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Passive Houses in Cold Climates

An Overview for Homeowners and Architects

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The purpose of the thesis was to provide an overall picture of a passive house with topics and aspects that are of importance. The aim was to offer concise information on the subjects and provide a practical guide on designing a passive house in a cold climate. Recommendations for building a passive house in Southern Finland were also given. Two passive house projects in Canada and Sweden were discussed.

Literary sources such as the Passive House Details Solutions for High-Performance Design book and the Passive House Design book were studied to provide practical knowledge on each topic. The thesis included some lessons learnt from experiences that were shared by passive house experts. Recommended characteristics of a passive house in Finland were given based on recommendations of passive house experts. The blogs of the two passive house projects in Sweden and Canada were reviewed for information. The owner of the passive house in Sweden was interviewed for insights.

The thesis gives a starting point to architects and homeowners for their journey in studying passive house. All topics discussed are essential in passive house design to provide the basics and preliminary understanding on the subjects. Therefore, the level of details of the thesis remains at the introductory level.

Keywords	passive house, cold climate, homeowner, architect, energy efficient, detached house

Contents

List of Abbreviations

ACH50	Air Change Rate Per Hour At 50 Pascal Pressure Differentials
CCSPF	Closed-Cell Spray Polyurethane Foam
CLT	Cross Laminated Timber
CMU	Concrete Masonry Unit
COP	Coefficient of Performance
DHW	Domestic Hot Water
EPS	Expanded Polystyrene
ERV	Energy Recovery Ventilation
HRV	Heat Recovery Ventilation
ICF	Insulated Concrete Form
LAM	Liquid-Applied Membrane
LVL	Laminated Veneer Lumber
MVHR	Mechanical Ventilation with Heat Recovery
OCSPF	Open-Cell Spray Foam Insulation
OSB	Oriented Strand Board
SAM	Self-Adhered Membrane
SIP	Structural Insulated Panel
SPF	Spray Foam Insulation
TFA	Treated Floor Area
T&G	Tongue and Groove
TPO	Thermoplastic Polyolefin
XPS	Extruded Polystyrene Insulation
WBS	Water Barrier Sheathing
WRB	Water Resistive Barrier

1 Introduction

Climate change is a consequence of human activities. Buildings account for 30% of the global emissions [1], which certainly requires our concerted efforts to diminish their impact on the environment. One solution is high-performance construction in terms of energy, which includes the passive house concept – a German building concept born in 1996 [2]. Over the years, the concept has proven its practicality and viability. Numerous passive houses have been built in North America, Europe, Australia, and some countries in Asia. Nevertheless, the number of passive house projects in Finland seems to be still quite modest and the concept itself is not yet widely well-known.

Nowadays, information about passive houses is abundantly available online or in books, and training courses. However, most of it is very topic specific and in-depth, which does not always attract people to the concept. Homeowners and architects have the power to decide the type of building to be constructed. Thus, they should be informed about this concept in a brief but informative way.

Hence, the purpose of this thesis is to provide an overall picture of passive houses with topics and aspects that are of importance. This paper aims at offering a preliminary understanding of passive houses for non-construction professionals. Architects are given an idea about the passive house concept, in order to recognize the aspects that require attention in the design, and to know what to study more. Homeowners will get an overall understanding of passive house concept and its characteristics.

In every passive house project, a certified passive house designer to plan and execute the project is a necessity, because a passive house project solidly depends on details that require specialized know-how and experience. A single incorrect detail could have a great impact on the overall performance of the building, or unnecessarily complicated mechanical systems could have an adverse rather than positive effect on the building. Therefore, a professional has a higher chance at delivering project objectives with better outcomes at lower cost.

This thesis is a compilation of theories mainly from two books, highly recommended for further in-depth studies:

- Passive House Details Solutions for High-Performance Design by Donald B. Corner, Jan C. Fillinger, and Alison G. Kwok. First edition published in 2018.
- Passive House Design by Gonzalo Roberto, and Rainer Vallentin. First edition published in 2014.

The thesis introduces the principles of designing and executing a passive house. Recommendations for Southern Finland are also given. Furthermore, some examples of detailing work from existing projects are shared in chapter 5. Finally, the thesis discusses two passive house projects in cold climates. This thesis is written under the guidance of Passive House Association Finland (Passiivitaloyhdistys), an association dedicated to the passive house concept in Finland.

Homeowners are recommended to read from chapter 1 to chapter 4 and the conclusion (chapter 7) to gain a holistic view on the passive house concept. Chapter 5 has relatively detailed information which might not be of interest to non-construction professionals but might be to architects. Chapter 6 offers the characteristics of two passive house projects in Sweden and Canada.

2 What Passive House Is and What It Entails

The term Passive House (Passivhaus or Passiivitalo) means an ultralow-energy design standard. All elements in the envelope are pushed to the limit to achieve high isolation of the indoor atmosphere from the outdoor climate without compromising the living comfort. It is important that the living comfort is not diminished in any way to gain improved energy performance. As equally important, financing in construction, such as material and equipment costs, financial gains from lower utility bills and/or incomes from renewable sources, are decisive factors that need to be put on the drawing table as well. Hence, it truly is an art to design a passive house, since the outcome is the most balanced solution harmonizing building performance, living comfort, finance, and the homeowner’s wishes. The design is case dependent and there is no such thing as a one-fit-all design.

Passive house is not a brand name, but rather is a construction concept that is simultaneously truly energy efficient, comfortable, affordable, and ecological [2]. In other words, the designated outcome of a passive house project is a building that is highly energy-efficient, considerably durable, thermally pleasant, and aesthetically pleasing, with great indoor air quality. Most of these outcomes are addressed by the design of the building envelope, and some are addressed by the mechanical systems in the building. Nevertheless, it comes with stringent standards, as shown in table 1 below. [3, p. x.]

Table 1. Summary of passive house requirements [5, p. 23].

Passive House requirements

Criterion	Abbreviation	Passive House requirement
annual specific space heat demand (or cooling demand)	q_h/q_c	≤ 15 kWh/m²a
average daily heat or cooling load	P_h/A_{TFA}	≤ 10 W/m² (P_c/A_{TFA} ≤ 10 W/m²)
primary energy factor (non-renewable primary energy) heating, cooling, ventilation, domestic hot water, auxiliary power and all other uses of electricity in the building	q_p	≤ 120 kWh/m²a
airtightness (blower door test, 50 pascals)	n_{50}	≤ 0.6 h^{-1}
frequency of overheating (number of hours with temperatures over 25 °C)	$h_{(\geq 25°C)}$	≤ 10 %
window U-value (installed)	$U_{w,installed}$	≤ 0.85 W/m²K
energy criterion of glass (relation between U_g and g-value)		U_g – 1.6 W/m²K • g ≤ 0
effective heat output capacity of ventilation unit	$\eta_{HR,eff}$	≥ 75 %
power efficiency of ventilation unit	p_v	≤ 0.45 W/m³h

The devil is in the detail. This idiom figuratively describes the key to meeting the strict requirements of a passive house. The success lies in the details, which need both the designer's and the builder's utmost attention to perfect and improve for the best holistic building performance. The challenge in design is to creatively meet the stringent performance requirements, which demand exactitude in every detail. The challenge of construction lies in understanding the meaning of meeting these stringent performance requirements to maintain perfection in the details, which sometimes requires more effort than normal constructions. [3, p. ix.]

A building is used to close the gap between our comfortable living conditions and the ambient climate at a given place. The width of that gap is determined by how well the building envelope is constructed, in other words, how well it can insulate the indoor environment from the outdoor climate. The remaining of the gap is bridged by active space heating and cooling, which must be kept at a lowest possible level. Renewable sources of energy should be exploited to achieve such goals, for instance, sunlight for heating, lighting, and electricity. However, as more sunlight is used for heating in the winter, it creates a cooling demand in the summer. Therefore, we must reconcile our needs to find the point where everything is balanced and optimized. The primary instrument to control all the variables is the building envelope, at which we must look very critically how it is made, what it is made from and how it performs. [3, p. 2.]

The design of the building envelope determines all our possibilities. For instance, a high-performance envelope in a commercial building diminishes the expense needed for mechanical systems such as cooling and heating, number of ducts and pipes installed for air conditioning. In addition, the operating energy for fans and pumps is greatly reduced. The goal of a passive house is to bring the operating energy demand down to a level that on-site renewable sources can supply. Optimizing the envelope allows it to happen. [3, p. 2.]

Designing heat loss through building envelope is essential in building enclosure design. Lower heating demand is the result of the reduced heat flows through walls, floors, roofs, and windows or skylights. Designers achieve them by adding thermal resistance (R-value) to various assemblies, i.e. decreasing the thermal conductivity (U-value) of the components. The lower the thermal conductivity, the less heat is transferred through the envelope elements. This theory applies well to homogeneous elements, yet it is not necessarily always true for non-homogeneous elements. A wall assembly with a wooden or metal framing, filled with mineral wool insulation between, does not have an even heat flow through the wall surfaces, as wood or metal framing transfers heat significantly better than mineral wool does. Hence, the heat loss through the frame acts as a drag on the overall thermal performance of the assembly. It is a weak link in the assembly, which is also called a thermal bridge. A passive house abhors thermal bridges. [3, p. x.]

The potential weak links in the building enclosure could be in the transitions between assemblies, for example window to wall, wall to roof, wall to floor, and within assemblies for example sills, headers, and corners. Unintentional air leaks can occur at these places if they are not carefully sealed. Through unintentional leaks, air can flow into or out of the building with nothing to stop it. It takes a concerted effort to seal these gaps in the design and during construction. Failure to eliminate air leaks increases the building heating demand and, potentially, leads to another major problem: condensation in the structure. Accumulation of moisture in the structure in places where it should not get wet causes a major risk of material degradation, stimulating mold growth which may lead to indoor air quality problems. The structure is at a high risk of damage in the long run, not to mention the risk of health hazards caused by poor indoor air and mold. Moisture damage is to be avoided in a passive house. [3, p. x.]

In passive house design, the designer must be able to draw the line – literally. There must be a continuous line that defines the plane of thermal barriers, and another one that defines the plane of an air barrier. Likewise, it may be advisable to have an unbroken line defining the plane of the vapor retarder, although it is not clear that obstructing the vapor flow is always the best approach. Anyway, impeding heat and airflow are preferable in a passive house. It is the infiltration rate which must be kept low in a passive house since a higher air flow through the building envelope results in a higher heat flow. A passive house does not need excessive infiltration. [3, p. x.]

Another weak link in the building enclosure are the windows and doors since their thermal conductivity (U value) is a few times higher than that of walls, roofs and floors. In a passive house, windows have a major influence on the energy balance of the building, hence, they must be implemented and managed with great care. [3, p. 9.] Manufacturers developed the characteristics of these elements and have succeeded with great thermal performance results. However, they are still not comparable to the opaque elements. The windows of a passive house often have triple or quadruple panes with details that enhance their thermal performance such as spacers, frames, etc. The installation method and location have also a major effect.

Mechanical systems for ventilation, heating, domestic hot water, renewable energy and even home appliances contribute to a sizable portion of a building’s energy demand. A ventilation unit with heat recovery is already a common construction practice in Finland, hence it is not difficult to adapt to passive house certified ventilation units which can have a heat recovery rate of more than 90%. The selection of a heating system is the most important decision since it dictates what the auxiliary systems are possible. This, in turn, defines what renewable sources, such as geothermal or solar energy can be used. In passive house, it seems to be common to use a heat pump and ventilation as the main source of heating, thanks to its thermally well insulated building fabric.

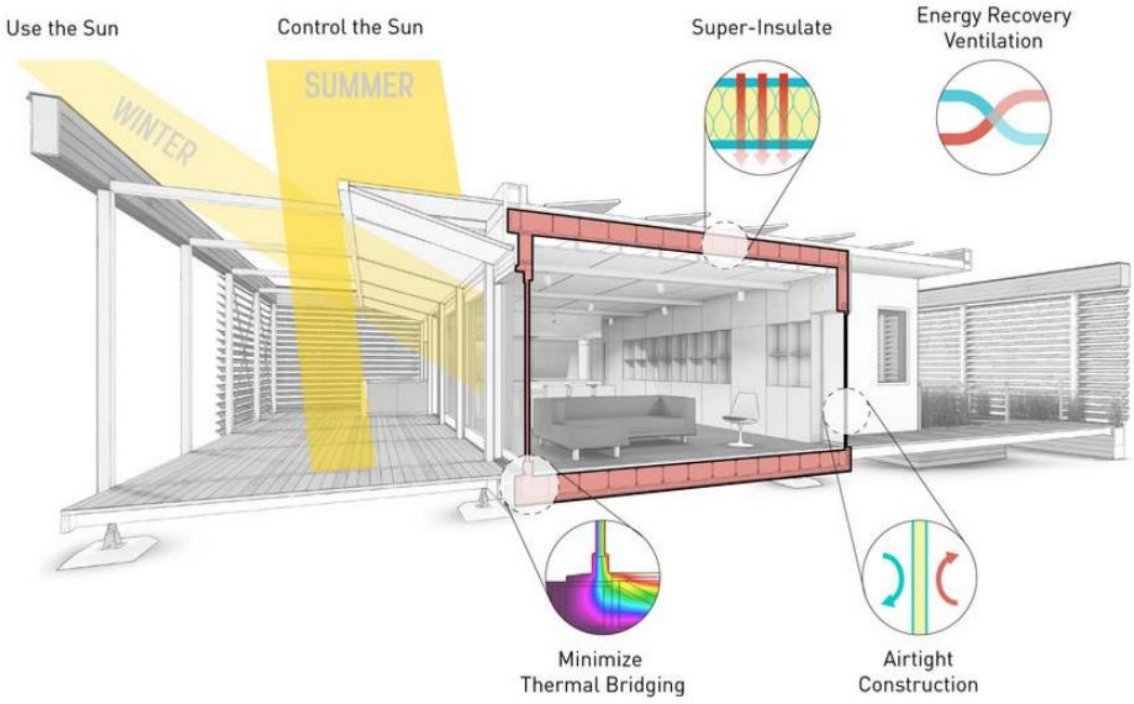


Figure 1. Basics of passive house design principles [4].

The aforementioned aspects are few of the many that a passive house designer should attend to. Corner D. et al. have pointed out five building science principles, which are also illustrated in figure 1 above, of passive house building standards:

1. Thermal bridge free envelope with continuous insulation through the entire building enclosure.
2. Extremely airtight envelope to prevent infiltration of outside air and loss of conditioned air.
3. High-performance windows, typically triple-paned and high-performance doors.
4. A balanced form of heat and moisture recovery ventilation with a minimal space conditioning system.
5. Management of solar gain to exploit it during the heating season and minimize it in cooling seasons. [3, p. 2.]

Passive house standards lay down holistic performance standards for the entire building rather than prescriptive standards for the individual parts. It allows freedom in designs and stimulates creativity in the solutions of the designers. Nevertheless, the key to success is simplicity. Complicated solutions result in complexity during construction, hike in cost of both construction and operation. The performance-enhancing details in a passive house should be elegant and simple to construct. [3, p. x.]

3 Principles of Design

3.1 Compact Design

Passive house values compactness. In average, the costs per m^2 of building envelope are greater than those for the interior building components. This is further increased in passive house due to requirements for thicker thermal insulation and air tightness layer. Hence, it emphasizes the fact that the smaller the total sum of envelope area in relation to the building volume or the useful floor area, the lower the heat loss. The area-volume ratio in question is called the form factor, which expresses the degree of compactness of the building. It has possibly the most serious impact on the building's embodied energy. As a rule of thumb, the more compact the building is, the less transmission heat losses through the building envelope. [5, p. 34.]

In simple non-technical words, a large and wide one-story house does not perform efficiently in terms of heating, since the area to be heated is widespread. However, a two-story building with the same total floor area would perform much better since heat goes upward from the first floor to the second floor and is re-used. Furthermore, a compact space may be much easier to heat up since the heat does not have to travel far from the source, which results in smaller heaters. As a result, the thermal comfort might be more pleasant and even everywhere in the space.

The form factor can be defined as:

- The A/V ratio, which is envelope surface area (A) over the building volume (V). Nevertheless, this ratio is slightly imprecise because it includes unused spaces hidden in the volume, such as jamb wall areas or voids.
- The A/TFA ratio, which describes the relationship between the envelope surface area (A) and the treated floor area (TFA). [3, p. 34.]

The form factors are illustrated in figure 2 below. The recommended form factor for a detached passive house is less than 0.8 [6].

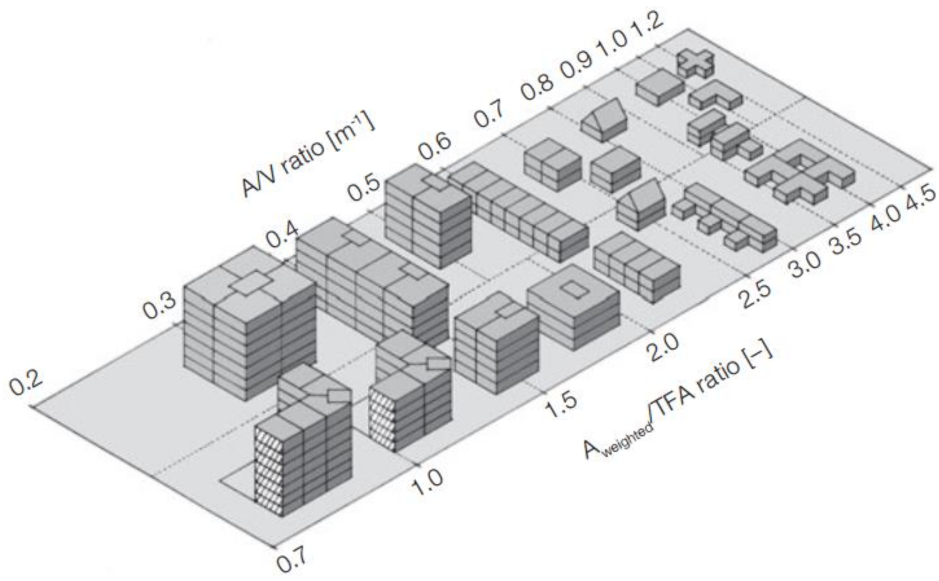


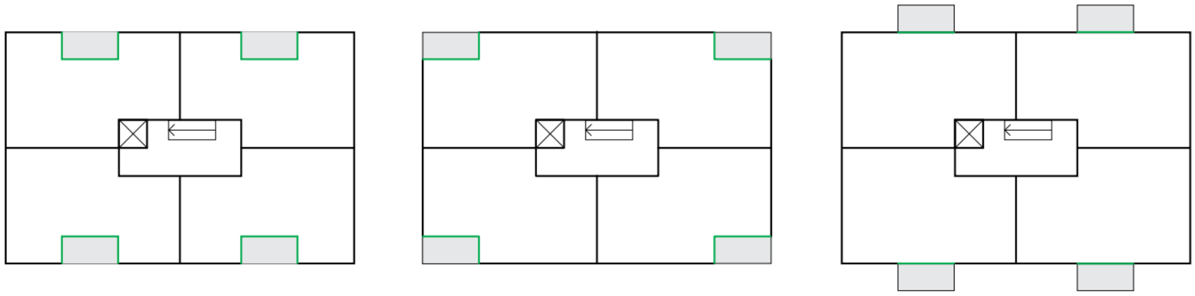
Figure 2. Various form factors for various types of a residential building [3, p. 35].

For a compact residential building, there are some parameters that designers should focus on:

- Total volume of the building.
- Number of floors.
- Building depth.
- Roof design. [3,34.]

The factors above impact on the features of the building. A one-story building is generally not at its advantage, whereas a five-story building or taller hardly gain any further improvement. The recommended depth of a building is 7 meters. It is unfeasible to go beyond this depth. Buildings that are deeper than 12 – 15 meters require artificial lights for the interior spaces.

In reality, there are numerous reasons for a potentially compact building to become less compact in terms of energy efficiency. The shape of the building depends on its architectural layout, spatial wishes and decisions, not to mention the internal structures, such as spaces for loggias, integrated balconies, and protruding elements in the facade. Figure 3 below demonstrates the effects of the locations of loggias to the space heating demand on the assumption that the insulation of the thermal envelope is homogeneous and continuous. Junction lengths affected by thermal bridges are presented in green line. [3, p. 34.]



	Loggias, central position	**Loggias, corner position**	**Balconies, set in front of facade**
thermal bridges:	40 m	30 m	20 m
$A_{weighted}$/TFA =	1.54	1.39	1.28
reduction factor for overshadowing:	0.51	0.55	0.70
space heat demand:	17.0 kWh/m²a	14.7 kWh/m²a	10.2 kWh/m²a

Figure 3. Comparison of different ways to locate loggias and balconies [3, p. 35].

Figure 3 shows that setting balconies in front of the facade results in the lowest space heating demand and A/TFA ratio. Loggias and balconies are generally unheated spaces. Hence, placing loggias in a central or corner position increases the thermal envelope area and junction length affected by thermal bridges, compared to balconies set in front of a façade. However, such balconies act as shading objects for lower floors. As can be seen the impact of balconies on the degree of compactness of the structure is not small. [5, p. 35].

The form factor or compactness has a noticeable impact on all building energy standards, especially in a passive house since a mechanical ventilation system with heat recovery reduces specific heat losses through ventilation. Therefore, the relative influence of transmission loss through the building envelope takes a much higher proportion and increases dramatically. [5, p. 35.]

3.2 Orientation and Response to Climate

3.2.1 Passive Solar Design

A building has a reciprocal relationship with its site, as the attributes of the site could help to reduce the environmental stress on the building, and the building could improve the ecology and microclimate of the site [3, p. 7]. The priority of a passive house is to reduce the building's active energy demand for heating and cooling by utilizing passive energy sources, one of which is the sun, an unlimited source of heat and power. This design concept is referred to as "Passive Solar Design". This concept takes into consideration various criteria, such as the surrounding trees and buildings, wind directions, heat absorber and distribution, thermal mass, solar aperture, sun positions, and shading, as shown in figure 4. [7.]

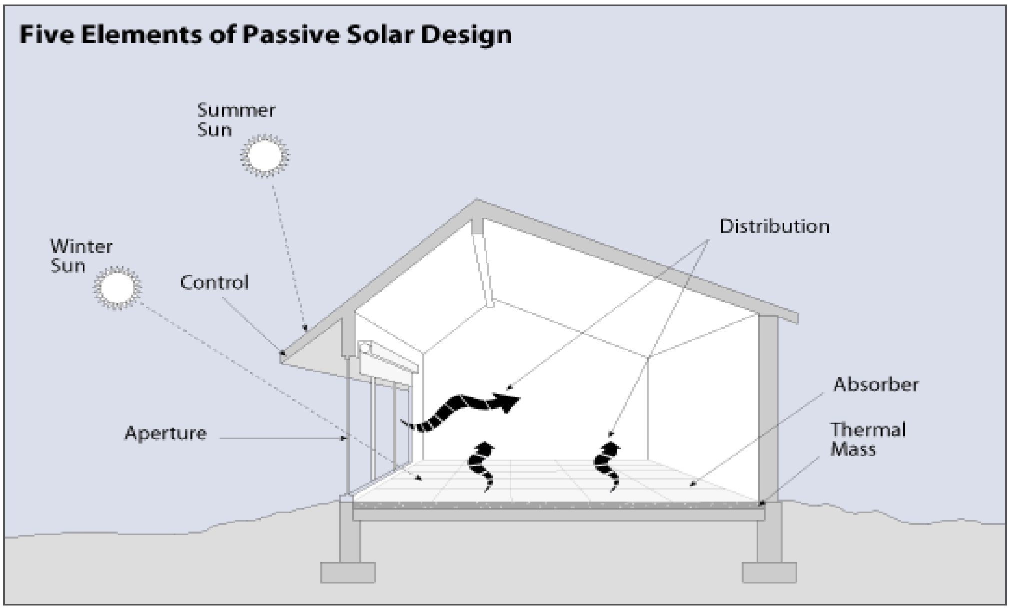


Figure 4. Elements of Passive Solar Design [7].

Orientation is critical in a passive house and the passive solar design concept, since it determines the amount of solar gain that can be utilized. In the Northern hemisphere, South-facing surfaces receive the most solar gain from the low-angle sun in the winter. Hence, it is suggested that the long-axis of the building should be in the East-West direction. Areas with most activities should be situated on the South-facing side for obvious reasons. That leaves unattended spaces, such as a garage, storage, and service spaces on the North side. [3, p. 8.]

South facing windows and thermal mass are the two primary elements of the passive solar design concept. The idea is to absorb heat from the sun through windows into the floors and walls and all other thermal masses. The heat is meant to be released during the absence of the sun. The actual living spaces act as a solar collector, heat absorber and distribution system. Solar energy is admitted through the south facing glass where it is captured and stored in the masonry floors and walls. That heat radiates back into the room when the sun is gone. [7.] In the Villa Circuitus project discussed in chapter 6.1, the inner wall is built of bricks for the same purpose.

To absorb as much heat as possible, the thermal mass elements are normally dark colors. Indoor water containers could also function as thermal masses; however, they would require additional structural support which could cause complexity in the design of the house. Of the solar energy passing through windows, 60 – 75% is stored in direct gain elements. To reach the optimum efficiency of this passive heat use, thermal mass must be insulated from the outdoor temperatures to prevent dissipating heat outwards. [7.]

3.2.2 Shading and Summer Overheating

Overheating can be a serious problem for all buildings, not just passive houses. It not only raises the cooling energy demand but also reduces the thermal comfort significantly. Therefore, overheating must be resisted with concerted efforts when the building is still a plan on paper.

Shading is a critical aspect in a passive house during the summer. As stated above, it is advantageous to capture as much solar gain as possible in the passive solar design concept, yet during the summer, excessive solar gain causes problematic overheating. Hence, it is important to stress that in a passive house, the solar gain should be optimized at a balanced point where it is beneficial. The passive house standards regulate that the total hours with temperature over 25°C must be less than 10% of the total annual hours [8].

There are several ways to prevent a building from overheating. Providing shades may be the most effective solution. Blinds, shutters, overhangs, and balconies are solutions that with careful calculations on their width and the angles for blocking the sunlight should not interfere with the winter sun. The windows on the East and West side should have more focus on having proper shading, since these windows receive more sunlight from the lower sun from these directions during the summer, whereas the midday sun coming from the South is rather high and poses less risks [8]. Transitional spaces like shaded terraces stretching on the Eastern or Western side can enhance the aesthetic look of the site without obstructing the Southern winter sun. Deciduous trees are a great natural shade since they allow sunlight to pass through in the winter, yet offer shade in the summer. [3, p. 8.]

It is very important to optimize the glazing area to prevent overheating. The Passivhaus Trust in the UK recommends that the area of South-facing windows should not exceed 25% of the external wall area, while the proportion should be significantly less than 25% on the other walls. Their rule of thumb for glazing is that glazed area (without frames) should be around 15 – 20% of the Treated Floor Area (TFA) in a passive house. The skylight area should be less than 10% of the room floor area. In addition, it is not wise to try to maximize the solar gain through South-facing windows according to the Passivhaus Trust UK. Solar heat gain is not entirely 'free', since the cost of a high-performance window is more than the cost of the wall it replaces. It has been calculated that the cost of solar heat gain through windows is around 0.5 £/kWh (approximately 0.58 €/kWh, windows lifetime: 20 years) while the cost for district heating in Finland is approximately 0.07 €/kWh (excluding distribution) and the cost for electricity is roughly 0.15 €/kWh (prices in 2019). Windows, however, have also other functions, such as providing daylight, ventilation, views and contributing to the building's appearance. Hence, windows should be designed with these features in mind, not with the sole intent of heating the building. [8.]

Mitigating the impacts of internal heat gains would also mitigate the risk for overheating in the summer. It goes without saying that low-energy appliances and fittings should be used in a high-performance building. Inefficient appliances tend to emit heat, which could contribute to rising internal heat gains. Similarly, minimizing heat losses from building services brings the same benefits. For instance, the constant running hot water systems have hot water pipes that must be insulated, not only the straight running pipes, but also the valves. Pipe sizes also matter. Hot water stays inside the pipes between the water tank and the taps when the taps are closed, which gradually emits heat. Therefore, smaller the pipe sizes and the smaller the distance from the tank to the tap, the less potential heat loss in the pipes. Likewise, the same attention should be given to ventilation ducts if heating is provided via ventilation. [8.]

A mechanical ventilation system with heat recovery (MVHR) must have a summer bypass function, which allows the extract air to bypass the heat recovery unit when the indoor temperature is higher than the outdoor temperature. This allows the cool intake air to enter the building without unnecessary heat up. Figure 5 below illustrates how this system functions. [8.]

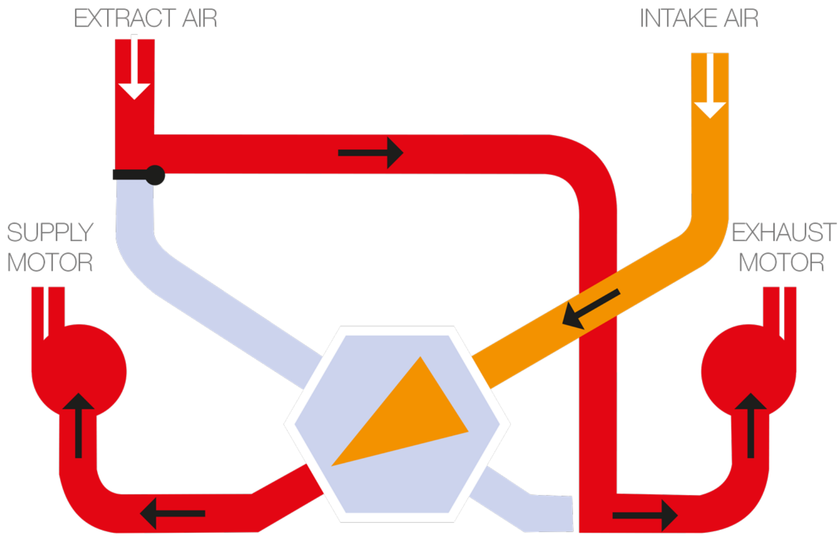


Figure 5. A summer bypass function in a heat recovery unit [9].

Openable windows are appreciated in a passive house. Contrary to some misperceptions that the windows of a passive house must be fixed and closed, opening windows for cross-ventilation is actually recommended and a great practice to remove indoor heat. The MVHR only extracts air very slowly. Therefore, only a very limited amount of heat can be removed, whereas opening windows can rapidly replace the hot indoor air with fresh cool outdoor air in the evening, overnight, or early morning, and sometimes even during the daytime in summer. [8.]

Even though the indoor temperature might be no higher than 25ºC, it might feel unpleasant after a day of being heated by the sun and indoor activities. As the outdoor air starts to cool in the evening, cross-ventilation can flush out all the excess heat and moisture and cool the internal surfaces. Windows can be left partially open overnight to prepare for a fresh start in the morning if security, air and noise pollution are not the issues. It can be more useful for non-residential passive house buildings such as schools. [8.]

3.2.3 Suggested Criteria for Site Selection

The location of a building site plays an important role in building high-performance buildings. The decision-makers should bear in mind the orientation already in the site selection stage, if possible. The following questions are recommended to consider:

- Does the lot allow a private side (backyard) facing South? This allows major rooms to open to the South.
- Can the building be constructed above or against a slope? Each degree of tilt toward the sun acts as a change in latitude.
- Will there be deciduous trees surrounding the house?
- Are there evergreen trees that block the winter wind?
- If such trees are not available in the beginning, is there room to plant them? [3, p. 7.]

3.3 Thermal Comfort

The ultimate goal of a building is that the residents find it comfortable to live or work in, in terms of convenience, appealing architecture, and thermal comfort. It is perhaps the thermal comfort that is the most difficult topic in passive house design, since it is subjective and depends on numerous variables and parameters. This thesis only points out some specific criteria in this matter to offer an idea on the framework of designing a thermally comfortable dwelling.

Thermal sense is significantly different from one person to another. It can be determined by four parameters affecting a person in a room: radiation temperature of the surrounding surfaces, room temperature, relative air velocity close to the human body, and humidity.

Ole Fanger in 1970 has discovered that body-heat balance functions as an objective criterion for comfort levels. The following factors are of importance in this matter:

- The activity, and the generation of body heat it involves
- The thermal resistance and wind-tightness of clothing
- The thermal conduction, radiation, convection and evaporation in and on the human body and in interaction with the surroundings. [5, p. 12.]

Regarding homes and offices, 90–95% of people in the survey have agreed on the following to be considered as comfortable:

- Air temperature can be in range from 18 to 24ºC, where 21ºC (± 1 Kelvin) is the most selected set temperature. In the summer, temperatures higher than 24ºC (± 2 Kelvin) can be tolerated by wearing appropriate clothing.
- The difference between the average surface temperature and air temperature should not exceed 2 – 3 Kelvin. The surface components should not differ from each other by more than 3 – 4 Kelvin. Floor temperatures are perceived as pleasant at between 19ºC and 26ºC.
- The air relative humidity should be between 40% and 70%. Relative humidity levels under 30% are considered unhealthy.
- In habitable rooms, the indoor air movement should not exceed 0.08 m/s (danger of draughts).
- In summer, an increased air velocity can help to readjust thermal perceptions and make residents feel more pleasant when operating temperatures are above 25ºC.
- At high operative temperatures (over 25ºC), all radiating heat sources with radiation temperatures over 25ºC (for instance, overhead skylights) are considered uncomfortable.
- Countermeasures, such as cooling and dehumidification, must be executed when temperatures are over 30ºC and relative humidity levels are over 50%. [5, p. 12–13.]

Windows play a significant part in providing great thermal comfort in a passive house. Using windows with high quality frames and glazing is the only way to achieve even indoor surface temperatures and limit draught through windows. [5, p. 13.]

3.4 Homogeneity

3.4.1 Thermal Bridge Free Design

Homogeneity is of great significance for a passive house building enclosure. The homogeneity principle focuses on consistent quality of the thermal envelope and junctions regarding energy performance. This means implementing a homogenous quality of insulation throughout the surfaces of the building enclosure with no interruptions at the junctions. Careful attention must be paid to all installations, such as windows and doors, and penetrations of load-bearing components through the insulation. The goal is a continuous insulation layer with the same thickness or thermal-insulating quality surrounding the building enclosure without any interruptions. Therefore, the frames of windows and doors should also be placed inside the insulation layer. Such design is called Thermal Bridge Free design. [5, p. 36–37.]

According to Passipedia, a thermal bridge is defined as “a localized area of the building envelope where the heat flow is different (usually increased) in comparison with adjacent areas (if there is a difference in temperature between the inside and the outside)” [10]. In other words, it is an area that conducts more heat than an adjacent area. Thus, the heat loss is greater through this area than through a highly insulated area. This usually occurs at junctions of the envelope, i.e. where walls and floors meet but where there is no overlapping thermal insulation. The total heat losses through an average number of thermal bridges could be the same as through opening a window [5, p. 8].

In solid constructions, it is sometimes challenging to avert thermal bridges at places where load-bearing elements penetrate the insulation plane, for instance, at the base of the building, if the below ground level is not insulated, or where balcony slabs protrude beyond the facade. To avoid thermal bridges in these circumstances, using materials with lower thermal conductivity in the bottom brick course or dividing the load-bearing structure into a few point bearings with insulation layer in between are the effective solutions. [5, p. 132.]

An example of a thermal bridge at a junction is illustrated in figure 6. The drawing on the left shows that heat flows freely through the concrete foundation wall to the ground due to the absence of overlapping thermal insulation at the junction. In addition, much heat is lost through the floor slab as well because of inadequate thickness of the insulation, discussed in more detail in the next section. The drawing on the right illustrates the thermal bridge free design, in which the wall insulation is further extended over the floor insulation level and there are wooden planks or blocks, which have a much lower thermal conductivity than concrete, to separate the concrete wall from the ground. Hence, the thermal bridge is diminished.

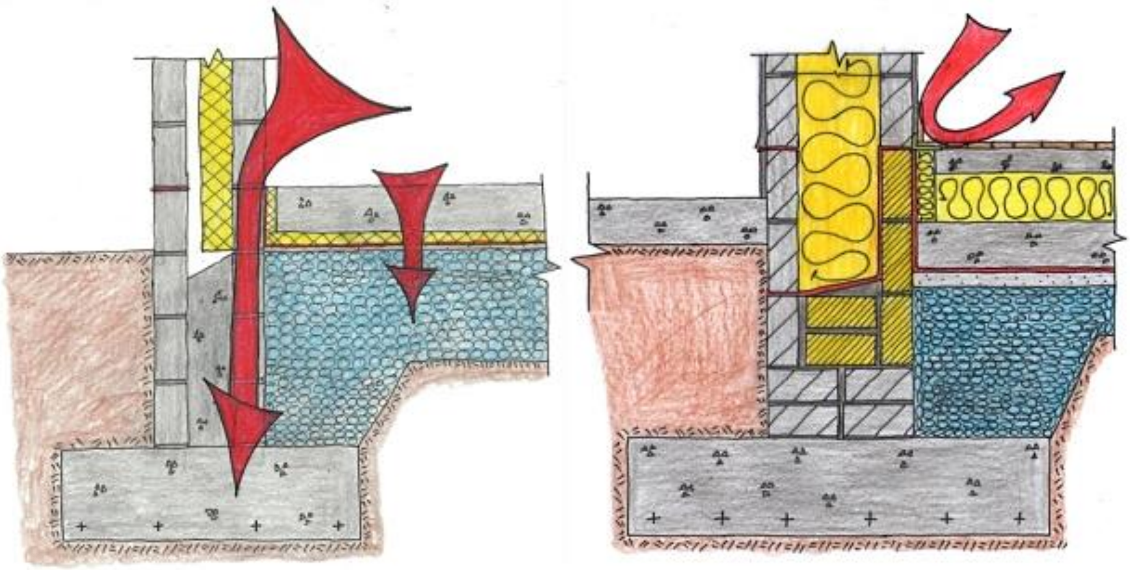


Figure 6. Example of thermal bridge at junction between foundation wall and floor slab [21].

Calculations of thermal bridges must be done carefully, and impact of thermal bridges must be considered as additional transmission heat loss. The passive house Institute offers guidelines for thermal bridge calculations. Experience has shown that the effect of a thermal bridge can sometimes be assumed as an additional 10% of the total transmission heat losses. However, this figure should only be used for quick estimations. [12.]

3.4.2 Super Insulation

Heat losses through external walls and roofs account for more than 70% of the total heat losses in existing buildings. Hence, passive house standards demand a high level of thermal insulation to minimize the heat losses. The standards require a thick layer of insulation, of course depending on the thermal conductivity of the material. A lower thermal conductivity is better. Wayne Shick refers to continuous, thick insulation with an airtight enclosure as super insulation [5, p. 9]. In Southern Finland, it is recommended to have the overall U-value for walls, roofs, and base floor in the range of 0.06 – 0.10 $W/m^2.K$ [13].

Conventional insulations materials, such as mineral wool, polystyrene, or cellulose, could require a layer of 30 cm or more in a passive house. Polyurethane foam insulation materials can reduce the necessary thickness to 20 cm. State of the art vacuum insulation allows for a very thin, yet highly insulated building envelope but it comes with great cost. With straw bale walls more than 50 cm may be required to meet the passive house standards. [14.]

3.4.3 Airtight Envelope

Air leakage is a critical issue in a building. It causes significant heat losses and structure damage due to infiltration of moisture. There are numerous places (figure 7) where air leaks could occur such as

- Penetrations for plumbing, ventilation ducts, and wiring through floors, ceilings and walls.
- Fireplace dampers, attic hatches, dropped ceilings in bathrooms.
- Electrical outlets and switches, especially on exterior walls, recessed lights in ceilings.
- Windows, doors, and baseboard moldings. [15.]

Air barriers in a passive house follow the same homogeneity principle as the thermal insulation layer. They must be continuous without any interruptions. Due to the high requirements for the infiltration rate of a passive house, it is critical that the air tight layer must be carefully planned in detail prior to the construction phase, not leaving it for the builder. As a rule of thumb, the layer must form an unbroken line that can be traced along with a pencil without stopping at any point on the design plan. Furthermore, only one complete airtight layer should be planned and implemented. Two “almost” airtight layers bring no benefits, similarly to two buckets with holes that do not stop water from dripping out even if they are placed one on top of the other. [17.]

There is a wide variety of air barrier products available, ranging from liquids to membranes. Some of them can act as a vapor barrier as well. In solid or concrete constructions, a coat of plaster is suitable for achieving airtightness. Concrete surfaces are generally airtight. However, if they are prefabricated concrete, the joints between two panels must be properly sealed with specialized airtight tape. In lightweight constructions, wood-based panels such as OSB boards or gypsum boards with all seams taped can be used to create an airtight layer. Other air barrier materials could be a self-adhered bituminous membrane, which is usually attached on the exterior side of a wall, or a polyethylene membrane, attached on the interior side. [18.]

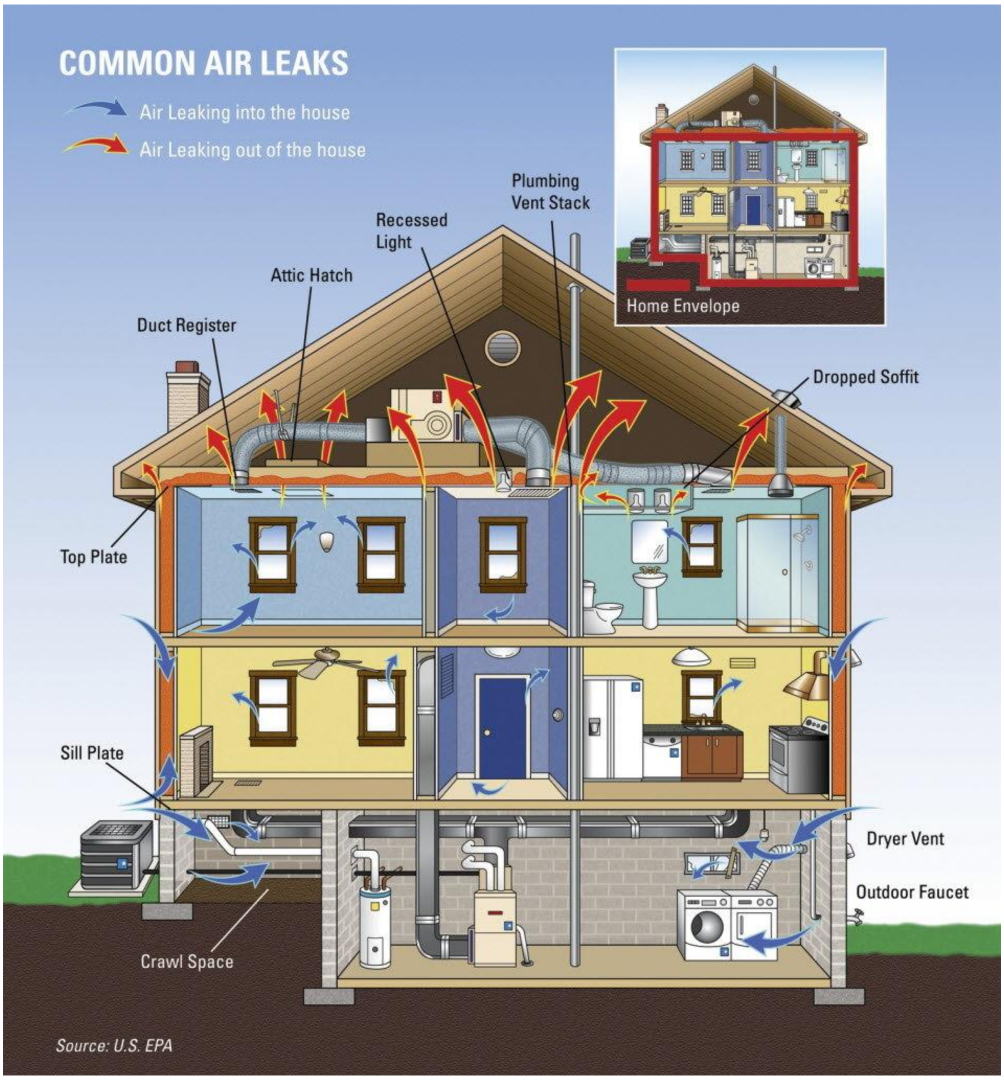


Figure 7. Common air leaks in a house [16].

Regardless of the air barrier method, the following actions must be taken for an airtight structure:

- There must be overlaps between two air barrier membranes and the joints must be sealed with airtight tape.
- Pipes, ventilation ducts, or wiring penetrating the walls, floors, or ceilings must be sealed with airtight membrane, tape, and grommet.
- Electrical boxes (outlets, switches), or recessed lights on ceilings must be properly taped. Airtight electrical boxes and light fixtures that are enforced with a foam gasket, can be also used.
- Wall-wall, wall-floor, wall-ceiling, door frames and window frames to the sill junctions must be taped or filled with airtight foam or silicone caulk. Corners are important.
- An additional layer of membrane must be applied at places where there are punctures from nails or screws.
- The wall air barrier layer must also cover the top plate and be connected with the roof air barrier. Likewise, it must overlap with the air barrier layer of the base floor or foundation wall. It is recommended that the wall air barrier is installed prior to the placement of trusses on the top plate.
- A chimney cap with airtight damper must be installed on the roof with a proper seal edge, the fireplace door must have proper gasket for airtight seal. A separated insulated duct channeling fresh intake air directly from the outdoors to the stove is highly recommended. There must be a shutter in this supply air duct.

Examples of interior seals for lightweight constructions are shown in figure 8, the seam seals are illustrated with a pink line.

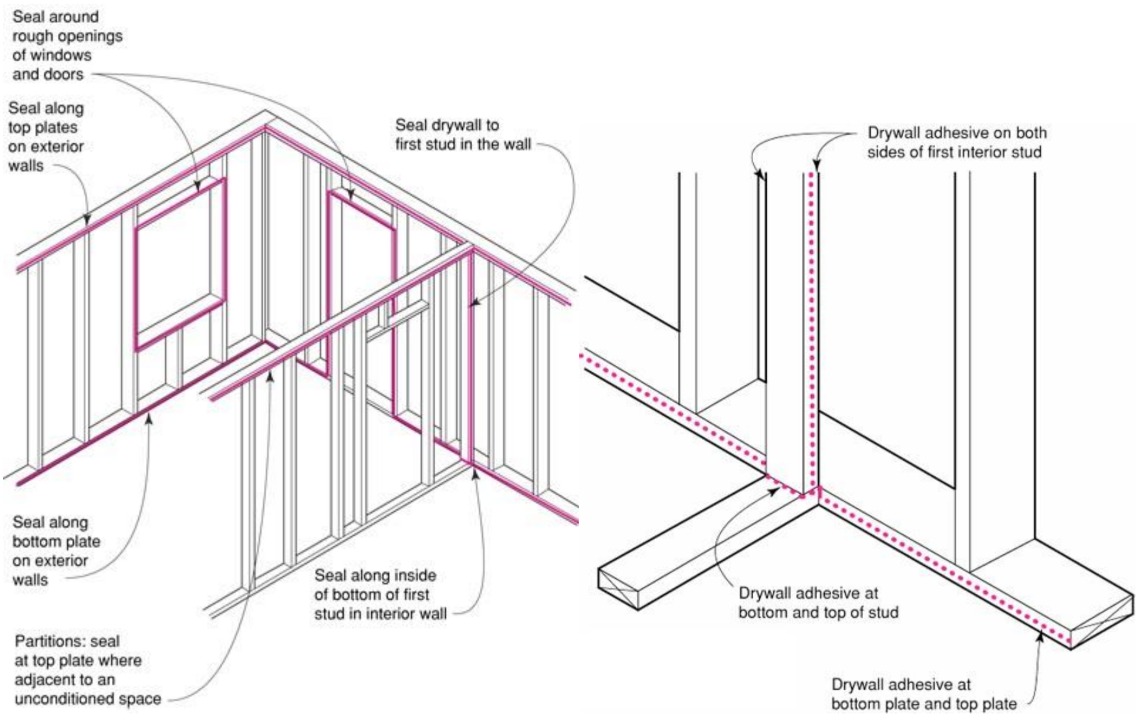


Figure 8. Interior air barrier using gypsum board, seal lines for openings and intersecting walls [18].

A great way to prevent air leaks is the avoidance planning mindset, i.e. keeping all mechanicals systems and distributions inside the thermal envelope. Instead of having ventilation ducts in the attic, they can be installed under the roof which would eliminate the ducts penetrating the airtight layer. In general, the necessity of all penetrations should be carefully considered. [12.]

3.4.4 Moisture Management

It is as critical to protect a passive house against moisture damage as any other construction concept. In the winter, indoor moisture tends to migrate into the structures since it is generally warmer and more humid inside. There are three possible outcomes: the moisture reaches a vapor barrier that limits its further travel, it reaches a surface that is cold enough to condensate on (i.e. the humidity reaches its dew point), or it escapes the structure into the outdoors. The most problematic outcome is when the moisture condensates in the middle of the structure, which must be avoided at all cost. It is extremely important that the envelope can withstand any moisture expected to present in the structure during an expected amount of time in the design, and the building fabric can naturally dry itself. [3, p. 8.]

The Finnish building techniques already handle this moisture management very well. They bear a resemblance to the passive house. A vapor barrier must be located on the warm side of the wall at a point where moisture cannot reach its dew point, i.e. condensate, which requires hygrothermal analysis using software such as WUFI. The vapor barrier is generally located near the thermal center plane of a wall. A water resistive barrier (WRB) must be installed on the exterior surface of the exterior insulation layer behind the wall cladding, to protect the wall from water intrusion. To enhance the drying capability of the structure, a small ventilating air gap can be left between the WRB and the wall cladding. In any case, it is crucial that a ‘vapor sandwich’ is not constructed, where there are two vapor barriers on both sides of the wall which results in vapor being trapped inside the wall structure. [3, p. 9.]

It is important to distinguish the difference between an air barrier, a vapor barrier, and a water resistive barrier. A vapor barrier limits the diffusion of vapor through a wall, while a water resistive barrier blocks the (rain) water from entering the building fabric, but still allows the vapor to diffuse outwards to the air gap or the exterior. Meanwhile, an air barrier can only provide air tightness, without the ability to block vapor diffusion. However, there are materials that can be both air and vapor barriers. [18.]

3.5 High-performance Windows, Doors, Ventilation, and Heating Systems

3.5.1 Windows

High performance and passive house certified windows have several features to reduce any heat losses. Triple pane windows are the most common selection, although there are quadruple pane windows currently available on the market. These windows not only have less thermal conductivity, but they also offer better comfort, by reducing draughts, and better noise insulation.

Heat is transferred through windows by conduction (heat transfer through solids), convection (heat transfer through gas), and radiation (heat transfer as electromagnetic wave). Frames are responsible for most of the conduction heat losses, together with the glasses and spacers. Hence, the frames should be slender and made of low thermal conductive material such as wood. In addition, modern window spacers have a warm edge that is made of a non-metallic material such as steel reinforced polymer or glass fiber. It reduces the heat transfer more than the traditional aluminum spacer. [20.] Figure 9 illustrates the concept of a passive house certified window.

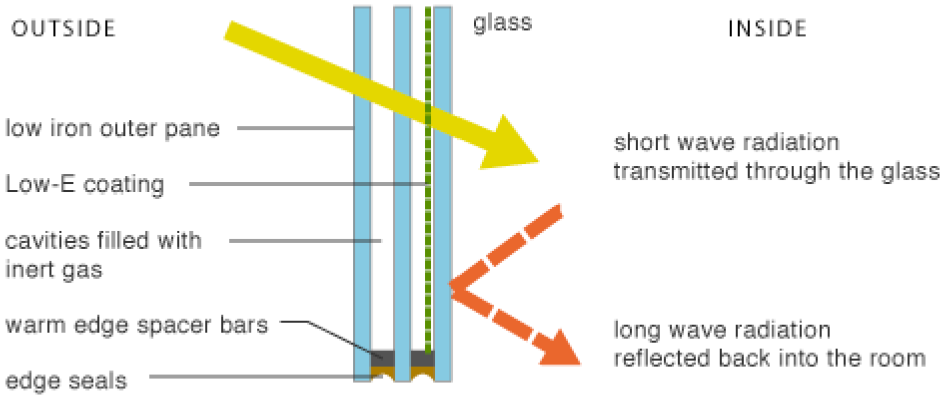


Figure 9. A passive house certified window [19].

An inert gas, usually Argon, sometimes Krypton, is used to fill the gaps between the window panes to reduce conductive and convective heat transfer. Heat losses due to convection can be neglected when the gap between the panes is less than 20 millimeters, which is true in triple-pane windows. [20.]

Removing iron from the outer glass increases the light transmittance, i.e. solar gains. The inner pane surfaces are coated with an extremely thin metallic coating, called low-emissivity or Low-E coating, to reduce the infrared radiation from inside the house to the exterior. [20.]

For windows selection in cold climate, there are two values that should be used as the target.

- The overall U-value of the window, which should be 0.7 – 0.9 $W/m^2.K$ for openable windows, and 0.6 – 0.8 $W/m^2.K$ [13].
- g-value, which should be 0.5 or higher.

The overall U-value should not be confused with the specific U-value of the frame or glazing. The g value represents the solar transmittance through the window.

3.5.2 Doors

A passive house certified door entails the following features

- Three or more locking points along the edge of the door frame.
- Three seals between the door and the frame, and two seals along the bottom.
- Highly insulated body. [21.]

A U-value in the range of 0.4 – 0.7 W/m^2.K is recommended for a cold climate [13].

3.5.3 Ventilation and Heating System

HRV and ERV

Heat recovery ventilation units play an important role in reducing the heating demand, by utilizing the heat from the exhaust air and transferring it to the fresh intake air. Although the Finnish National Building code only requires 55% heat recovery efficiency, it is recommended to be over 80% in a passive house in Finland. In fact, technology can offer ventilation units with more than 90% heat recovery efficiency. Electricity consumption of a ventilation unit is should be less than 0.45 Wh per 1 m^3 of the transported air. [23.]

Heat recovery ventilation (HRV) only recovers (sensible) heat from the exhaust air. However, there is another type of system that can recover both heat and moisture from the air (latent heat). This system is energy recovery ventilation (ERV). Both systems work in a similar way. Nevertheless, during the winter time the ERV system can offer humid warm fresh air by taking some moisture from the stale air, while the fresh warm air from HRV can be dry. ERV is very helpful in balancing the indoor relative humidity, which has a close relation to thermal comfort. Hence, an ERV system is recommended in cold climates with long winters like in Finland. [24.]

Regardless of the type of the ventilation system, its location must facilitate having as short connection ventilation ducts as possible. It is highly recommended to have the ventilation system inside the thermal envelope to eliminate possible air leaks at the penetration points through the envelope. The ducts must also be well insulated. [24.]

In the Finnish cold winter when temperatures can drop far below 0^{o}C, a pre-heater installation in the system is recommended to protect the HRV and ERV units. A pre-heater unit warms the air to the operational temperature of the heat recovery unit, in some systems as low as -4^{o}C. Otherwise, the humid exhaust air can condensate inside the unit and obstruct air flow. [24.]

The underground temperature at the depth 1.5 – 2 meters is 5^{o}C on average in Southern Finland [13]. Hence, it is possible to utilize the ground heat or geothermal heat for pre-heating of the air. A brine circuit, which can be a few hundred meters in total length, is laid in the ground to absorb heat. The heat is then carried by the brine and transferred to the intake air from outside in a water-based pre-heater. Geothermal can be used for both heating in winter, and cooling in summer. [12.]

Thanks to the air tightness, super insulated thermal envelope and high heat recovery rate of a passive house, it is possible to heat the entire house with only ventilation. In such a case, a post-heater is required, although it is unnecessary otherwise, to fulfill the gap between the after-heat-recovery air and the desired supply air temperature. [44.] The post heater can be an electric coil or a water-based heater battery, which takes heat from a hot water tank to heat up the supply air (see figure 11). The water temperature must be at least 55^{o}C. Domestic hot water (DHW) still requires another heating source. [25.]

Finally, a summer bypass is an indispensable feature of the HRV or ERV for reasons explained in chapter 3.2.2 above.

Heat pumps - compact unit

A heat pump is a great solution for energy efficient heating, thanks to its high coefficient of performance (COP), which can be up to 3.0 – 4.0. It means that 1 kWh of input power can result in 3 or 4 kWh of heat. There are several types of heat pumps, such as air-air, air-water, ground source or geothermal, and exhaust air heat pumps. They all have advantages and disadvantages as well as different COP.

Figure 10. A compact heat pump unit from manufacturer Nilan [25].

In a passive house, a compact heat pump unit is a common solution for heating. The unit can combine multiple heat sources. A compact heat pump unit can neatly fit a heat exchanger, preheater, post heater if necessary, and a water tank (see figure 10). Floor heating and/or radiators, domestic hot water, geothermal and/or solar thermal can be connected to the tank. Figure 11 explains briefly how the system can be connected, although it does not illustrate the radiators and/or floor heating and geothermal.

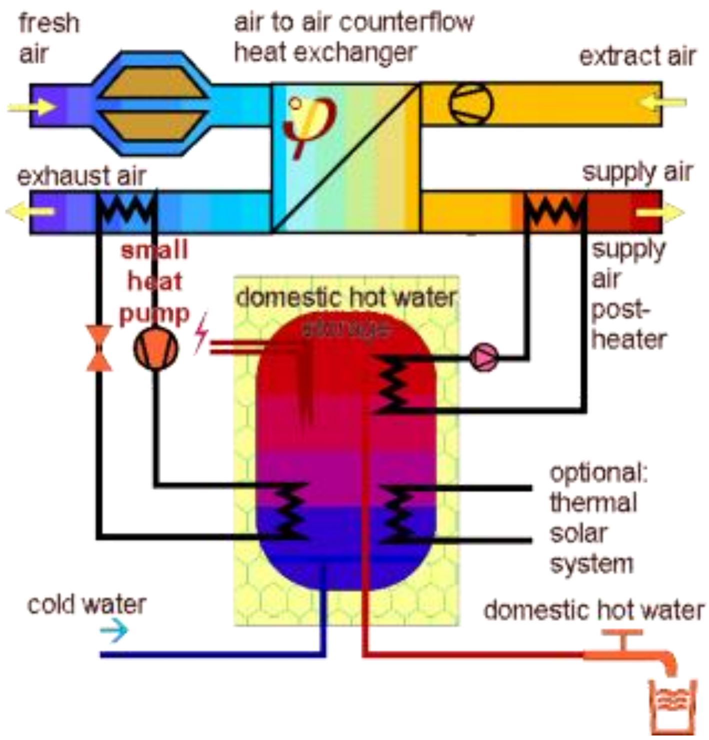


Figure 11. Operational scheme of a compact heat pump unit [26].

Wood or pellet stove

A high-energy-efficient biomass stove can be the main heating source of a passive house if the heating power demand is between 1000 and 2000 Watts only. Like a heat pump, heat from the stove is transferred to a water tank, from which it is used for domestic hot water and space heating, radiators and/or floor heating. There are stoves that are fully automatic and only consume a few kilograms of pellets for fuel for the entire day. It is also possible to connect solar thermal energy to the water tank, alongside the stove. [26.]

Nevertheless, close attention must be paid to the air tightness of the stove and the chimney. New technology has improved the efficiency of the stove. For instance, there is a hydronic stove which not only burns wood but also burns the gas that is generated from burning the wood in a secondary chamber. It is used in the Wolfe Island Passive House project discussed in chapter 6.2.

4 Passive House Planning Package and Blower Door Test

4.1 Passive House Planning Package

Passive House Planning Package (PHPP) is a design and verification tool for passive house building developed by the International Passive House Institute. It enables a designer to complete the verification of the passive house standard according to a uniform and proven method. With this tool, which is an excel file, designers can input all information about the structures, mechanical systems, soil, location, climate, etc. The tool will do complex calculations and immediately show results, such as annual space heating or cooling demand and annual primary energy consumption (figure 12), which determines whether the building fulfils the passive house standards. [12.]

Specific building characteristics with reference to the treated floor area

					Criteria	Alternative criteria	Fullfilled?²
	Treated floor area m²		156,0				
Space heating	Heating demand	kWh/(m²a)	13	≤	15	-	yes
	Heating load	W/m²	10	≤	-	10	
Space cooling	Cooling & dehum. demand	kWh/(m²a)	-	≤	-	-	-
	Cooling load	W/m²	-	≤	-	-	
	Frequency of overheating (> 25 °C)	%	1	≤	10		yes
	Frequency of excessively high humidity (> 12 g/kg)	%	0	≤	20		yes
Airtightness	Pressurization test result n_{50}	1/h	0,2	≤	0,6		yes
Non-renewable Primary Energy (PE)	PE demand	kWh/(m²a)	40	≤	-		-
Primary Energy Renewable (PER)	PER demand	kWh/(m²a)	32	≤	30	32	yes
	Generation of renewable energy (in relation to projected building footprint area)	kWh/(m²a)	125	≥	120	124	

² Empty field: Data missing; '-': No requirement

I confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this verification.

Task:	First name:	Surname:	Passive House Premium?	yes
1-Designer			Signature:	
	Issued on:	City:		

Figure 12. Example of a certified project on PHPP, verification page.

Before the PHPP is used, training is recommended for thorough understanding of the calculations. In addition, the International Passive House Institute has a detailed guide on the use of the programs, not to mention many books available online. Designers must really understand the meaning of every value in the file before putting in any numbers. [12.]

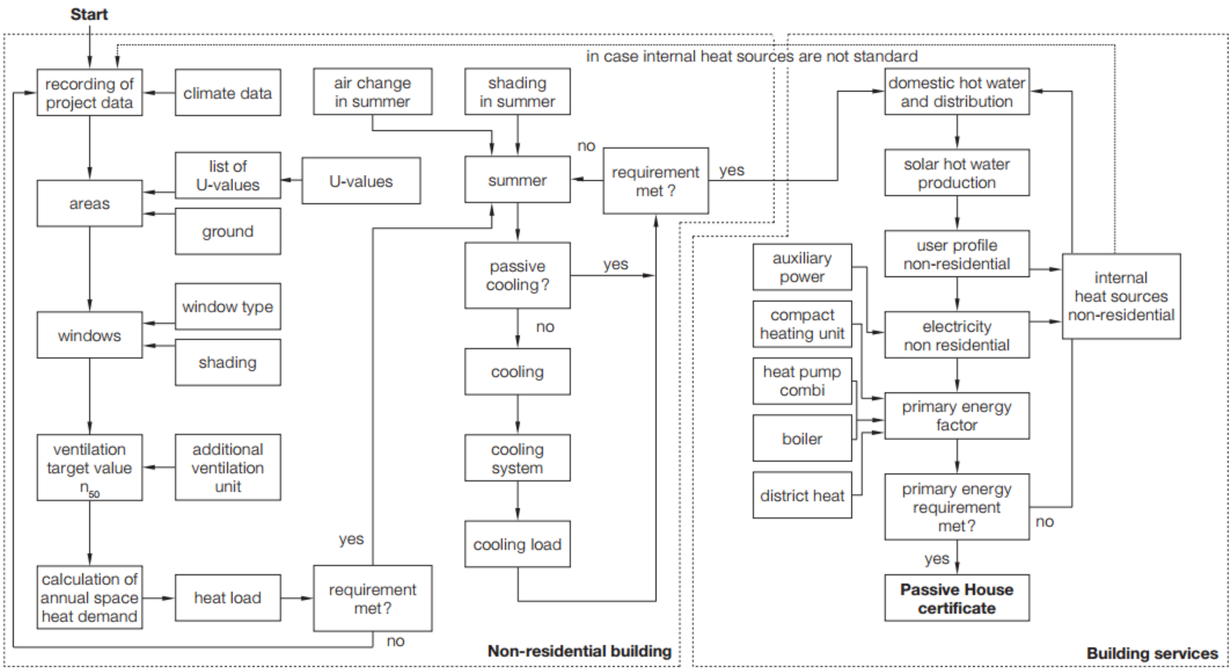


Figure 13. Flowchart of the data input process for PHPP calculations [5, p. 25].

Due to the complexity of PHPP, details on its usage cannot be shown in this paper. However, to give architects and homeowners an idea on which aspects are considered in PHPP and the recommended process for inputting the data, figure 13 maps a flowchart about calculations systems in PHPP.

4.2 Blower Door Test

The blower door test can be used to check the air tightness of the building and to identify any air leakages in the envelope. The test should be conducted in accordance with the standard EN 13829. Blower door test is important when checking the quality of the air barriers in a construction. The test should be carried out when the airtight membranes are completely installed but still exposed, so that any leakages can be remedied. [27.]

If there are any leakages, they are sealed and then a second blower door test is normally performed to ensure the perfection in the air barrier installations. The test report shows various data, yet the most important piece of information is the volume flow rate V_{50} which is used to calculate the air change rate per hour at 50 Pascal pressure differentials, ACH50 or n_{50}. The passive house standards regulate that the ACH50 should be equal to or below 0.6 h^{-1}. [37.] With proper air barrier installations, the ACH50 can get down to 0.2 h^{-1}, such as in Villa Circuitus project, discussed in chapter 6.

Figure 14. Blower Door Test installation [28].

The operating mechanism of the blower door test is to create a pressure difference of 50 Pascals between the indoor and outdoor environments. A fan installed on a red sealing sheet as shown in figure 14 is used to blow out air from the building. This creates negative pressure, which causes an exact amount of air flowing in the structure through any leak. The leaks can be easily detected and taken care of. [29 p. 9.]

There are several ways to trace air leakages during a blower door test. Photographs are to record places with air leak. The quickest and easiest method to detect a leakage would be to use one's hand to detect any draughts. However, technical methods are more reliable

- Smoke makes air flows become visible.
- A fog machine is useful in large rooms, sometimes at overpressure.

- Thermography shows the cooling or heating of surfaces because of air flows or from the outdoors (see figure 15). [29, p. 21.]

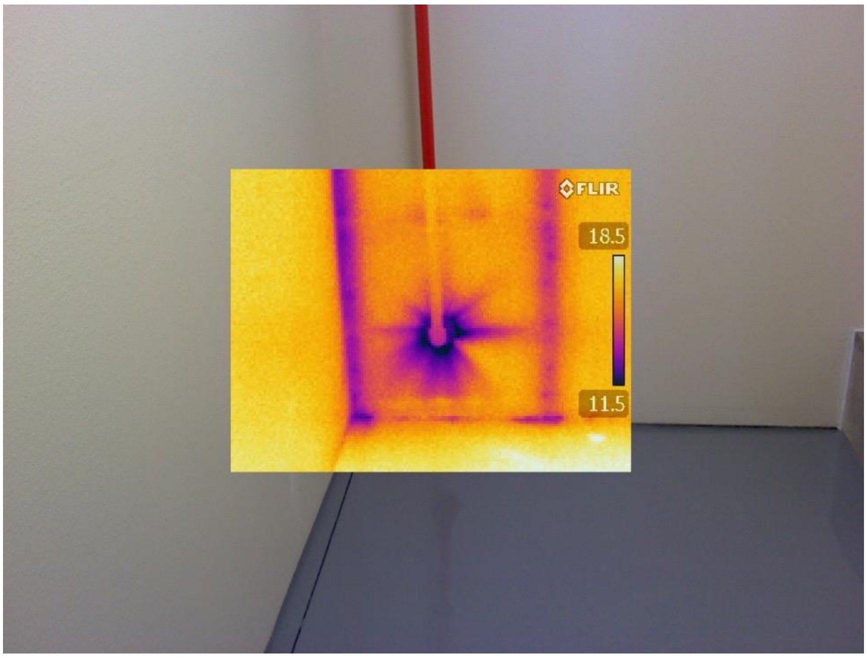


Figure 15. Air leak detection by infrared camera. Air leakage at pipe penetration to the wall [22].

The local fire department should be notified beforehand if a fog machine is used. The thermography method uses an infrared camera. It is useful for detecting air leakages at high spaces or inaccessible places, hence, thermography is commonly used for air leak detection.

The actual airtightness measurement takes place after the leakage detection. The volume flow rates are measured for at least five different negative pressure stages. The same measurements are then done at positive pressure for at least five pressure stages. The average value of the volume flow rate at 50 Pa is calculated from these measurements. The leakage volume flow rate V_{50} is equal to the volume of air flow through the fan. The air exchange rate n_{50} at 50 Pa is calculated as

$$n_{50} = \frac{V_{50}}{V} \quad (n_{50} = 0.6\ h^{-1})$$

where V is the total internal volume of the building. [29, p. 19.]

5 Construction Details

This chapter discusses the six elements of a passive house in more detail: foundation, floor, wall, roof, openings for windows and doors, and ventilation. Not only theory and experience sharing, but also real constructed examples are shown for better visualization. The sections presented in this chapter are extracted from detached house constructions in the United States. These are only a few of numerous possible approaches to tackle the challenges in detailing. Furthermore, the projects are in North America where the climate is generally not as cold as in Finland, therefore, the thickness of insulation in Finland might need to be larger.

The annotations of the drawings show in this chapter always start from outside to inside, top to bottom. The insulation layer is highlighted in light red, and the plywood acts as the air barrier. Legend for the abbreviations used in the drawings can be found in the list of abbreviations.

5.1 Foundation

Slab-on-grade and conditioned basements impose challenges for continuous thermal insulation. The prime challenge is to reconcile the inbuilt conflict between structural continuity and thermal isolation. Concrete is a good material for structural strength but rather poor for thermal insulation. Concrete in direct contact with the ground is a threat of thermal bridge, which may also pose the risk of condensation. Therefore, the foundation must be located either completely inside or completely outside of the thermal envelope. [3, p. 12.] Furthermore, the ground may freeze down to 1.5 meters in Southern Finland and 2.5 meters in Lapland during winter time [23]. Hence, foundation insulation plays a bigger part in frost protection in Finland.

Embedding rigid insulation, such as EPS, below the concrete (see figure 16) requires careful load calculations. Although EPS has a decent bearing capacity that matches the soil strength up to a moderate level, such as that of sandy clay, it cannot take concentrated loads in piers and piles foundation type. On the contrary, the bearing load must be evenly distributed along the foundation walls. [3, p. 19.]

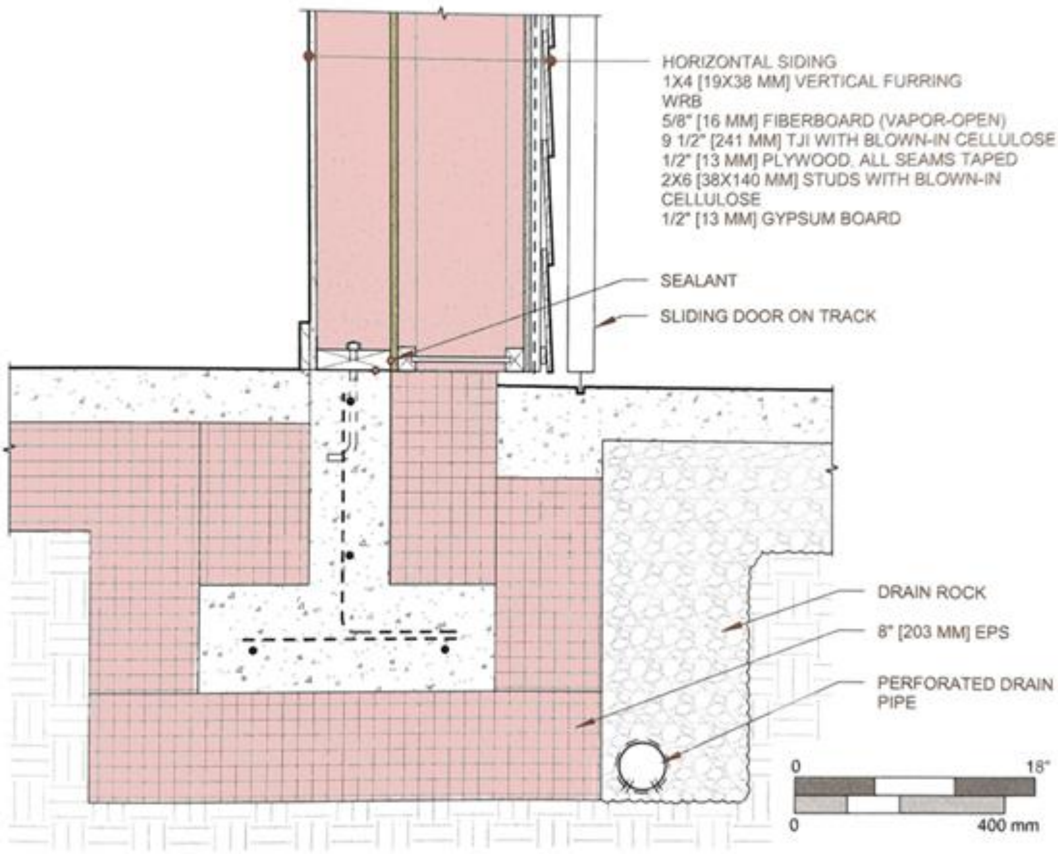


Figure 16. Perimeter footing and stem wall completely insulated within EPS layers [3, p. 23].

The foundation in figure 16 is surrounded by 200 millimeters of EPS, both on the sides and under the stem wall as well as base floor. This solution allows the mass of the foundation and the backfill piled against it, to hold the building down. In this case, steel anchor bolts and tie-down strap are not considered as thermal bridges. [3, p. 20.] A perforated drain pipe is installed below the footing level for drainage purposes. The plywood boards with all seams taped act as an air barrier and a sealant is applied at the junctions between the plywood and sill plate. Concrete is generally airtight, and thus there is no need for a floor air barrier. The gypsum board on the interior wall surface could act as a second air barrier as well. The surrounding EPS of the foundation wall eliminates the necessity for a vapor barrier, since EPS is dense and vapor resistant. [12.]

Experience shows that it is less complicated to place the foundation inside the thermal envelope than outside of it. The concrete then enhances the thermal mass within the conditioned enclosure, which helps to diminish the effects of rapid outside temperature changes on the indoor environment. Furthermore, this alternative requires that there must be rigid insulation, typically EPS (Expanded polystyrene), installed between the soil and the concrete floor where the foundation is below grade, and between the concrete wall and outdoor air where it is above grade. However, in extreme structural conditions, such as tall retaining walls, unstable soil, the foundation must be located outside of the thermal enclosure, which removes the thermal mass benefit. In this case, the insulation must be installed on the interior side, as shown in figure 17. [3, p. 12.]

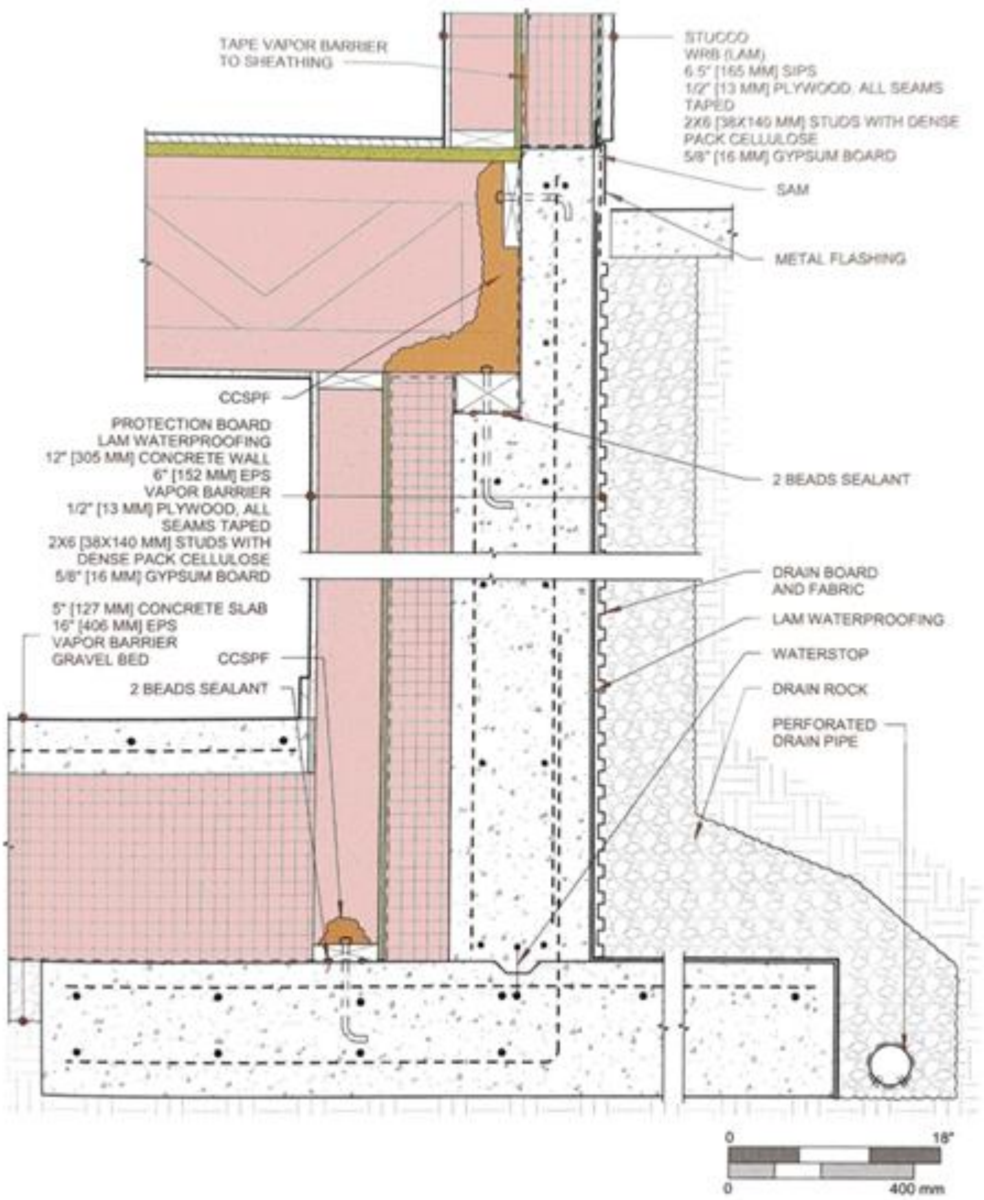


Figure 17. Retaining wall constructed directly against a steep hill, basement interior on the interior [3, p. 31].

The hybrid strategy shown in figure 17 is common for structures with a basement partially below grade and against the side of a hill. The basement has interior insulation which might be cheaper to construct, yet the insulation occupies more internal space. [3, p. 21.] The anchor bolt penetrates through the sill plate into the insulation layer, which could be a potential thermal bridge. Hence, it is filled with CCSPF (Closed-Cell Spray Polyurethane Foam), which is a sprayed insulation material, to mitigate heat transfer through these points. CCSPF is also applied at the contact surface between the stem wall and floor structure. The vapor barrier is continuous from wall to the foundation footing. [12.]

To meet the passive house standards in a harsh climate, like in Finland, the foundation should be entirely isolated from any thermal contact with the soil. The foundation perimeter must be insulated downward to a sufficient depth so that the temperature difference between the soil and the foundation is no longer considered an issue. As a common alternative solution, insulation can be extended horizontally outward, just below grade, which protects the subsoil from losing heat to the surface. Air flow and moisture movement from the ground to the building must be controlled with appropriate barriers, especially ventilated crawl spaces. To reduce the fluid pressure against the foundation, perimeter drainage systems must be installed, which in addition protects the barriers and decreases the soil thermal conductivity as the soil is not saturated with water. [3, p. 19.]

5.2 Floor

The design of a floor is considered hand in hand with the design of the wall and foundation structure. The basic strategy is to keep the floor’s edge inside the wall assembly to be thermally protected, thus thermal bridges are avoided. However, the design depends on load bearing and the type of the wall structure, which determines how the vertical load of the floor is transmitted to the wall and down to the foundation. For instance, the intermediate floor plate should rest on the inside stud framing in case of a double stud framings structure (see figure 18). The floor can also be supported by a timber frame wrapped with foam panels entirely on the warm side. [3, p. 37.]

Insulating a ground floor is a bit more complex than insulating an intermediate floor. A couple of options are shown in the ‘Foundation’ section above. In general, isolating the perimeters of the floor remains the primary concern. If the wall, floor plate, and foundation are all protected by the outer insulation shell then vertical loads can be transferred from one element to another without a risk for thermal bridges. In case of a solid slab, concrete slab, it can be cast directly on the rigid insulation (see figure 16) only if the insulation layer only bears the floor load and no superimposed loads from walls or columns. In a partially above grade basement, the concrete mass when exposed to solar gain through windows can stabilize the indoor temperature and lighten the heating demand. [3, p. 38.]

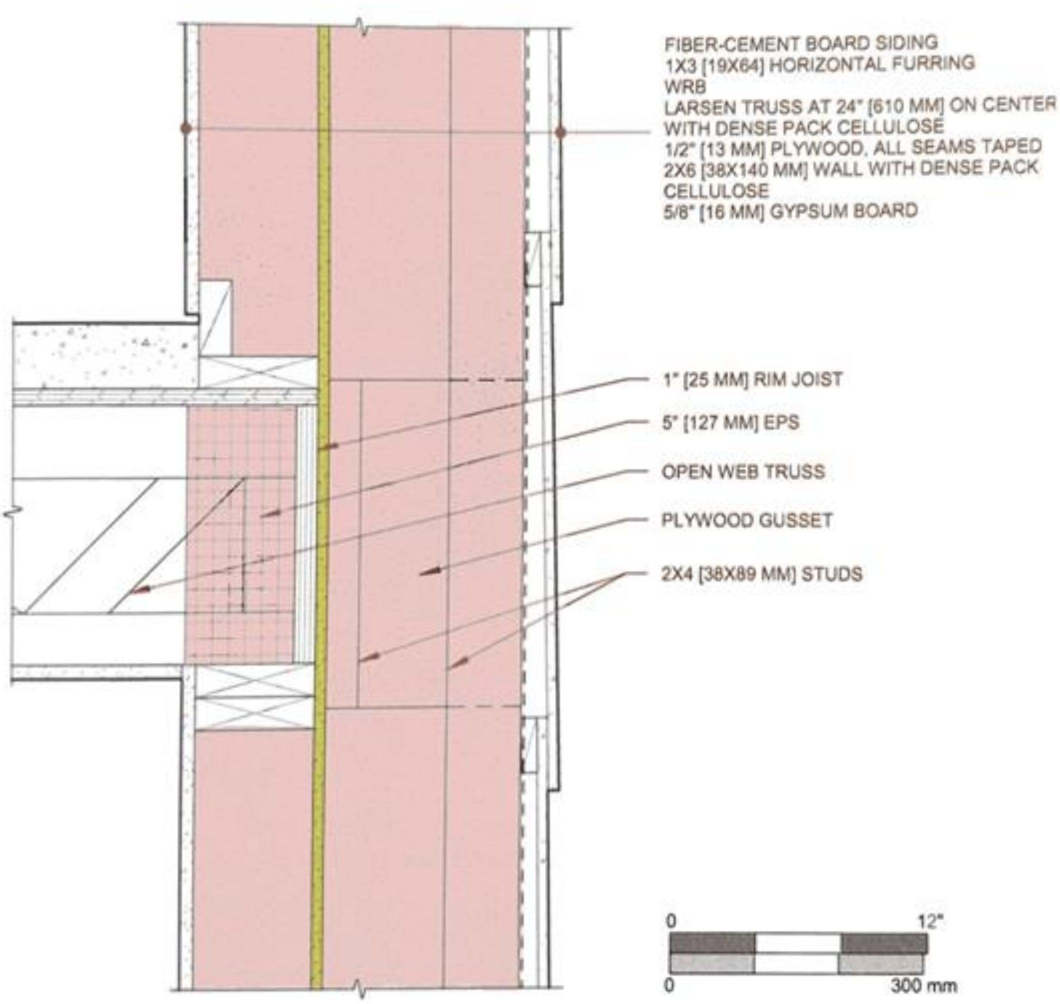


Figure 18. Platform framed second floor with an exterior insulation layer contained by Larsen Truss [3, p. 41].

The second floor in figure 18 bears the load on the interior stud frames. EPS is fitted in between the floor framing to mitigate thermal bridges. This allows continuous thermal insulation and air barrier that is provided by the 13-millimeter plywood boards with all seams taped, on the exterior. [3, p. 39.]

Floor systems which are directly exposed to the exterior, such as recessed porches, must be treated with great care. Not only the upward exposed floor with conditioned space underneath should be insulated to minimize heat losses through structural members, but the barriers should also be carefully planned in terms of position and details in these areas (see figure 19). [3, p. 39.]

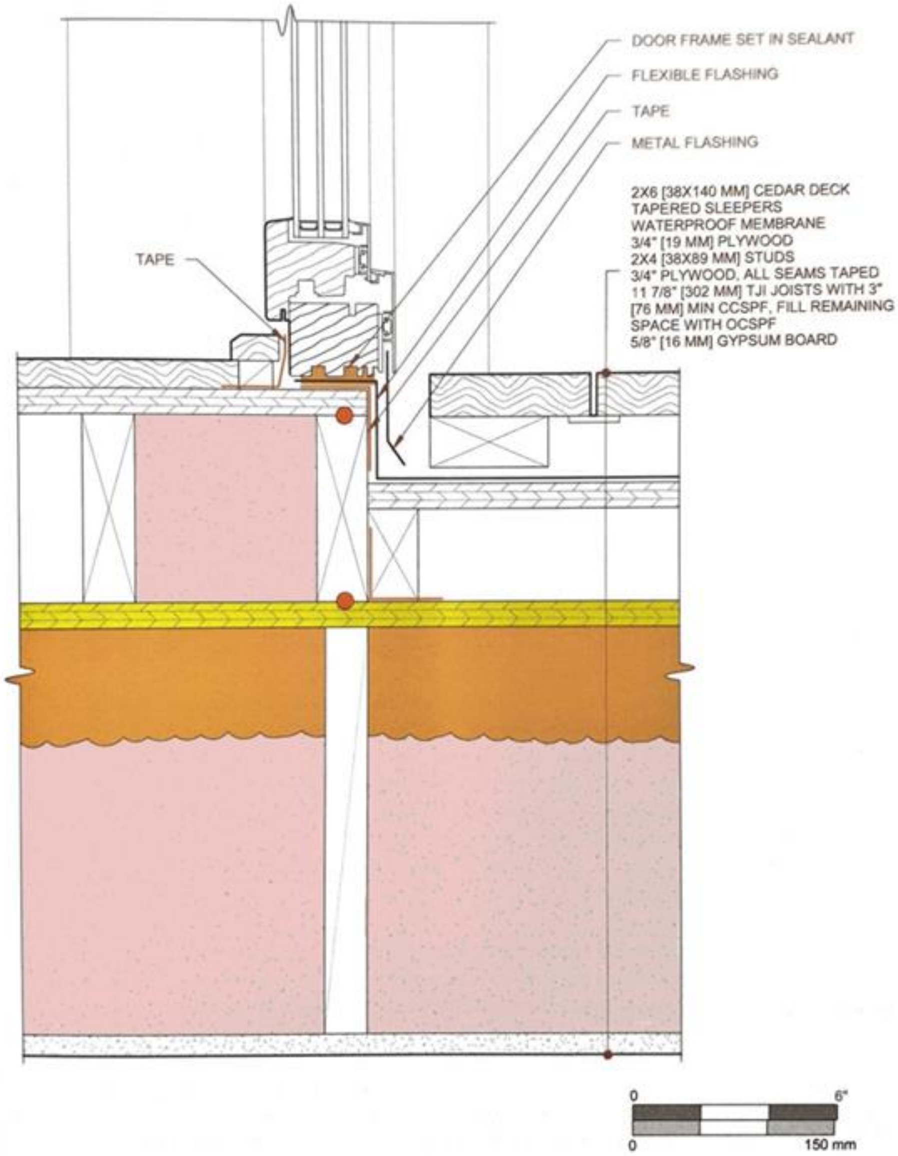


Figure 19. Second-floor bedroom door leads to an exterior balcony with heated space underneath [3, p. 51].

The location of an air barrier must allow the number of penetrations to be manageable. Vapor control must allow adequate drying potential in all directions, which could be upward or downward, inward or outward, depending on the climate, season, and the direction of exposure. It is especially important that moisture movement should be well anticipated so that it is not trapped anywhere, for instance, between two impermeable layers. [3, p. 39.]

Figure 19 illustrates the floor junction between a bedroom floor and an outdoor balcony with a heated room underneath. In this area the door sill requires much attention to thermal and water sealing. There should be metal flashing and proper sealing taped under the door sill. The tape on the interior side of the door sill is to ensure air tightness, which can be easily forgotten during construction. [3, p. 39.]

5.3 Wall

The prevailing logic for wall design in cold climates is to construct a double leaf wall with an inner structural leaf and outer insulating leaf. Framings for the inner leaf have to be sufficient to support the load of the floors, roofs, windows and doors. In other words, it is the load-bearing wall. [3, p. 55.]

On the other hand, the outer leaf framing should be as minimal as possible to decrease thermal bridges. However, it still has to be able to carry the lightweight exterior finishes or claddings. Substantial connections to the load-bearing wall within may be required for heavier claddings or operable exterior shading systems. The role of the outer leaf is to overlay the entire walls with homogeneous thermal protection (see figure 20). [3, p. 55.]

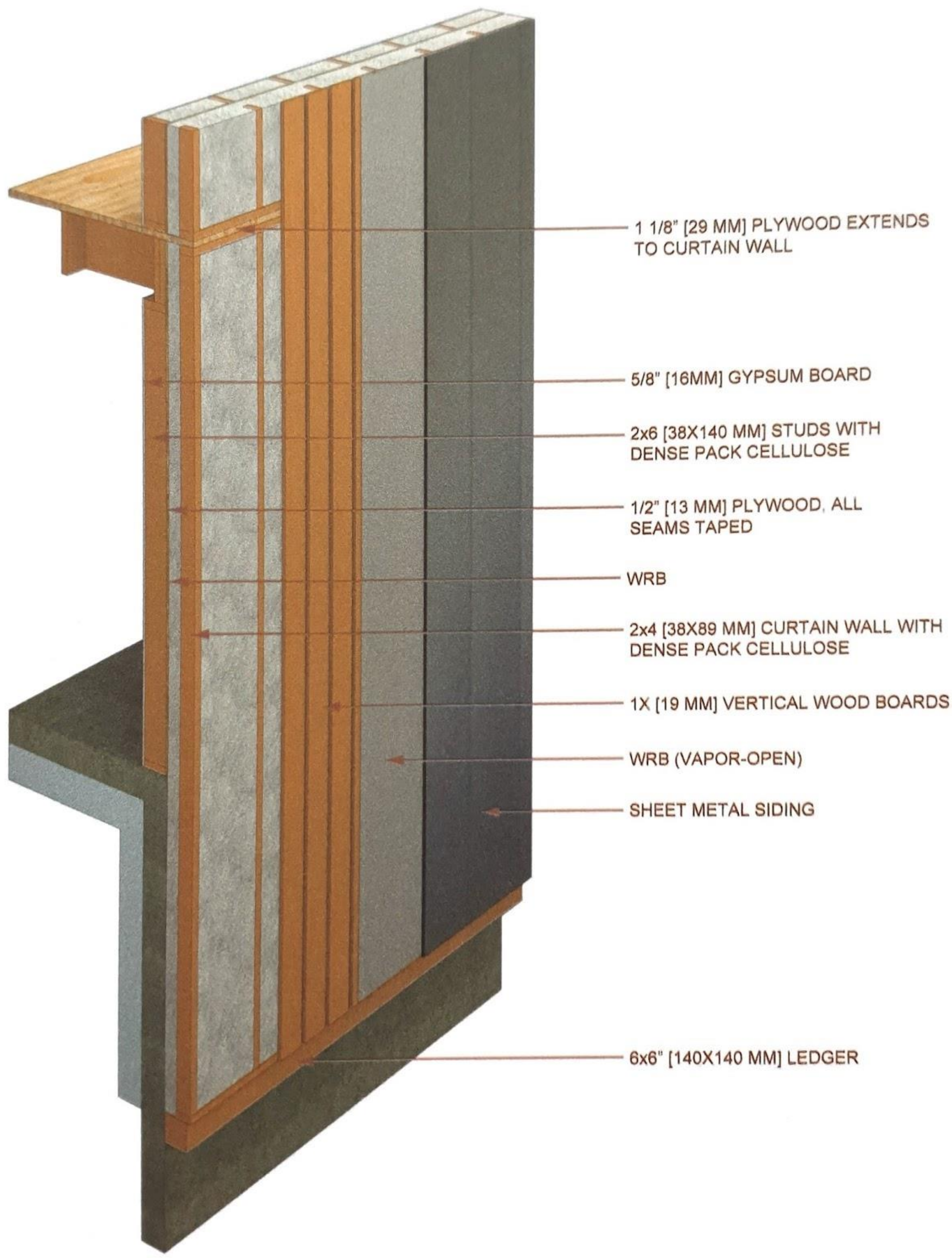


Figure 20. Double stud wall with inner load-bearing leaf standing on concrete foundation and outer leaf with insulation overlay standing on ledger [3, p. 61].

‘Over-framing’ is another name for a double stud wall, which has a structurally sheathed inner leaf and the outer leaf directly attached to it. In a new over-framing wall, Larsen trusses or manufactured I-joist with thin continuous webs can be used to create space for insulation infill (see figure 21). The short segments of webs in the Larsen trusses or the slender web in the I-joist contributes a huge part in reducing conductivity. [3, p. 54.]

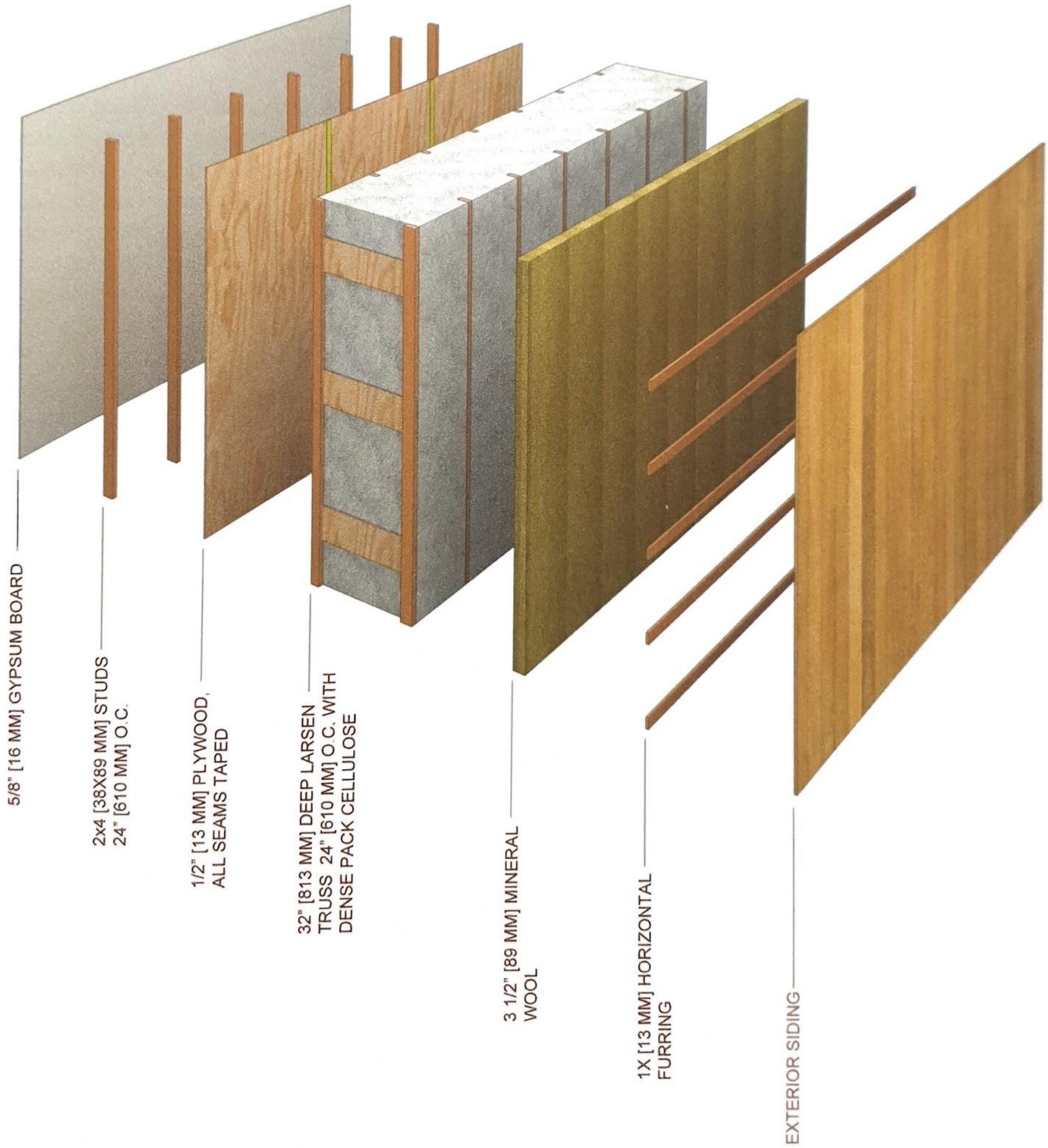


Figure 21. Wall with service space created by open studs (second layer from the left-hand side) and sheathing, and over-framed with significantly deep Larsen trusses [3, p. 67].

Moisture and vapor control are of great significance in the wall assembly. The relative location of the vapor barrier depends on the climate factors. In the assembly, the plane of vapor control, vapor barrier, is located at the stable temperature point in the wall section, where vapor being driven outward in the winter will not condensate or reach the dew point. The ultimate goal is not to have condensation in the wall. Therefore, a hygrothermal analysis of the wall assembly must be done during the design phase. The permeability of materials must be carefully selected to promote drying. All materials, especially insulation, must be able to withstand the presence of moisture at whatever level and duration predicted for that location in the wall. [3, p. 55.]

5.4 Roof

In comparison to walls, the roof has to deal with additional structural and hygrothermal challenges. Hot and moist air rises and is trapped under the roof especially during the winter. Furthermore, being exposed to the clear night sky, the roof exterior surfaces can have strong radiant cooling effect, which makes the roof layers more susceptible to condensation. Therefore, venting the air beneath the roof to outdoors is a common practice to remove unnecessary moisture. It also helps to prevent the formation of ice dams, as the roof is cooled down, in high snowfall areas like Finland. [3, p. 13.]

The durability of a building depends greatly on the roof overhang that shelters the sidewalls and windows from rainfall. The rafter tails supporting the roof overhang must not have thermal bridges or puncture the air barrier. Alternatively, a roof overhang can be supported by brackets projecting around the perimeter. They are mounted at the top of the wall, outside the sealed and sheathed volume of the house. The only penetration to the plane of barriers is the fasteners. Furthermore, these roof appendages must be able to withstand uplift in high-wind areas. [3, p. 73.]

In cold climates, loose insulation such as cellulose blown in the attic has been a common practice, as it provides high levels of thermal isolation. The insulation layer must completely cover the trusses, whose web member is a potential thermal bridge despite its small size in cross section. Rigid insulation can be another alternative for attic insulation. I-joists are widely used because its slender web allows more useful spaces for insulation in the roof attic. [3, p. 72.]

For attic ventilation, the roof assembly must be vapor open in both directions from the vapor barrier, which can be located at the plane of structural sheathing in the center of the overall assembly. Additional space above the insulation and beneath the impervious layers of the roof can be created by additional layers of furring or by a similar ‘over-framing’ concept as for walls (see figure 22). Moreover, it is rather complicated to sufficiently ventilate complex or low-pitched roofscapes. In those cases, a careful hygrothermal analysis must be conducted. [3, p. 72.]

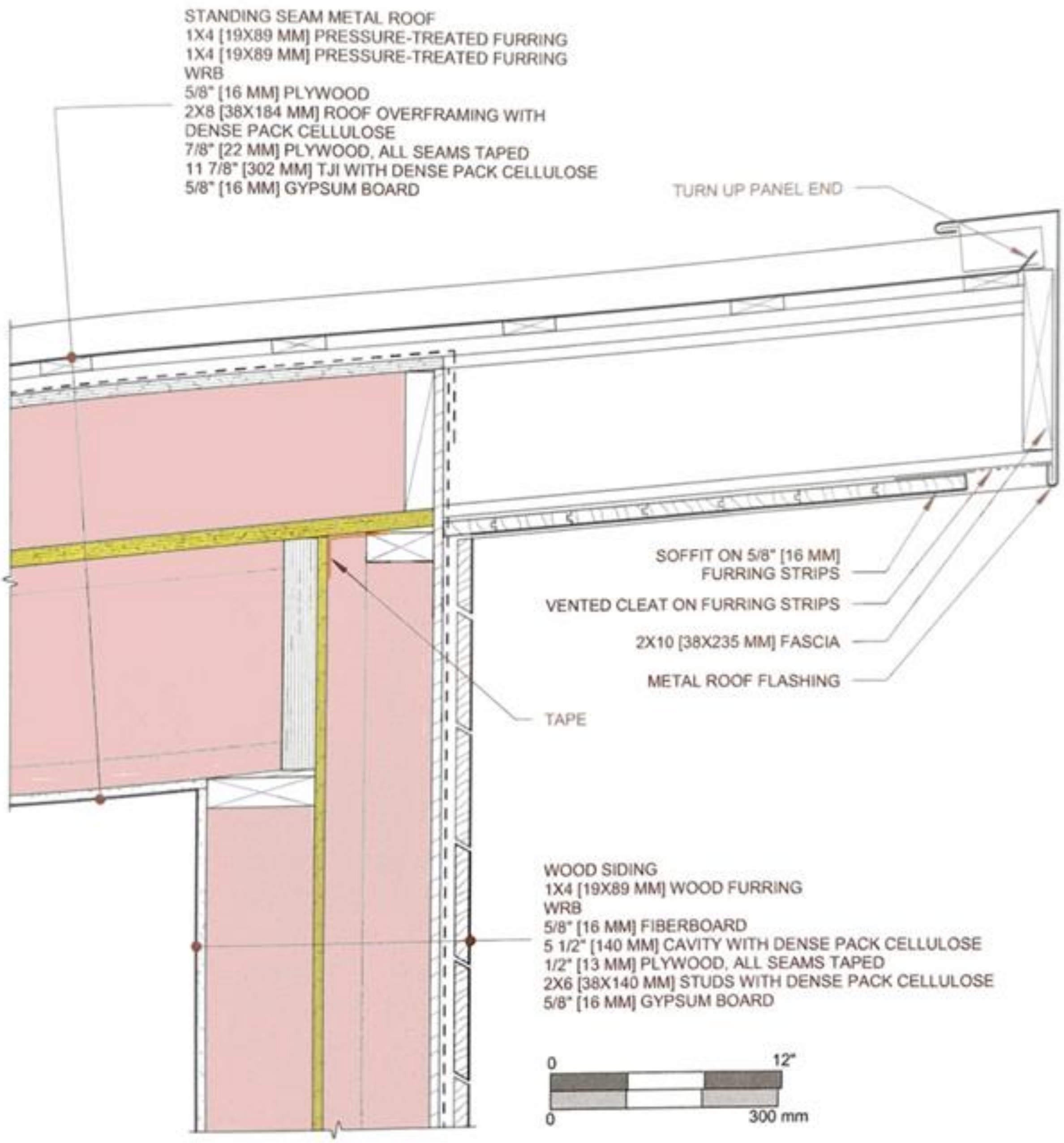


Figure 22. Over-framed roof with I-joists and air barrier sheathing. Overhangs generated with a second layer of framing [3, p. 83].

Nowadays, prefabricated trusses dominate over rafters framed onsite. Pressed-plate trusses can create virtually any desired space for insulation. Various roof shapes are widely available: flat planes, low slope sheds, partial attics, and cathedral ceilings – using parallel chord truss configurations. Triangular and parallel chord trusses can be combined to create a very large roofscape (see figure 23). [3, p. 71.]

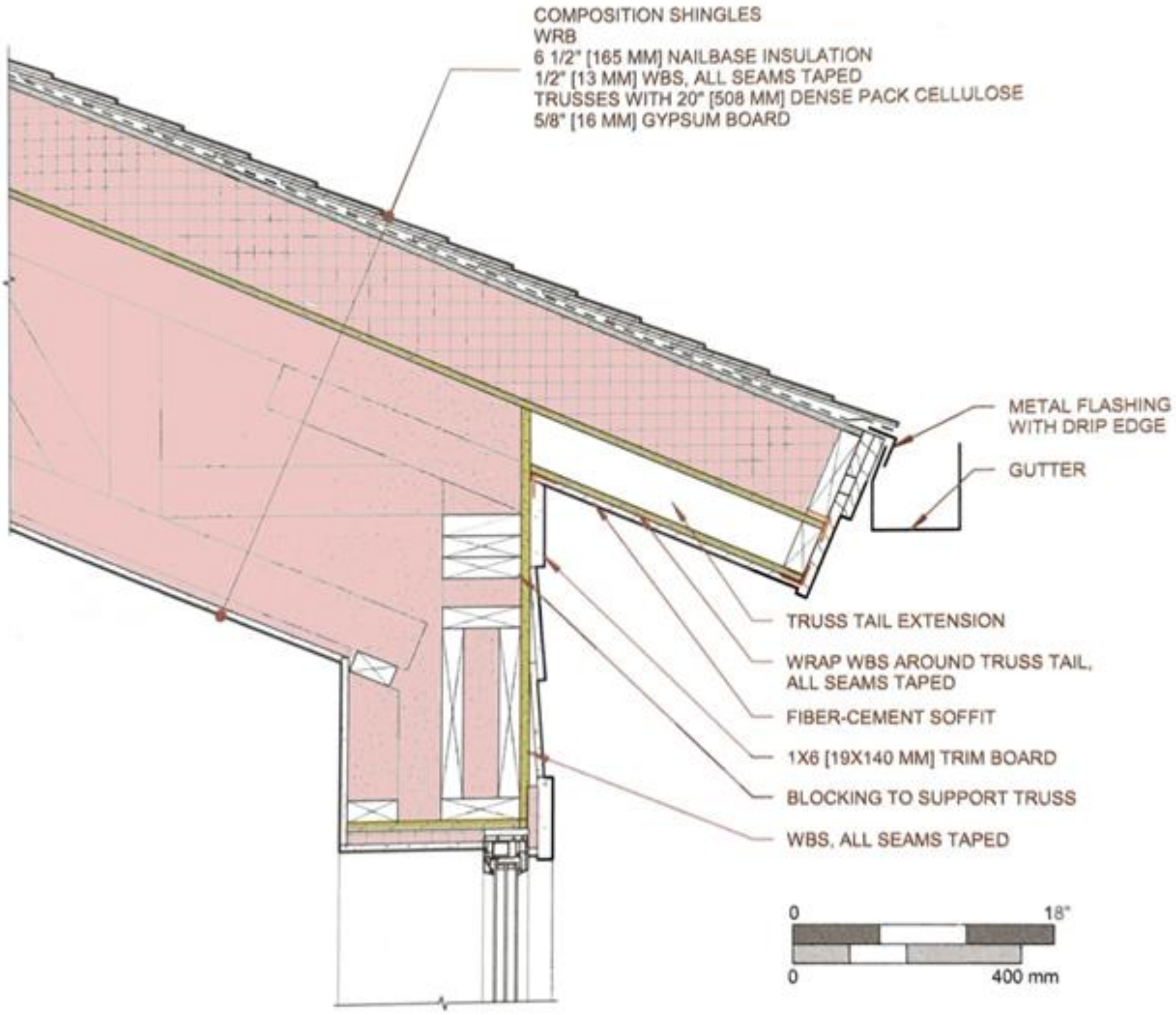


Figure 23. Deep trusses used to create long spans and large insulation volume [3, p. 77].

The over-framing roof in figure 23 provide two rigid insulation layers. The plywood sheathing with all seams taped provide air tightness. The framing inside the barrier creates a service space for electrical wiring and junction boxes that can be installed directly on the gypsum ceiling without interfering the air barrier. [3, p. 72.]

5.5 Openings for Windows and Doors

Windows and doors are a necessary and inevitable thermal compromise in the building envelope, due to their frames and potential leaks at the air seals. Hence, as repeatedly mentioned in previous chapters, the junctions and connections at the window and door openings must be carefully sealed and designed to be thermal bridge free. Fortunately, passive house walls are thick. Therefore, windows and doors can be positioned near the thermal center of the wall, which is the best position. [3, p. 95.]

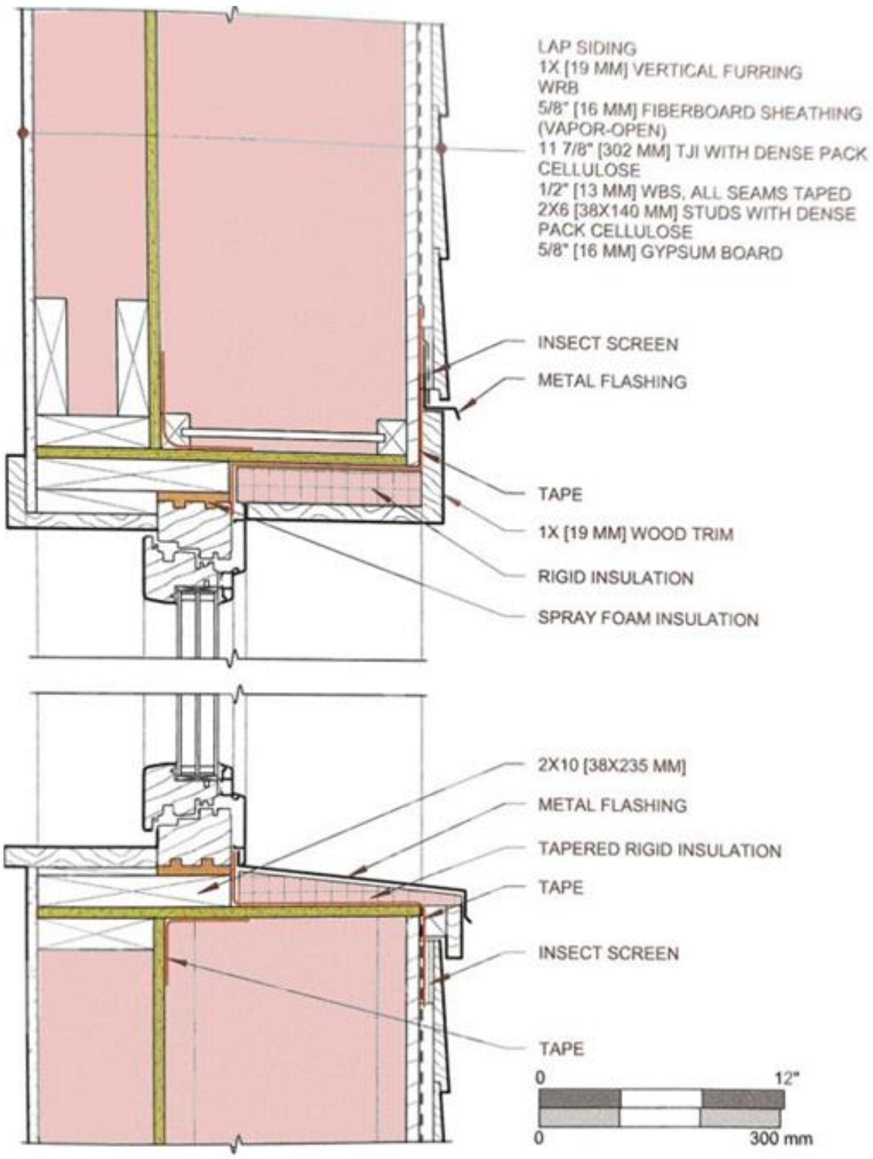


Figure 24. Deep over-framing with I-joist secured with plywood throat at the opening. Window unit mounted on a wood buck to reach thermal center of wall [3, p. 103].

Despite the freedom of choice, windows generally remain close to the structural sheathing plane at the load-bearing part of the wall. The outer face of the frames is overlaid with insulation to prevent the frame from being exposed to the cold, which consequently reduces heat losses. Furthermore, SPF (spray foam insulation) can be applied at the contact surface between the frame and the wall structure for extra insulation. The air tightness and moisture protection are formed with an air and vapor barrier installed under and above the sill. A metal flashing is installed on the outside of the window, to protect the sill from weather. In addition, the vapor barrier must overlap the edge of the metal flashing. An example of all small details mentioned above is shown in figure 24 above. [3, p. 94.]

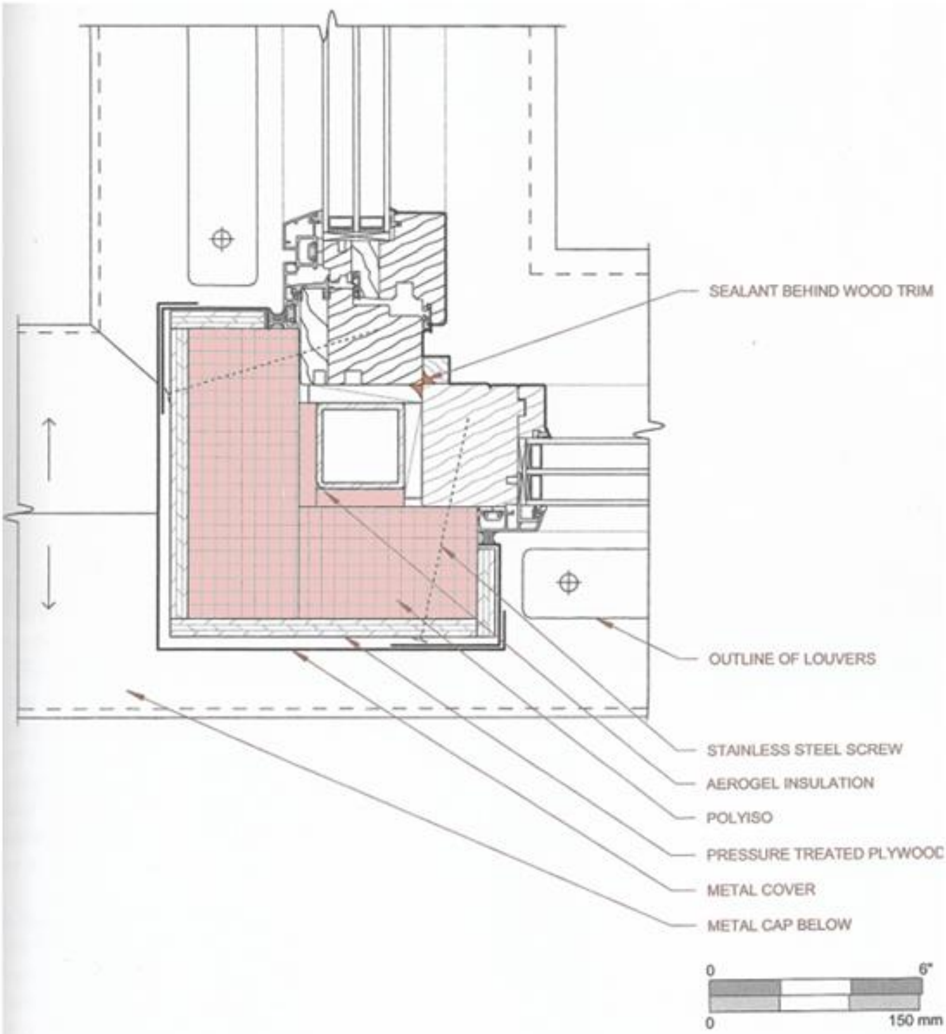


Figure 25. Floor plan view of windows at corner with over-insulation of the frames on the exterior [3, p. 227].

Windows at corners present technical challenges. Aesthetically they open up the space. Nevertheless, the corner usually has structural columns that compete for space. Hence, the wooden post is replaced with a slender steel tube to reduce the bulk, and the tube is over-insulated on the exterior (see figure 25). [3, p. 94.]

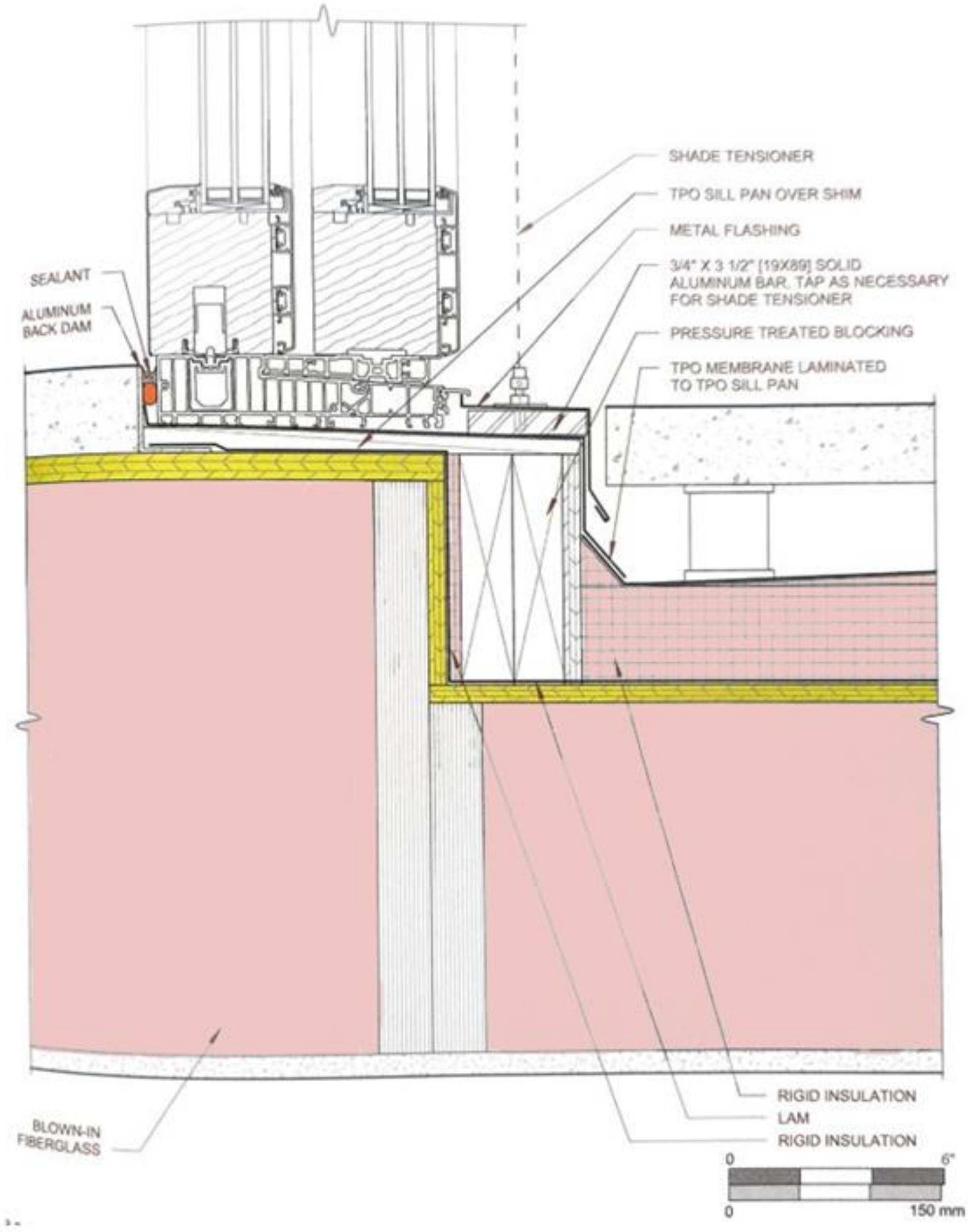


Figure 26. Door threshold [3, p. 223].

Doors pose the same challenges as windows do. The connections of doors to the structural frame are even more important since they have to withstand greater impact loads when they swing shut. The door threshold must be able to support foot traffic or a hand truck moving in appliances. Meanwhile, it must not have any impact on the thermal, vapor and air control. Figure 26 above illustrates a well-designed detail, which has a gap for drainage with aluminum back dam to prevent water intrusion under the sill, and sealant to complete the air barrier. [3, p. 95.]

6 Passive House Projects

6.1 Villa Circuitus – Växjö, Sweden

Villa Circuitus (figure 27) is a passive house designed and built by Simone Kreutzer, Tommy Wesslund, architect Nina Sandahl from SAJT Arkitekstudio AB. Kreutzer, Wesslund are certified passive house experts specialized in energy and ventilation. The house was designed to meet the passive house requirements in terms of environmental design and construction materials. Hence, every aspect of the house was designed with this goal in mind, from the structure to the mechanical units installed in place. For instance, the spherical shape, which is the first of its kind in Sweden, was deliberately designed to minimize the exposed surface to the outdoor air, thus reducing heat losses, meaning lower heating bills. [31.]

Figure 27. Villa Circuitus front view from outside [30].

The building is spacious with a total area of 175 m^2 and has four bedrooms, a large kitchen with a dining area and large openings facing south-east, which help passively gain more heat from the low sun in the winter. The building has triple glazed Smartwin passive-house-certified windows with U-values of 0.6 – 0.7 W/ m^2.K, depending on the direction they face. The windows are inward and placed a bit further into the wall to seal and insulate the outside face of the frame with 100mm mineral wool, which reduces the heat losses. [31.]

Villa Circuitus has a widespread use of natural and eco-friendly materials. Recycled paper and glass are used throughout the interior while the exterior is constructed in Kebony cladding – a modified softwood that undergoes a patented process to make it very sustainable. The exterior is packed with 400 mm loose cellulose insulation and 120 mm Pavatex fiber board insulation, which makes a U-value of 0.8 W/m^2.K for exterior walls. On the second floor, a portion of the wall has large windows, hence, the other walls must have similar thickness for aesthetic appearance. This is achieved with 40 mm of vacuum insulation panel, which has the equivalent U-value to 240 mm of mineral wool. [31.]

The house has two circle walls, the outer circle is built as a light-weight structure with wooden framing, while the inner circle is built of brick. It is a creative solution to increase the thermal mass for the house. The additional thermal mass helps to balance the heat during any sudden change of the outdoor temperature. [31.]

The roof structure has 500 mm loose cellulose insulation with a U-value of 0.07 W/ m^2.K. I-joists are used to create more space for the insulation. The base floor has a U-value of 0.11 W/ m^2.K that consists of 150 mm of foam glass panels and 600 mm of recycle glass insulation, Hasopor skumglas, on top of a layer of macadam. The ground has extended insulation outward to insulate the soil from air temperature. [31.]

Air tightness has been well achieved with measured air change rate at 50 pascal pressure differential $n_{50} = 0.2\ h^{-1}$. The continuous air barrier plane runs from the top of the foam glass insulation panels on the floor, to behind the interior insulation plane, and then continues under the gypsum boards on the ceilings. All penetrations for ventilation ducts, electrical wiring, and plumbing pipes are properly taped and air sealed. [31.]

Heating for the house is provided by the Paul Novus 300 ventilation unit, with heat recovery efficiency of 94%. Floor heating is installed in the bathroom for extra comfort. The supply air is preheated by the circulating brine in a 180 m double folded pipe was installed underground downward to a depth of 90 m. Furthermore, a small heat pump, Thermia 3.5kW, is installed to heat hot water and provide extra heat in case of severely cold weather. The Thermia mini heat pump also utilizes the heat from the circulating brine. This geothermal system has an opposite effect in the summer, when it is used to cool the indoor air as well. [31.]

A photovoltaic system of 6170 Wp are installed on the roof of the first floor and some as railings for the second floor. In fact, after 10 months of occupation, the house had reportedly consumed 2800 kWh for space heating and hot water generation and the solar panels generated 1900 kWh after 4 months in use, according to Kreutzer's blog. As a result, the building meets the requirement of 15 kWh/(m^2.a) for annual energy consumption, and the real energy consumption is 16.6 kWh/(m^2.a) [31.]

For more information about the house, the blog is highly recommended to pay a visit at http://circuitus.se (in Swedish). More pictures with explanatory captions are presented in Appendix 2.

6.2 Wolfe Island Passive House – Ontario, Canada

Wolfe Island Passive House (figure 28) was the first passive house project in Ontario, Canada. The two-story detached house was designed by a local architect Mikaela Hughes and finished in 2017. The owner's original wish was to renovate their current house into a passive house, yet it encountered numerous problems because of the building's orientation and the unfavorable conditions of the foundation. Therefore, a new building was built next to the old one. The owner chose prefabricated cross laminated timber (CLT) as the main construction material. The prefabricated elements were shipped from Germany. [33.]

The house is oriented to take maximum advantage of the sun for light, passive solar heating, solar thermal water heating and solar photovoltaic generation. All the traditional reasons for house orientation on the island are ignored, such as alignment with roads or lake views. All the utility spaces are located on the North side of the house, while the living room, kitchen, and the bedrooms are on the South side. [33.]

Figure 28. Wolfe Island passive house South face [33].

The base floor is a concrete slab poured on a 300 mm layer of EPS type IV which also wraps around the edges. On top of it is a two-story building built by screwing together the prefabricated CLT elements. The assembly process took only three days to put up the entire CLT house. [34.]

Air tightness was well taken care of in this house. The house was wrapped with an air and vapor barrier, Tyvek HomeWrap, before the installation of exterior insulation. Optiwin windows and doors were installed at this stage as well, and the air gap are sealed with tapes or expansion foam. All ventilation ducts, wiring, and pipe penetrations are properly sealed. In fact, the air barrier was so well done that the air change rate after the blower door test was 0.185 h^{-1} at 50 Pa. [35.]

Both the walls and the roof have the same two layers of fiber insulation boards, 240 mm and 40 mm thick for the inner and outer layer respectively. However, due to shipping issues there was a shortfall of some 50 m^2 of fiber insulations, and EPS type II panels from Canada were selected to make up for it. The EPS layer was 240 mm thick and covered 500 mm up from the foundation insulation on the exterior walls. Since EPS is relatively vapor-impermeable, vapor and water can be trapped behind the panels. Hence, tiny channels in the base of the panels were cut to drain the potential vapor away. [36.] Details of the building are shown in table 2.

Table 2. Construction details of Wolfe Island Passive House [32].

Building Details	***Construction Type***	***U-value***
Base floor slab	Super Insulated EPS tray slab, 300mm	0.089 W/m^{2}K
Wall structure	100 mm, 4-layer cross-Laminated timber (CLT)	0.13 W/m^{2}K
Roof structure	130 mm, 5-layer Cross-Laminated timber (CLT)	0.13 W/m^{2}K
Wall insulation	Wood fibre board	280 mm
Roof Insulation	Wood fibre board	280 mm
Window type	Optiwin Resista (passive house Certified 2015)	
Window Frame	Fir / Thermally treated spruce	0.72 W/m^{2}K
Window Glazing	Saint Gobain triple low-e/argon	0.5 W/m^{2}K
Airtightness	0.185 ACH @ 50 Pa	
Ventilation system	Zehnder 200	92% efficiency
Heating System and Hot Water	Wood-Electric-Solar thermal	

The main heating source of the building is a high performance Walltherm Wallnofer hydronic wood stove. The stove provides heat for both space heating and domestic hot water. Moreover, heating is supported by solar thermal panels in water heating and the high heat recovery efficiency Zehnder ventilation unit in reducing heat losses. According to the homeowner’s blog the fan in the ventilation unit was broken, since the winter air temperature was below the guaranteed operational temperature of the unit. Therefore, the fan had to be replaced and an external pre-heater was installed. [37.]

Due to the limestone bedrock close to the surface, a geothermal system appeared to be unrealistic. A photovoltaic system is planned to be installed in the near future. [33.] The performance data of the building is shown in table 3.

Table 3. Building performance data [32].

Building Performance Data (via PHPP modeling)	
Gross Floor Area	172 m^2
Treated Floor Area (TFA)	154 m^2
Specific Annual Heating Demand	14.2 kWh/m^2
Annual Heating demand	2190 kWh / year
Annual Heating cost	€124/ year - electricity
Design Heating Load	1860 Watts
Specific Heating Load	12.1 W/m^2
Annual cooling cost	zero

More pictures with explanatory captions in Appendix 2. The home owner's blog about the house is surprisingly detailed and highly recommended for a visit: https://wolfeislandpassivehouse.wordpress.com/ (in English).

7 Conclusion

Although passive house standards define holistic targets, they require concerted efforts in detailing from the designer concerning the location, climate, architecture, compactness, orientation, building fabric, air tightness, and mechanical building services system. Designing a passive house follows five fundamental principles: thermal bridge free envelope, air tight enclosure, high performance windows and doors, controlled ventilation, and utilization of solar gain.

As discussed in chapter 3.2, the location is the initial determination factor that dictates the characteristics of a passive house. To utilize the solar gain for heating and day lighting, the lot should allow south-facing orientation of the building for commonly used spaces, such as living rooms, kitchen, and bedrooms. These spaces should preferably open to the backyard garden in the South for privacy. This leaves the North side for utility spaces, and garage. The surroundings of the lot are also an important factor. Land that is surrounded by tall buildings has less possibility to get sunlight compared to one that is not.

The location and sizes of windows are crucial for passive solar design, yet the design must also consider the overheating effect in the summer (see chapter 3.2.2). Passive house certified windows are highly recommended for best performance. South-facing windows receive the most solar gain in the Northern hemisphere. Therefore, they are highly beneficial for passive solar design. However, maximizing solar gains and passive solar heating should not be the sole purpose of window design. Over exploiting solar gains entails a high risk of overheating in the summer and the cost of passive house windows is not cheap, which results in the higher cost for passive solar heating than for electricity and district heating. Nevertheless, windows are essential elements for aesthetic architecture and they allow the residents to feel connected to the exterior. Moreover, the overheating effect can be controlled by having shading, such as overhangs, blinds, outdoor shades, and deciduous trees. Windows to the East and West must have proper shading.

It is of utmost importance that the construction of the thermal envelope is well planned. Thermal bridge free and high air tightness are the principal focus for the design. It is imperative that the thermal envelope and the air barrier layer is continuous and creates a closed thermal and air shell surrounding the six faces of the building, as could be seen in chapter 3.4. Heat losses are not tolerated and must be diminished as much as possible. Close attention should be paid to the junctions and connections in the building enclosure to lessen the thermal bridging effect by having overlapped thermal insulations. Openings and penetrations in the envelope are extremely susceptible to air leaks, which requires proper air seals such as tape or grommet. Blower Door Test must be used for air leak detection and infiltration rate measurement.

The requirement for low heating demand results in thick insulations in a passive house to ensure the low thermal conductivity of the building envelope. Table 4 below summarizes the recommended thermal conductivity coefficient for Southern Finland

Table 4. Recommended U value for Southern Finland [13].

Element	Overall U-value ($W/m^2.K$)
Wall, floor, roof	0.06 - 0.1
Window	0.7 - 0.9
Fixed window	0.6 - 0.8
Door	0.4 - 0.7

A perfect thermal envelope is worthless if there is no highly efficient ventilation system in the building, as explained in more detail in chapter 3.5.3. It is critical that heat must be recovered from the exhaust air, and the heat recovery rate for a cold climate is recommended to be over 80% [12]. The location of the entire system should be inside the thermal envelope to avoid penetrations of ducts through the ceiling. Short and insulated ducts must remain of priority; however, the length is determined by the location of the ventilation unit and utility room. Pre-heating or frost protection, which can be done with geothermal heat or an electric coil, is indispensable to protect the workability of the unit and the fan. Post-heating is optional; however, ventilation can be the sole heating source thanks to the low heating demand. The presence of post-heater is required in this case.

Other heating options can be biomass stoves fueled by wood or pellets if the heating power demand is under 2000 Watts [26], or a heat pump. A compact heat pump unit is recommended for its practicality and compactness, which reduces the need for space. It can provide heat for radiators, floor heating, domestic hot water, and for water-based pre-heater and post-heater of ventilation if needed. It is common to have floor heating and a towel warmer in bathrooms for thermal comfort. Solar thermal and geothermal heat can be connected to the system as well. However, the priority is simplicity. A complex system would result in high investment and maintenance cost. A photovoltaic system is highly recommended to have. However, it is not included in the scope of this thesis.

This thesis serves both homeowners and architects who wish to engage in the construction of a passive house. For an architect, the thesis offers some practical guidelines and recommendations for Southern Finland. The homeowners, on the other hand, get an overview of a passive house concept in cold climates. Nevertheless, further studies are highly recommended for more in-depth knowledge on each aspect.

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Appendix 1. Villa Circuitus

Figure 1. 300 mm of macadam for ground work [31].

Figure 2. Glass insulation panels for base floors [31].

Figure 3. Masonry inner wall vs wooden outer frames [31].

Figure 4. Water resistive barrier on outer wall [31].

Figure 5. Window installation with proper air seal and insulation at exterior face of the frame [31].

Figure 6. Large windows on second floor [31].

Figure 7. Vacuum insulation panel for second floor wall insulation [31].

Figure 8. Overlap air seal over the top course of bricks to create continuity for ceiling air barrier [31].

Figure 9. Installation of air barrier for ceiling, all seams properly taped [31].

Figure 10. Insulated ventilation ducts with air seals at every penetration [31].

Figure 11. Insulated flue with air seal [31].

Figure 12. All pipes and tubes are properly air seal on the wall and floor [31].

Figure 13. Solar panels on roof [31].

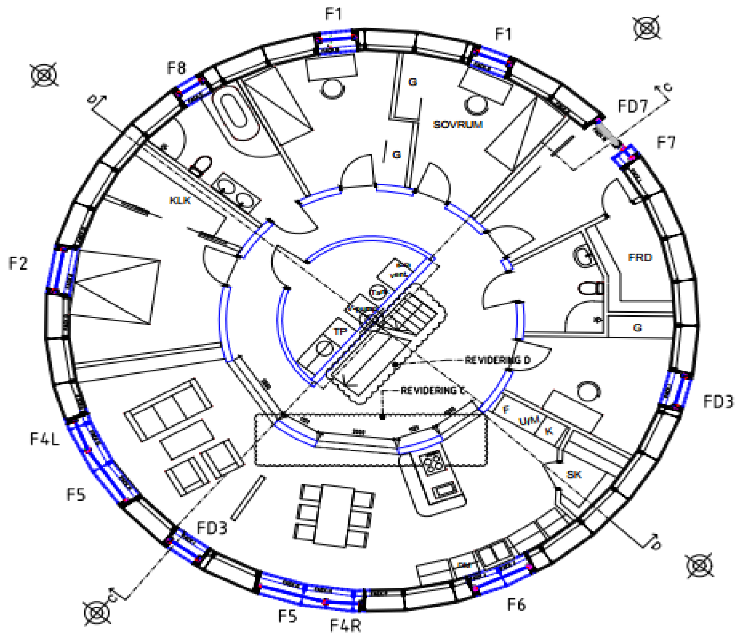

Figure 14. Floor plan 1st floor [31].

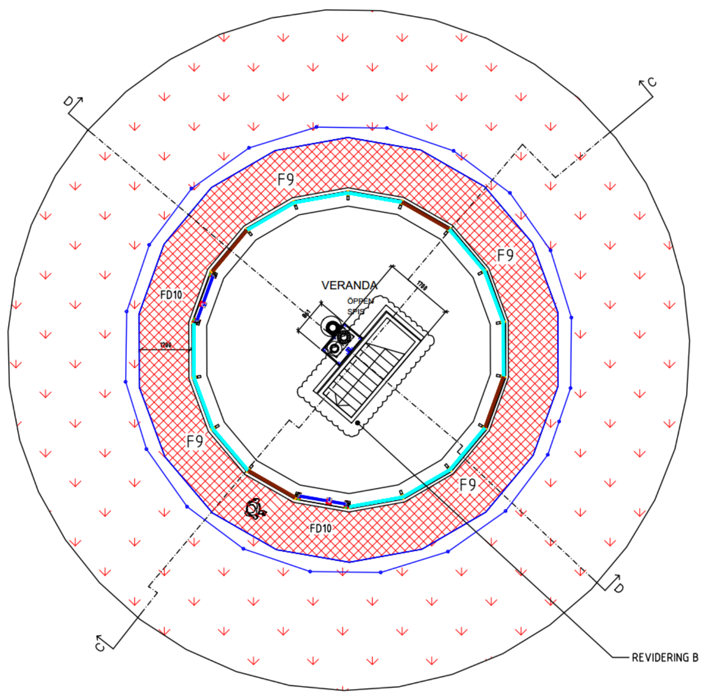

Figure 15. Floor plan 2nd floor [31].

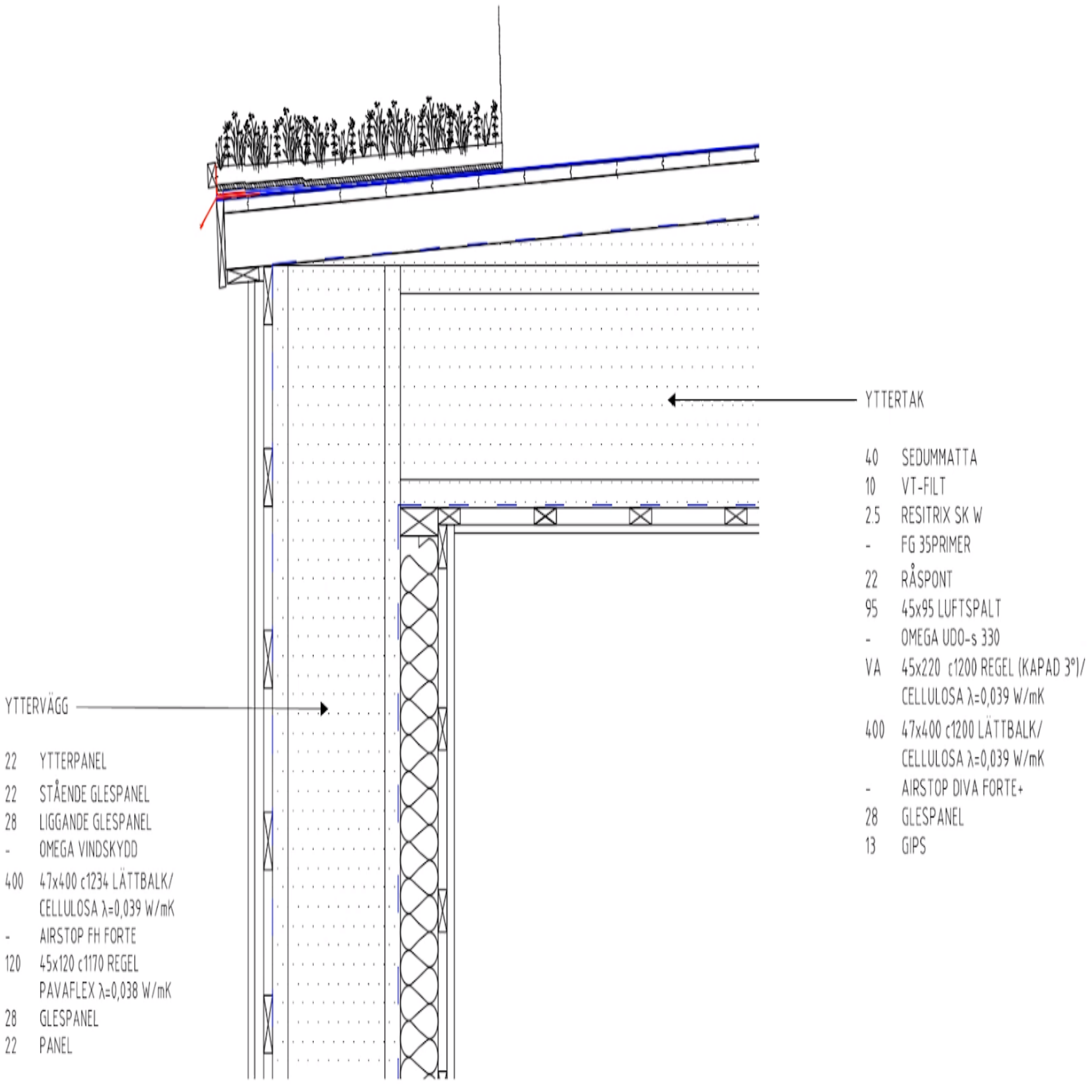

Figure 16. Roof and wall insulation with blue dotted line illustrated as air barrier [31].

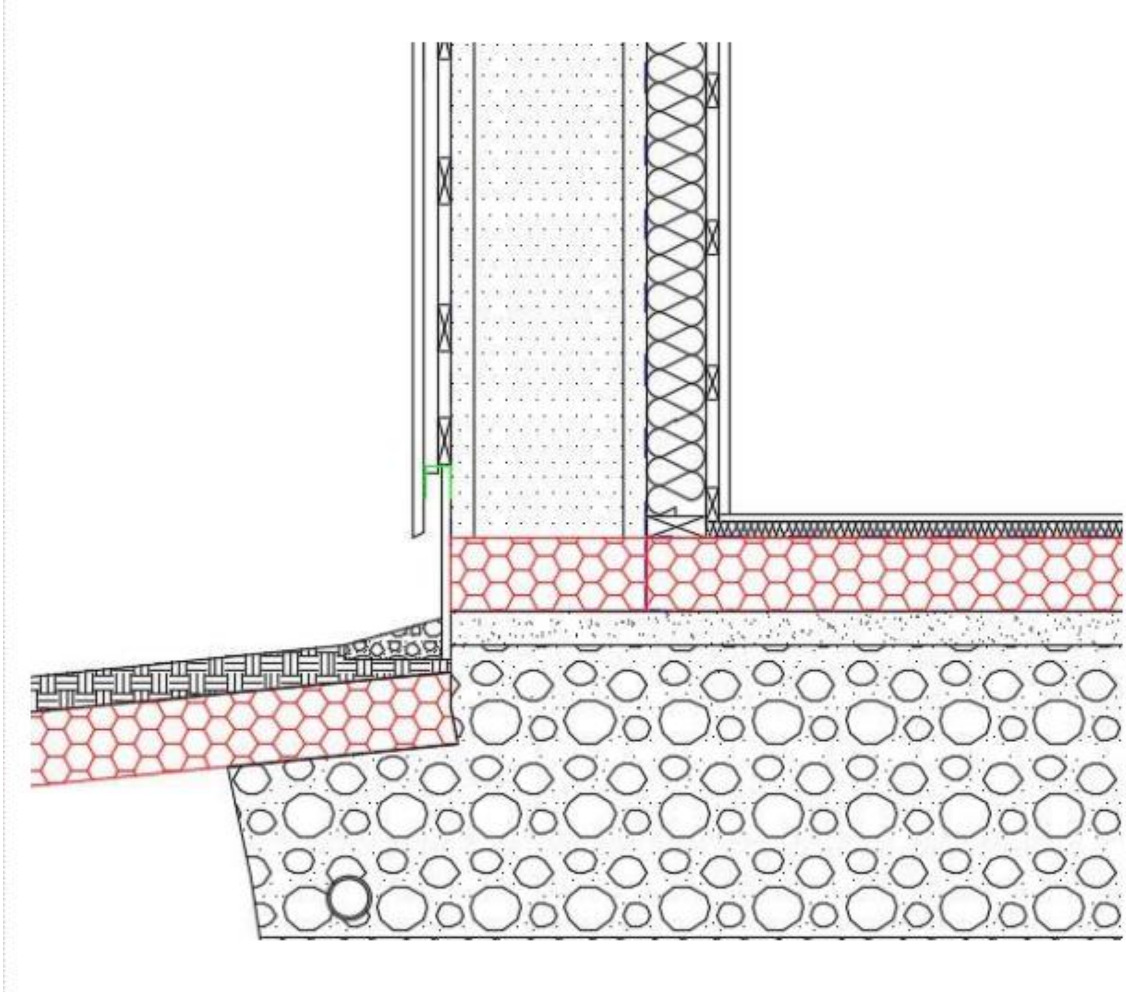

Figure 17. Wall and floor insulation with ground outward insulation [31].

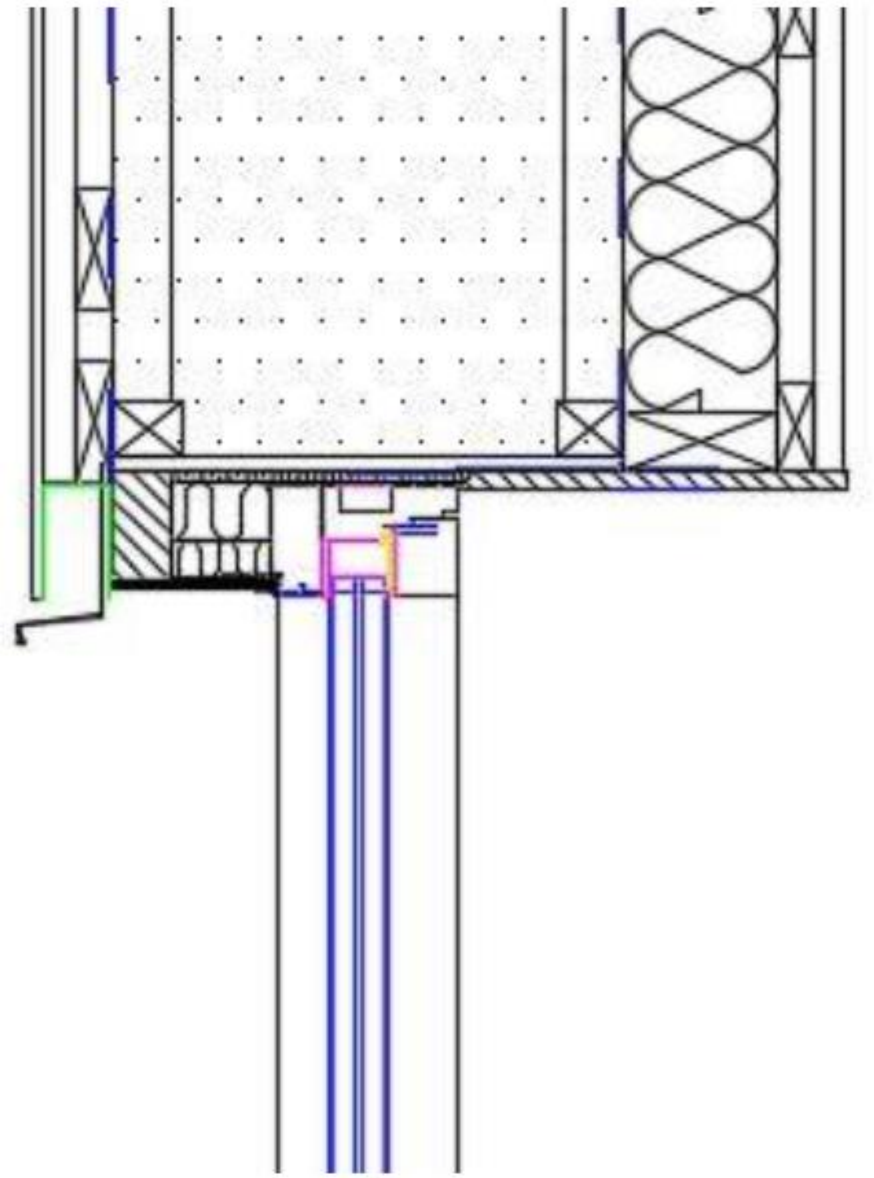

Figure 18. Wall and window junction with insulation overlay over the exterior side of window frame [31].

Appendix 2. Wolfe Island Passive House

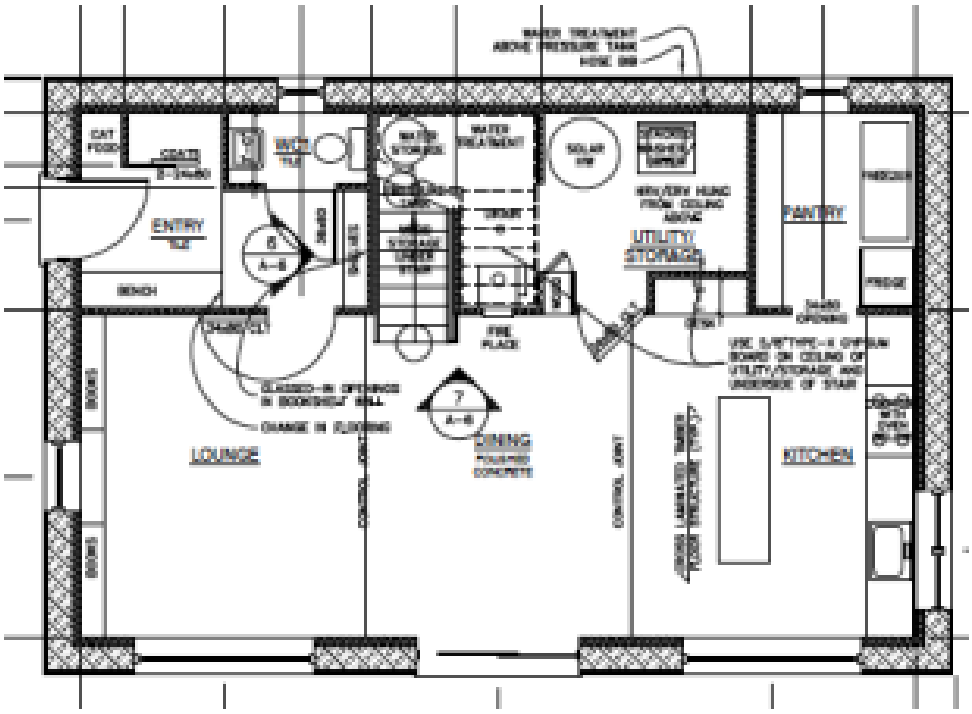

Figure 1. Floor plan, 1st floor [38].

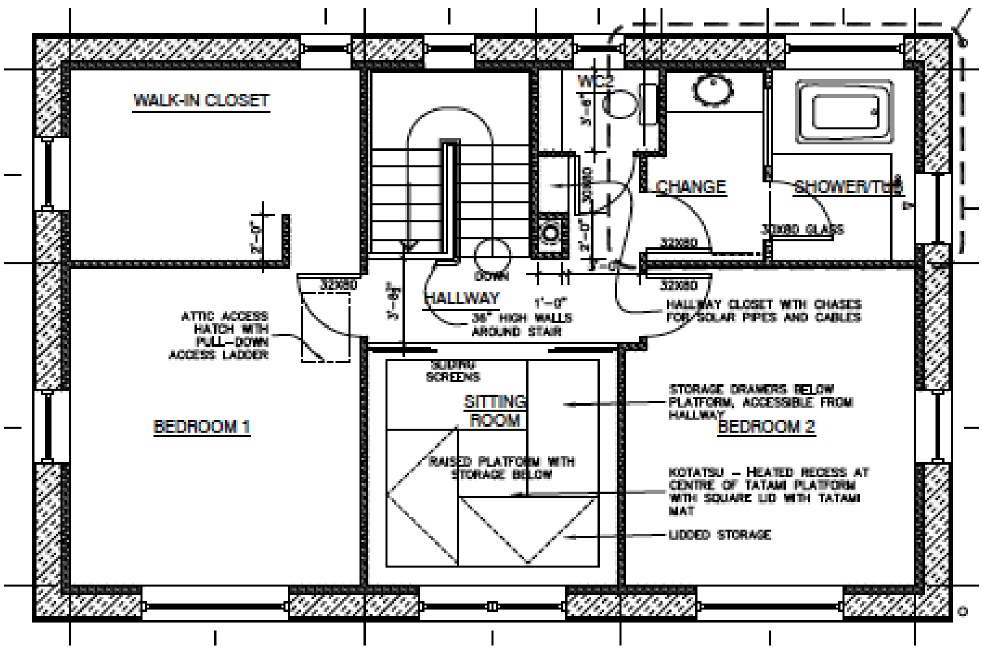

Figure 2. Floor plan, 2nd floor [38].

Figure 3. The edges of the insulated foundation [39].

Figure 4. Reinforcement for base floor concrete slab on 300mm EPS [40].

Figure 5. Second floor wall being craned for assembling [41].

Figure 6. Two base EPS type II layers for wall insulations [36].

Figure 7. Plastic head covers and polystyrene plugs to prevent thermal bridges for EPS screws [36].

Figure 8. Installation of roof insulations, fiber panels [42].

Figure 9. Half-way finished wall insulation [42].

Figure 10. Gap at the window 12.5mm, which will be filled with a special expanding foam [43].

Figure 11. Insulation tight at the window frame [43].

Figure 12. Aluminum trim cover [43].

Figure 13. Ceiling mounted Zehnder ComfoAir 200 unit [37].

Figure 14. The main heating source of the building, hydronic wood stove [44].