614.2	4,512.6	138
Annual Cost in Vancouver AD x $0.108/kWh	$1,578.3	$487.4	$14.9
Annual Demand in Toronto* HL x 93 (kWh/a)	19,697.4	6,082.2	186
Annual Cost in Toronto AD x $0.108/kWh	$2127.3	$656.9	$20.1



Balcony Stepdown Detail

Thermally Broken Slab Detail
(Isokorb CM20)

Figure 9: The example on the left (no thermal break) has a ψ value of 1.059 W/mK (0.612 kBtu/hr-ft-F) and degrades an R-29.1 h-ft^2-°F/Btu (5.15 m^2K/W) wall build-up to R-8.6 h-ft^2-°F/Btu (1.51 m^2K/W). The example on the right with the thermal break installed has a ψ value of 0.329 W/mK (0.189 kBtu/hr-ft-F] and degrades the same wall build-up to R-13.6 h-ft^2-°F/Btu (2.40 m^2K/W)[17].

perimeter (if the balcony detail ran the full length north and south of the academic wing of Pitt River Middle School, it would be this long). Also noted are the effects of the same detail in a different climate (Toronto), for illustrative purposes.

4.5 Window Installation Thermal Bridge

Part of the study's aims was to examine the process of thermal bridge modelling and calculating PSI (ψ) values. This is a scope of work that is integral to Passive House projects, but not required in typical projects. This was conducted using heat transfer analysis software THERM, developed by Lawrence Berkley National Laboratory. The window sill detail was examined, as seen in Figure 10, with the results shown in Table 8.

Repeating thermal bridges (e.g. studwork in an wall assembly) are generally accounted for in degrading the R-value of the wall. Non-repeating thermal bridges are measured by assigning a thermal bridge loss coefficient. These may be 2D/linear (e..g a length of parapet) or 3D/point thermal bridges (e.g. a steel beam penetration). Using modeling software, such as THERM, the design team can determine the exact heat loss through a detail of a building component. This can be compared to the heat loss that is estimated within an energy model (e.g. PHPP) by using the U-values and areas of the assemblies. This comparison of real versus estimated values gives an adjustment factor to be applied to the detail to account for the thermal bridging effects. This is essentially an accounting principle that compensates for the difference in heat loss between values modelled based on assemblies and the actual heat loss.

For point (3d) thermal bridges, the correction factor is known as the Chi (χ) Value. In Passive House design, these bridges are usually designed out and can be ignored unless they contribute to significant heat losses (in which case they may require specialist thermal bridge modelling, such as for a steel beam penetration).

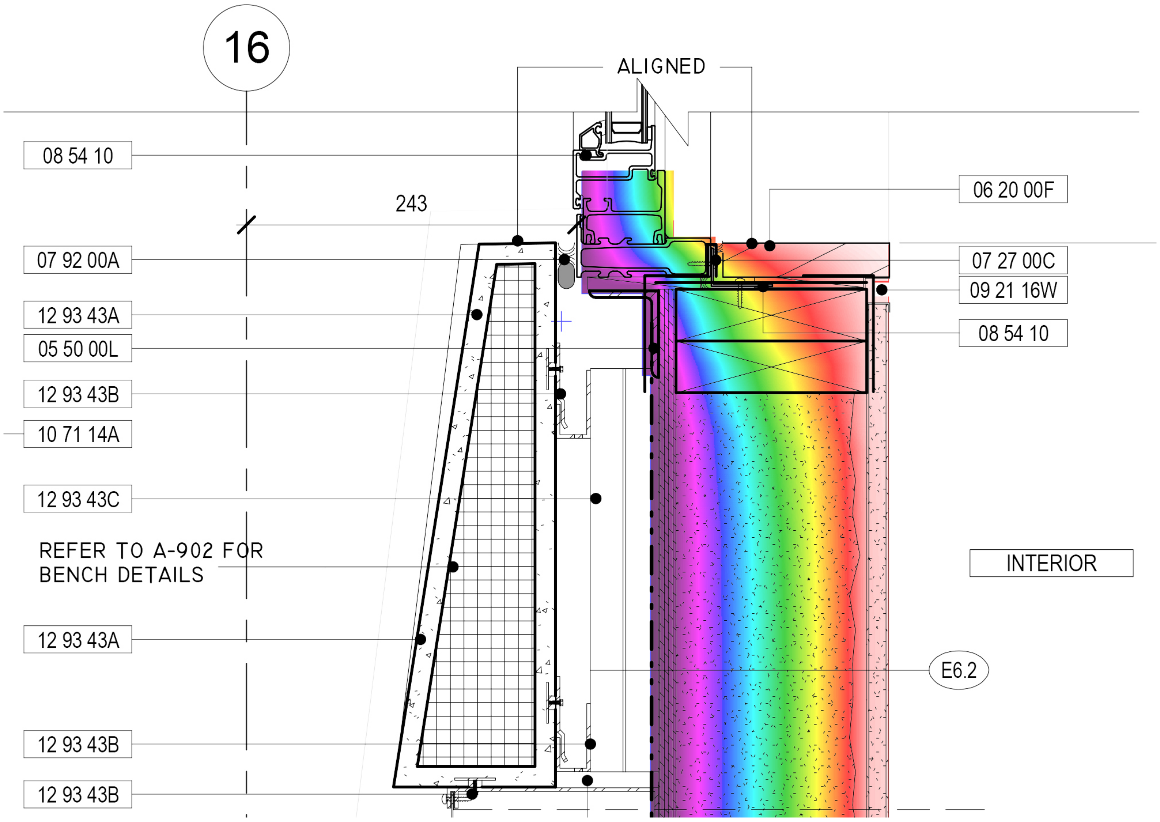


Figure 10: Pitt River typical window sill detail, where the PSI value was calculated using THERM software as 0.129 W/mK.

Table 8: Heat loss and cost of thermal bridging of window installation detail.

		TB total length (m)	ψ value (W/mK)	Total Annual Heat Loss (kWh)ψxLx69	Total Annual Cost @$0.108/kWh
Window Sill	As Built	591	0.129	5260.49	$568.13
	Passive House	591	0.04	1631.16	$176.17

For linear (2d) thermal bridges, this value is known as the PSI (Ψ) value. Multiplying the Ψ value by the linear length (L) of the junction will give the heat loss as a result of thermal bridging for this detail. This can be used as an input for PHPP to give the correct heat loss from thermal bridging. A design without thermal bridging can be defined as $\Psi \leq 0.01$ W/mK (0.006 kBtu/hr-ft-F). It is possible to have a negative PSI value. PHPP uses external dimensions for measuring heat loss. This means that the heat loss at external junctions may be overestimated (accounted for twice). The negative PSI value compensates for this.

For Passive House, U-value of the glazing must account for U-values of the glass (center of pane) and the frame, and the Psi values of the glass spacer. This is not the actual U-value that a window will have in reality, as the installation detail can have a thermal bridging effect and needs to be accounted for. The default in PHPP for a well-designed detail is $\Psi = 0.04$ W/mK (0.023 kBtu/hr-ft-F). The typical Pitt River window detail was modelled in THERM, giving a resultant thermal bridge value of $\Psi = 0.129$ W/mK (0.074 kBtu/hr-ft-F).

A typical classroom window in the project is 2.575 m x 2.350 m, and there are 60 windows in total, giving a total perimeter length of 591 m. The window sill thermal bridge ψ value may differ slightly at the jamb and head due to detailing, but for the purposes of this research was assumed constant. The heat loss (and cost) is reduced by 70 percent by bringing the value to the default 0.04 W/mK.

Assuming that the wall assemblies are optimized to achieve recommended Passive House U-values, it is possible eliminate thermal bridging (ψ value <0.01W/mK). The junction with the wall requires careful detailing in order to eliminate the thermal bridge of window installation. Some basic rules of thumb to improve the ψ value are:

1. Placing window as close to centre of insulation layer as feasible;
2. Over-insulating frame;
3. Avoiding extra framing and blocking at rough opening; and
4. If possible, using non-metal flashing.

5.0 CONCLUSION

This study demonstrates that the recommended Passive House levels of thermal performance are a step beyond existing best practices. This study was limited to examining the role of Design PH as a precursor to PHPP modelling, and discussed the process of calculating thermal bridging. Specifying Passive House levels of performance for the building envelope, assuming an optimized mechanical system specification and layout, will get a project approximately half way there (in this case from 49 kWh/m^{2}a in the BC Hydro Report, 44 kWh/m^{2}a in the LEED Report to ~23 kWh/m^{2}a). The final reduction, in this case ~8 kWh/m^{2}a, is always the hardest to achieve. This shows the importance of setting the target as a goal at a very early stage in the project, as a project cannot be "made" Passive House compliant at the end of schematic design stage or beyond, once important design decisions have been made. It requires careful planning and consideration, as well as engagement of the whole project team.

As was the case with the first LEED projects, the first Passive House projects will have a steep learning curve. The question of identifying and quantifying any required extra cost to achieve the Passive House standard is usually one of the first to be asked. This is closely tied to the impact on schedule. The cost impact can be broken out into:

1. Impact on construction (costs and schedule);
2. Building operation/running costs;
3. Impact to design stage (costs and schedule), such as additional work required by the architect and design team; and
4. Passive House consultancy and certification costs.

While this is outside the scope of what was explored in the context of the study on Pitt River Middle School, further study into this area is being explored by the author and will be the subject of subsequent articles.

In terms of the effect on the design process, there are a number of elements that differ from a traditional project, specifically requiring additional scope of work and sequencing of work. There is more detailing required, particularly in terms of meeting the required performance levels for airtightness and thermal bridging.

Acknowledgements

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