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HEATING SYSTEM FOR A PASSIVE HOUSE IN FINLAND

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DESCRIPTION

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Abstract

In this thesis work a passive house situated in Finland is examined. The aim of this work is to compare these systems and decide which one suits best to the passive house with cold climate conditions of Finland. The comparison is made by the economic criteria.

The study consists of the theoretical part which describes the Passivhaus standard and structural features of the passive house, alternative energy sources and the three heating systems for the passive house; and practical part which includes energy and economical calculations.

The results are shown in tables and appendices following which the conclusions on the best heating system are made.

Subject headings, (keywords)

Passive house, ground source heat pump, ventilation air heating, underfloor heating, pellet stove, energy consumption, heating power, capital costs, operational costs

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CONTENTS

LIST OF SYMBOLS

E_{purch} - building's consumption of purchased energy, kWh/(m^2a)

$Q_{heating}$ - heat energy consumption of the heating system, kWh/(m^2a)

$W_{heating}$ - electric energy consumption of the heating system, kWh/(m^2a)

$W_{ventilation}$ - electric energy consumption of the ventilation system, kWh/(m^2a)

$Q_{cooling}$ - heat energy consumption of the cooling system (district cooling), kWh/(m^2a)

$W_{cooling}$ - electric energy consumption of the cooling system, kWh/(m^2a)

$W_{appliances}$ - electric energy consumption of household or consumer appliances, kWh/(m^2a)

$W_{lighting}$ - electric energy consumption of the lighting system, kWh/(m^2a).

Q_{air} - leakage air leakage heat loss, kWh

Q_{supply} - air heating of supply air in a space, kWh

$Q_{make\text{-}up\ air}$ - heating of make-up air in a space, kWh

Q - conduction heat loss through a building component, kWh

U_i - thermal transmittance factor for a building component, W/(m^2K)

A_i - floor area of a building component, m^2

T_{ind} - indoor air temperature, °C

T_{outd} - outdoor air temperature, °C

Δt - time period length, h

Q_{air} - leakage energy required to heat air leakage, kWh

ρ_i - air density, kg/m^3

c_{pi} - specific heat capacity of air, Ws/(kgK)

$q_{v,\ air\ leakage}$ - air leakage flow, m^3/s

$Q_{iv,supply\ air}$ – energy required to heat supply air for a space, kWh

$q_{v,supply\ air}$ - supply air flow, m^3/s

Q_{iv} - net heating energy need for ventilation, kWh

t_d - ventilation system's mean daily running time ratio, h/24h

t_v - ventilation system's weekly running time ratio, days/7 days (day=24 h)

$q_{v,\ supply}$ - supply air flow, m^3/s

T_{ib} - inblown air temperature, °C

T_{recov} - temperature after heat recovery device, °C

$Q_{int.heat}$ - building's heat load energy recovered for heating, kWh

η_{heat} - degree of heat loads recovered by month, -

$Q_{heat\ load}$ - a building's heat load, kWh

Q_{person} - heat energy emitted by a person, kWh

$Q_{electric}$ - heat loads released into a building from lighting and electrical appliances, kWh

Q_{solar} - solar radiant energy coming into the building through windows, kWh

$Q_{DHW,circ}$ - loss from domestic hot water circulation, kWh/a

$Q_{DHW,tank}$ - loss from domestic hot water storage, kWh/a

Q_{solar} - solar radiant energy entering the building through the windows, kWh/month

$G_{radiant,\ horizontal}$ - total solar radiant energy on a horizontal surface per area unit, kWh/(m2unit)

$G_{radiant,\ vertical}$ - total solar radiant energy on a vertical surface per area unit, kWh/(m2unit)

$F_{direction}$ - conversion factor for converting the total solar radiant energy on a horizontal surface to total radiant energy on a vertical surface by compass direction,-

$F_{transmittance}$ - total correction factor for radiation transmittance, -

A_{win} - surface area of a window opening (including frame and casing), m2

g - transmittance factor for total solar radiation through a daylight opening, -.

$F_{transmittance}$ - total correction factor for radiation transmittance, -

F_{frame} - frame factor, -

$F_{curtain}$ - curtain factor, -.

F_{shade} - correction factor for shades, -.

F_{shade} - correction factor for shades, -

$F_{environment}$ - correction factor for horizontal shades in the environment, -

F_{top} - shade correction factor for shade provided by horizontal structures above a window,-

F_{side} - shade correction factor for shade provided by vertical structures on the side of a window,-.

$W_{dhw,\ circ}$ - specific power of DHW circulation pipe heat loss, W/m

L_{dhw} - length of the DHW circulation pipe, m

t_{dhw} - running time of the domestic hot water circulation pump, h/day

$W_{dhw,\ heating}$ - specific power of heaters connected to the circulation pipe for domestic hot water, W/pc.

$n_{heating\ device}$ - number of heaters connected to the circulation pipe for domestic hot water, pcs.

η_{heat} - degree of heat loads recovered by month, -

γ - heat load to heat loss ratio, -

a - a numerical parameter, -

τ - building's time constant, h

C_{build} - building's interior effective thermal capacity, Wh/K

H - specific heat loss of a building, W/K

Q_{space} - heat loss of building's spaces, kWh

$\Phi_{heating}$ - building's heating energy need, W

Φ_{room} - heating room heating power need, W

$\Phi_{supply\ air}$ - battery heating power need for a ventilation supply air after-heater battery, W

Φ_{dhw} - power required to heat domestic hot water, W

η_{room} - heating efficiency of a room heating system under design conditions, -.

$\eta_{supply\ air}$ - efficiency of a ventilation supply air heating system under design conditions, -

η_{dhw} - efficiency of a domestic hot water heating system under design conditions, -.

Φ_{space} - heating power required to heat spaces, W

$\Phi_{conduct}$ - conduction heat loss through the building shell, W

$\Phi_{air\ leakage}$ - air leakage heat loss, W

Φ_{supply} - air power for heating supply air in a space, W

$\Phi_{make\text{-}up\ air}$ - power for heating make-up air in a space, W

$\Phi_{air\ leakage}$ - power required for heating air leakages, W

$T_{outd\ design}$ - design outdoor air temperature, °C

$\Phi_{supply\ air}$ - power required for heating supply air in a space, W

Φ_{vent} - power of ventilation heater battery, W

$T_{recov,\ design}$ - temperature after heat recovery device, °C

$\eta_{t,design}$ - supply air temperature ratio in heat recovery under design conditions

ρ_v - water density, 1 000 kg/m3

c_{pv} - specific heat capacity of water, 4.2 kJ/kgK

$q_{v,\ dhw}$ - maximum normal flow of domestic hot water, m3/s

T_{dhw} - domestic hot water temperature, °C

T_{cw} - domestic cold water temperature, °C

$\Phi_{dhw,circloss}$ - power required by the DHW circulation pipe, kW

A - net heated area of a building, m2

$q_{v,\ dhw,\ circ}$ - designed flow of domestic hot water in circulation pipes, m3/s

T_{dhw} - domestic hot water temperature, °C

$T_{dhw,\ circ}$, - return temperature of the return water in the DHW circulation pipe, °C

C – capital costs, €

c_{hc} – the price of the heating coil for ventilation air heating, €

c_{sc} – the price of the solar collectors, €

c_{he} – the price of water-to-air heat exchanger, €

c_{ih} – the price of the backup immersion heater, €

c_i – installation costs, €

O – operational costs, €

c_{uh} – the price of the underfloor heating per m^2 of space, €

A_h – heating area, m^2

c_{hp} – the price of the ground source heat pump, €

c_{ghe} – the price of the ground heat exchanger, €

L – length of the ground heat exchanger, m

Q_a – annual energy consumption, kWh

q_s - specific heat flow through 1 meter of the pipe, kWh/m

c_{dsh} – the price of desuperheater, €

m – maintenance costs, €

c_e – the price of the electricity, €

p_e – the price of energy consumed, c/kWh

$\eta_{a.hp}$ – annual efficiency of ground source heat pump

c_{ps} – the price of the pellet stove, €

c_{he} – the price of water-to-air heat exchanger, €

c_{fuel} – cost of the fuel during one year, that can be calculated according

c_p – the price of the pellets, €

$\eta_{a.s}$ – annual efficiency of the pellet stove

i – bank loan interest, -

n – lyfe cycle of the system, years

1 INTRODUCTION

Energy efficiency is a much discussed issue nowadays. People know that usual energy sources are becoming more expensive, they are depleting, and many countries depend on those who have the reserves of fossil fuels. Besides, ecological situation becomes worse because of burning of fossil fuels. These two problems have become very serious and have a global scale. That's why many countries have included energy efficiency in their energy policy.

There are a lot of technologies which are developing in correspondence with energy saving ideas. One of these is the development of building of passive houses. Passive house is a building which consumes minimum of energy by means of its constructive and engineering features and doesn't need a heating system at all. The main principle of designing of this house is using all methods of heat storage. And it is necessary in such kind of buildings to provide all the energy by means of alternative energy sources. In this thesis work the idea is that the passive house is situated in Finland, i.e. in the cold climate. The difficulties in this case are to meet the Passivhaus standard. And also there must be a heating system, considering the passive house requirements, to provide a sufficient heat and not to let the building overheat at the same time.

In this thesis work three different alternatives of a heating system for a passive house are proposed. The research question is which of them is the best for a particular passive house in Finland. Different criteria are considered: suitability for the cold climate conditions, simplicity of installation and maintenance, efficiency, capital and operational costs.

The first part of this study describes the basics of the passive house construction. First, the passive house must meet the Passivhaus standard requirements. Then this is explained by which structural and engineering means it should be done, taking into account the cold climate conditions and Finnish National Building Code regulations.

In the next part different alternative energy sources are presented, which will provide heat for the passive house. Those are ground source heat pump and systems based solar collectors.

Further the three different heating systems are described in detail. They were chosen as the most suitable heating systems by different criteria for a passive house situated in the cold climate, where they can be the most efficient.

Then in order to apply these systems on practice, there is a particular passive house described as an example. This house is a real project, which was already built in Sweden.

And after that different calculations are made: annual energy needs and heating power of the passive house, in order to choose certain equipment for the systems and then to calculate the costs of the heating systems. On the basis of these calculations the comparison between the systems was made.

2 PASSIVE HOUSE AND ITS FEATURES

Passive house is a low-energy building. It has some structural features and devices which contribute to very low energy consumption and at the same time high living comfort. It is so air-tight and well insulated that the regular space heating is not needed. Heat losses are so small that they can be compensated by heat gains from occupants and household activities. The energy sources for a passive house should be renewable energy since the idea of this building is to be sustainable.

Such buildings are gaining popularity nowadays. The main target of building passive houses is reducing energy consumption as the energy prices are growing. Passive house is also environmental friendly with high indoor air quality. The essential condition for a building to be considered a passive house, is to meet the requirements of Passivhaus Standard.

2.1 Passivhaus Standard

Passivhaus Standard is a standard developed by Passivhaus Institut in Germany, setting requirements for a building to be a passive house. According to a Passivhaus Standard a passive house is “a house in which space heat requirement is reduced by means of passive measures to the point at which there is no longer any need for a conventional heating system; the air supply system essentially suffices to distribute the remaining heat requirement" /1/.

The term "Passive House" was originally invented by Passivhaus Institut. And the concept itself was originated by Professors Bo Adamson of Lund University, Sweden, and Wolfgang Feist of the Institut für Wohnen und Umwelt (Institute for Housing and the Environment, Germany). "It should be noted that the primary focus in building to the Passivhaus Standard is directed towards creating a thermally efficient envelope which makes optimum use of free heat gains in order to minimize space heating requirement" /2/.

So according to this standard "the outdoor temperature and as a consequence the temperature of the incoming ventilation air, the heat capacity of the air, and the maximum temperature to which the air can be heated to be comfortable, the maximum heat requirement was calculated to 15 kWh/m^2 per year" /3/.

Other requirements for achieving the Passivhaus Standard are not more than $10W/m^2$ of heating load and 15 kWh/m^2 per year of annual total amount of energy input. But as the standard was invented in Germany the question is if it is possible to achieve these requirements in Finland. Two different definitions of a term "Passive House" were created which make the requirements more flexible in respect of Nordic countries such as Finland. According to the second definition: "…For 60° and higher latitudes, it is necessary to adjust the figures in order to be able to achieve an ambitious yet realistic solution. This can be done on a national basis. However, the specific heat loss for transmission, infiltration and ventilation (according to EN ISO 13 789) normalized for treated floor area should not exceed 0.5 $kWh/(m^2a)$" /3/. Different passive house definitions for different European climates are shown in table 1.

TABLE 1. Definitions of Passive House in different parts of Europe /4, p. 7/

	Heating energy kWh/m²a	Cooling energy kWh/m²a	Primary energy kWh/m²a
South Europe	15	15	120
Central Europe	15		120
Nordic Countries (above 60° latitude)	20-30 depending on the building's location		130-140

Passivhaus Standard also defines the values for U-value for the main building's structure. So, they are the following: <0,175 W/m^{2}K for the walls, <0,15 W/m^{2}K for the roof and floor, and for the windows and doors < 0,8 W/m^{2}K.

These are the main criteria for a building to be a passive house. Also there are three different solutions based on the extent on which they are applied in each European country. More detailed requirements for different solutions are shown in table 2. The quality of the components of the passive house is presented in table 3.

TABLE 2. Passive house solutions/measures /5/

Measure/ solution	***Passivhaus standard***
1. Super Insulation	
Insulation walls	$U \leq 0{,}175$ W/(m^{2}K)
Insulation roof	$U \leq 0{,}15$ W/(m^{2}K)
Insulation floor	$U \leq 0{,}15$ W/(m^{2}K)
Window casing, doors	$U \leq 0{,}8$ W/(m^{2}K)
Window glazing	$U \leq 0{,}8$ W/(m^{2}K)
Thermal bridges	linear heat coeff $\psi \leq 0{,}01$W/(mK)
Air tightness	$n_{50} \leq 0{,}6$ h^{-1}
Minimal Shape Factor (Area TFA/ Volume TV)	
2. Heat Recovery/ IAQ	
Ventilation counter flow air to air heat exchanger	heat recovery $\eta_{HR} \geq 75$ %
Ventilation air sub-soil heat exchanger	air outlet after sub-soil heat exchanger

	above frost temperature
Ventilation ducts insulated	
Other heat recovery (e.g. ventilation & DHW return pipes)	
DHW heat recovery	
DHW pipes insulated	
Minimal space heating	postheater ventilation air/low temperature heating
Efficient small capacity heating syst.	biomass, heat pump, gas, cogeneration (e.g. district heating), etc.
Air Quality through ventilation rate	min. 0,4 ach^{-1} or 30 m^3/pers/h or national regulation if higher
3. Passive (Solar) Gain	
Window glazing	solar energy transmittance $g \geq 50$ %
DHW (solar) heater	
Thermal mass within envelope	
Solar orientation	
Night-time shutters	
Shading factor [%] (East & West)	
4. Electric Efficiency	
Energy labeled household appliances [Labeling A - G]	Energy reduction 50% of common practice
Hot water connections washing machines/ dishwashers	
Compact Fluorescent lighting	
Regular maintenance ventilation filters	
Direct Current motor ventilation	
Efficient fans: SFP (Specific Fan Power)	$\leq$ 0,45 W/(m3/h) (transported air)
5. On-site Renewables	
Wind turbine	
Photo Voltaics	
Solar thermal energy	
Biomass system	
Other	

= basic measure/solution

= often applied optional measure/solution

= other optional measure/solution

TABLE 3. Examples of component quality and construction suitable to reach Passivhaus ("recommended") and best available components ("best practice") /6/

Component or construction	Recommended	Best practice
Insulation of opaque envelope, U (W/(m^2 K))	<0.15	0.06
Thermal bridge free construction, i.e.		
Linear thermal transmittance, Ψ_e (W/(m K))	<0.01	<0
Glazing with low U-value and high g-value, i.e.		
Thermal transmittance, U_g (W/(m^2 K))	<0.8	0.51
Total solar energy transmittance, g (%)	>50	58
Window, thermal bridge free construction, insulated frame, U_w (W/(m^2 K))	<0.8	0.75 (with $U_g = 0.7$ W/(m^2 K))
Heat recovery with		
Net efficiency (see Glossary), η_{HE} (%)	>75	92
Heat loss through casing	<5 W/K	
Internal and external leakages (%)	<3	<1
Electric energy demand for ventilation (including control), p_{el} (W/(m^3/h))	<0.45	0.3
Largely reduced losses in the heating installation (including DHW)		
Energy efficient electric appliances (e.g. highest EU appliance energy-label class)	Class A	<60% of Class A average
Recommended limit for primary energy use for household electricity (part of PE requirement in Table 1), PE (kW h/(m^{2}a))	<55	27 (assuming European electricity mix)

Concerning the energy need for water heating, heat demand of the hot water system should be 12 - 35kWh/(m²a), depending on the number of occupants and distribution losses /7/.

Thereby, considering the Passivhaus Standard for cold climates, the design values for Finland (Helsinki) can be estimated . The annual total amount of energy input then is 20 kWh/m^{2}a, and the primary energy demand is 120 - 140 kWh/m^2. All requirements of Passivhaus Standard are in accordance by Finnish National Building Code.

In order to reach the Passivhaus standard the proposed design should be verified by a special PC software. It is the Passivhaus Planning Package (PHPP) which is a Microsoft Excel energy calculation tool specially applied to passive house designing. The PHPP includes tools for calculating U-values, energy balances, the heat load, summer comfort calculations, designing comfort ventilation, and many other tools. "The PHPP energy balance module was shown to be able to describe the thermal building characteristics of passive houses surprisingly accurately. This applies particularly to the new technique for calculating the heating load, which was developed specifically for passive houses" /1/. PHPP software perfectly corresponds to the Passivhaus Standard, therefore it provides some fixed values for calculations which contribute to meet the Passivhaus Standard. The latest edition of PHPP was launched in 2007. /1/

2.2 Structural features

As a passive house is a special building with its own standard there are some construction and engineering features which serve for reaching the Passivhaus Standard, also taking into account the cold climate conditions in Finland. These features are described in the following chapter.

2.2.1 Passive solar design and glazing

The house should be situated in such site where it can gain maximum of sun rays in winter without any shading from trees and other objects. The south face should be oriented within 10 degrees from true south.

The next issue which must be taken into account is the amount of glazing and window orientation. The area of south oriented glazing should be 5-12 % of total floor area of the building. It is also necessary to take into account possible summer overheating. So for cold climates overhangs should be designed so that they can fully shade the windows on the southern side during summer and not to shade the sun in winter time. In order to design the overhangs properly there is a special software, such as "Overhang Design Tool". The example of an overhang is shown in figure 1.

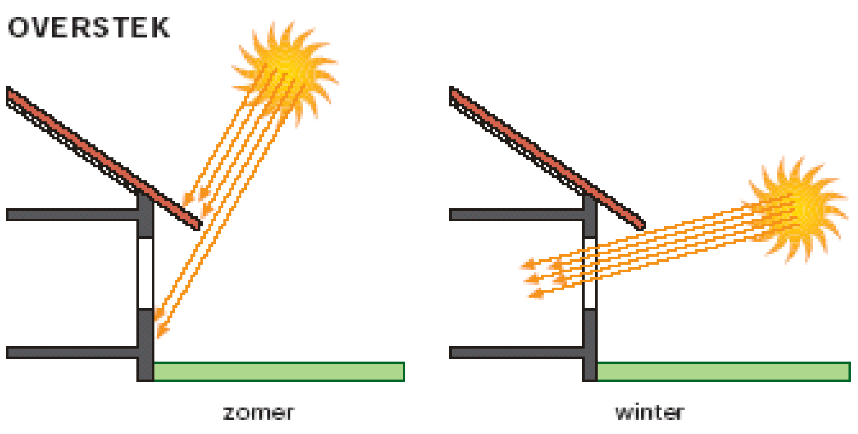


FIGURE 1. Application of overhangs in summer and winter /5/

The building materials in passive solar design play an important role too. The materials with high thermal mass should be used, such as brick, stone, ceramic tile, concrete. These materials store heat and lose it very slowly. A certain amount of mass is added depending on the amount of glazing. So, for above 7% of glazing for each square meter there are: 5,5 m^2 for floors that receive direct sunlight, 8,3 m^2 for walls and ceilings, and 40 m^2 for floors that don't receive direct sunlight. Therefore the maximum amount of mass for the floor is 1,5 times more than the area of south-oriented glazing. Certainly, passive solar design has to be decided along with other passive house features, which will be described further. /8/.

It is also very important to avoid irregular architectural shapes in the house's design. "Dormers, roof-windows, bay windows, long and narrow extensions to the main body, split-levels, are all examples of features that cost energy in practice" /9/.

Besides the orientation and overhangs windows should have triple low-emittance glazing and well insulated frames /5/. An example of triple-glazed window is shown in figure 2.

FIGURE 2. Cross section through a triple glazed insulated window and frame /2/

Passivhaus Standard gives a very low U-value for windows which can be achieved only by triple glazing, especially in northern countries. Firstly it is made for the comfort of the occupants, because during winter the coldest surface will be the window. And as passive houses don't have heat emitters it is very important that the temperature difference between the coldest surface (window) and the mean surface temperature in the room should not exceed 3 °C. Many windows manufactured in Europe are certified in the Passivhaus Institut, so it is always better to use Passivhaus-certified windows to avoid uncertainty with required U-values.

In some cases the so called heat mirror glazing can be used, especially in cold climates. "Heat Mirror glazing has only two panes of glass; between the inner and outer panes are one, two, or three plastic films that create separate air spaces" /10/.

Nevertheless, in cold climate, passive solar design is not of main importance, because there are very few sun shine periods in winter. So that's why the main emphasis should be made on the building structure, notably on insulation of the building envelope.

2.2.2 Insulation, thermal bridges, and air-tightness

Insulation

Insulation of a passive house plays the most important role in its heat storage. As it was mentioned earlier, the exact U-values for choosing the insulation for a passive house are given in Passivhaus Standard. But in Finland the U-values must be even lower in order to meet the requirements for energy demands of the Passivhaus Standard. The modified U-values applied for cold Finnish climate are shown in table 4.

TABLE 4. Properties of different structure insulation applied for cold climate /11/

Structure	***U-value, W/(m2K)***
Wall	0,07 – 0,1
Floor	0,08 – 0,1
Roof	0,06 – 0,09
Window	0,7 – 0,9
Fixed window	0,6 – 0,8
Door	0,4 – 0,7

In comparison, the National Building Code of Finland for heated, especially warm or cooled cold space abuts the outside air, unheated space or the ground, reference U-value of exterior wall should be 0.17 W/m^{2}K /12/. So in Finland the insulation thickness would be: for walls 500 – 600 mm, 700 - 800 mm for the roof, and about 400 mm for the floor /11/.

There can be a large variety of different solutions for achieving this criteria. Usually it depends on local constraints of each country. The example of practical usage of insulation in passive houses in Finland is shown in figure 3.

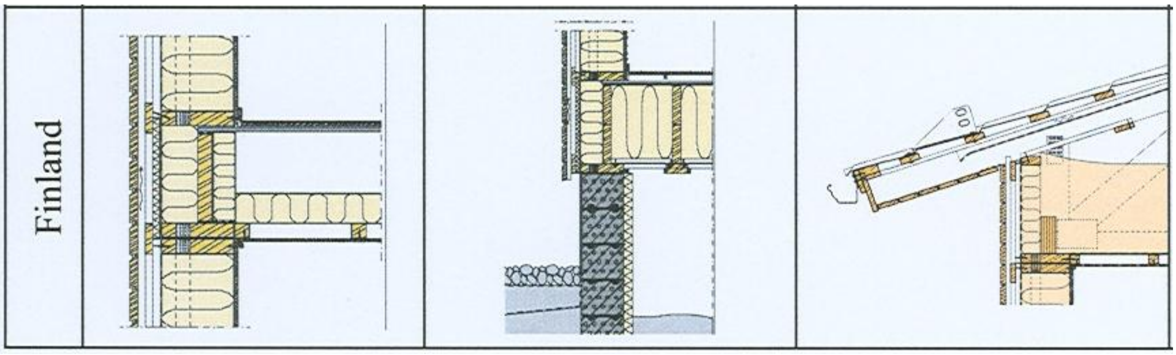


FIGURE 3. Thermal envelope details of Best Practice example in Finland /5/

The problem for cold climate in Finland is that in winter the ground can freeze down to 1,5 m in southern areas and down to 2,5 m in Lapland. So there should be frost protection of the foundations, notably more attention on insulation of the floor structures and floor external wall connections. /11/.

Thermal bridges

Heat losses through the joints, corners, and edges are usually higher than through the walls, roof, and floor. Besides the insulation the passive house shouldn't have any thermal bridges. Because of thermal bridges there are undesirable heat losses. There are a lot of solutions to minimize these thermal bridges, depending on a certain case. Passivhaus Standard also gives requirements regarding this matter. So the coefficient of thermal transmittance ψ shouldn't exceed 0,01 W/mK. "This requires the building designer to identify and locate all potential thermal bridging in the construction, applying careful specification and detailing of those elements providing where possible a continuous layer of insulation, as well as taking care to execute those elements on site as per design details" /2/.

Air tightness

One of the most important features of a passive house without which the house can't be considered passive is air-tightness. All the insulation and correct glazing will be ineffective if there are air leakages through the building envelope. The value of air-tightness set by the Passivhaus Standard is air leakage rate n_{50} = 0,6 h^{-1}, which means that air in a building changes 0,6 times per hour at pressure p = 50 Pa the air in the room changes 0,6 times per hour. An air-tight building can be effectively achieved by two different ways. First way is two skin plaster system. All the openings should be sealed into the plaster. The second alternative is air-tight membrane. It can be either stuck into the walls by a special adhesive or by counter battening the walls and sticking membrane into this. "The theory behind air-tightness is that you should be able to draw a continuous line around the inside of your house showing the air-tight barrier, returning to your start point without lifting pen from paper" /13/. To achieve air-tightness it's not only the responsibility of designers but also a qualified workmanship is needed along with building materials of good quality. After the building envelope of the house is finished air-tightness should be verified by a door blower test which is shown in figure 4. /14/.

FIGURE 4. A blower door test /14/

2.2.3 Mechanical heat recovery ventilation system

The precondition for a passive house to meet the Passivhaus Standard is to use heat recovery unit in ventilation system when the system itself is mechanical supply-exhaust ventilation. As there are no air leakages through the building envelope and the building is air-tight, the necessary amount of fresh air should be supplied mechanically as well as the exhaust air should be removed. The occupants can still open the windows but in cold periods of the year there can be caused extra heat losses. So opening the window is not necessary as the ventilation system brings the fresh filtered air continuously. /2/

Air distribution type should be cascade-flow ventilation principle. It means that the air is supplied to a room and the pollutions are removed efficiently. The flow direction is well defined. This simple principle is shown in figure 5, and the main components of ventilation system are shown in figure 6.

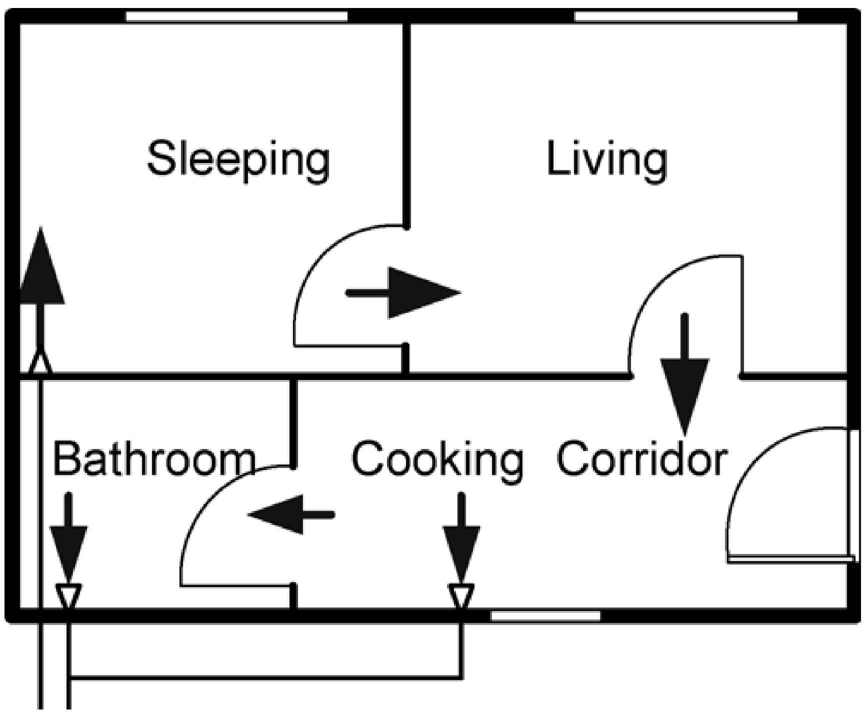


FIGURE 5. Air distribution by cascade-flow principle /6/

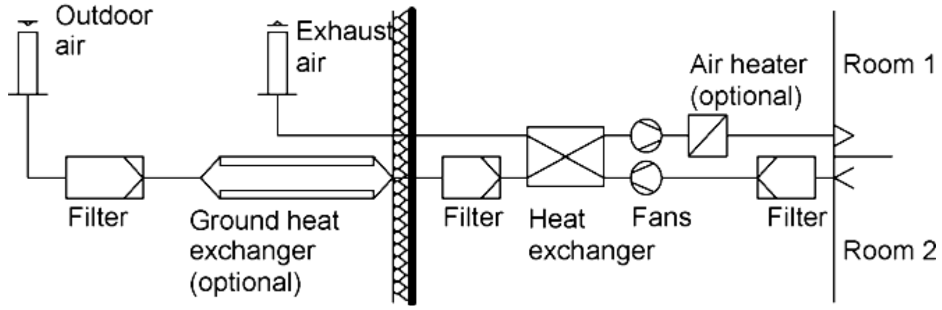


FIGURE 6. Ventilation system and components /6/

The Passivhaus Standard has set the efficiency of heat recovery to be at least 75% or more. Although ventilation system needs energy, it requires only 10% of the whole annual energy demand of the building. "On one hand, a high efficiency provides supply air temperatures close to the comfort level, even without additional heating. On the other hand, even with Passive House standard, a net efficiency of approximately 75% is required to reach not only energetic but also economic savings" /6/. The efficiency of 75% can be reached with counter flow plate heat exchangers, more than 90% is reached with channel-type heat exchangers. When the ventilation system is used during non-heating season there has to be a possibility to bypass the heat recovery. It is recommended that the heat recovery unit is verified by Passivhaus Institut.

"According to the Passivhaus Institut, the appropriate air change rate for dwellings is between 0,3 and 0,4 times the volume of the building per hour, with a general recommendation of leaning toward the lower rate" /2/. This contributes to a high indoor air quality and low energy consumption, meeting the requirements of NBC of Finland, part D2 "Indoor Climate and Ventilation of Buildings".

It is also recommended by the PHPP software that the amount of fresh air supplied to dwellings should be 30 m^3/h per person. For exhaust air the values are the following for different rooms: 60 m^3/h for kitchen, 20 m^3/h for shower, as well as for WC. That totally meets the requirements of D2 as well. Eventually the whole ventilation system should be in balance, whereas the amount of exhaust air is a little bit higher. Considering the energy demands of ventilation system, according to PHPP software the standard value for the consumed energy is 0,45 Wh for every 1 m^3 of transported air.

In order to avoid heat losses from the supply ventilation ducts, they should be well insulated. Usually the thickness of the insulation material is 60-100 mm. /2/.

The challenge which can be encountered in Finland is the risk of freezing of heat recovery unit. So the defrosting is needed. For example, the cyclic use of heat recovery in order to avoid freezing, reduces its efficiency. So the best solution is pre-heating of incoming fresh air with a heat exchanger of ground loop system. /11./ To avoid freezing of the heat recovery unit, the temperature of the air entering into the heat recovery unit should be more than -4 °C. Usually a system of air ducts with the length of about 40 m buried underground on the depth of about 1,5 – 2 m is used to connect the ground heat exchanger with the main ventilation system. /6/.

2.2.4 Drain water heat recovery

All the drain water carries away the heat which can be used for pre-heating the water. There is a lot of waste water from showers, washing machines that has 80-90% of heat that can be reused in water heating. Drain water heat recovery has the same principle as the heat recovery unit in ventilation system. So it recovers heat from waste water and uses it for preheating the cold water which enters the water heater.

The temperature of cold water entering the house is about 5-12 °C and is heated up to 58 °C. The temperature of drain water, for example, after the shower is usually about 40 °C which flows to the drainage system with the temperature of 37 °C. So this energy is very essential for being used for preheating the cold water in a sustainable building.

This unit can work well in all types of water heaters, especially solar water heaters. It can operate either with a storage device (when using it with dishwasher or washing machine) or simultaneously when the cold water is running (when using a shower). In systems which have a storage tank drain water flows through a spiral tube right to the bottom of the tank. “Water heater intake water is preheated by circulation through a coil at the top of the tank” /15/.

When a system doesn’t contain drain heat storage tank, it is equipped with a heat exchanger. “As warm water flows down the waste drain, incoming cold water flows through a spiral copper tube wrapped tightly around the copper section of the waste drain. This preheats the incoming cold water that goes to the water heater or a fixture, such as a shower "/15/. The principle of drain water heat recovery operation is described in figure 7.

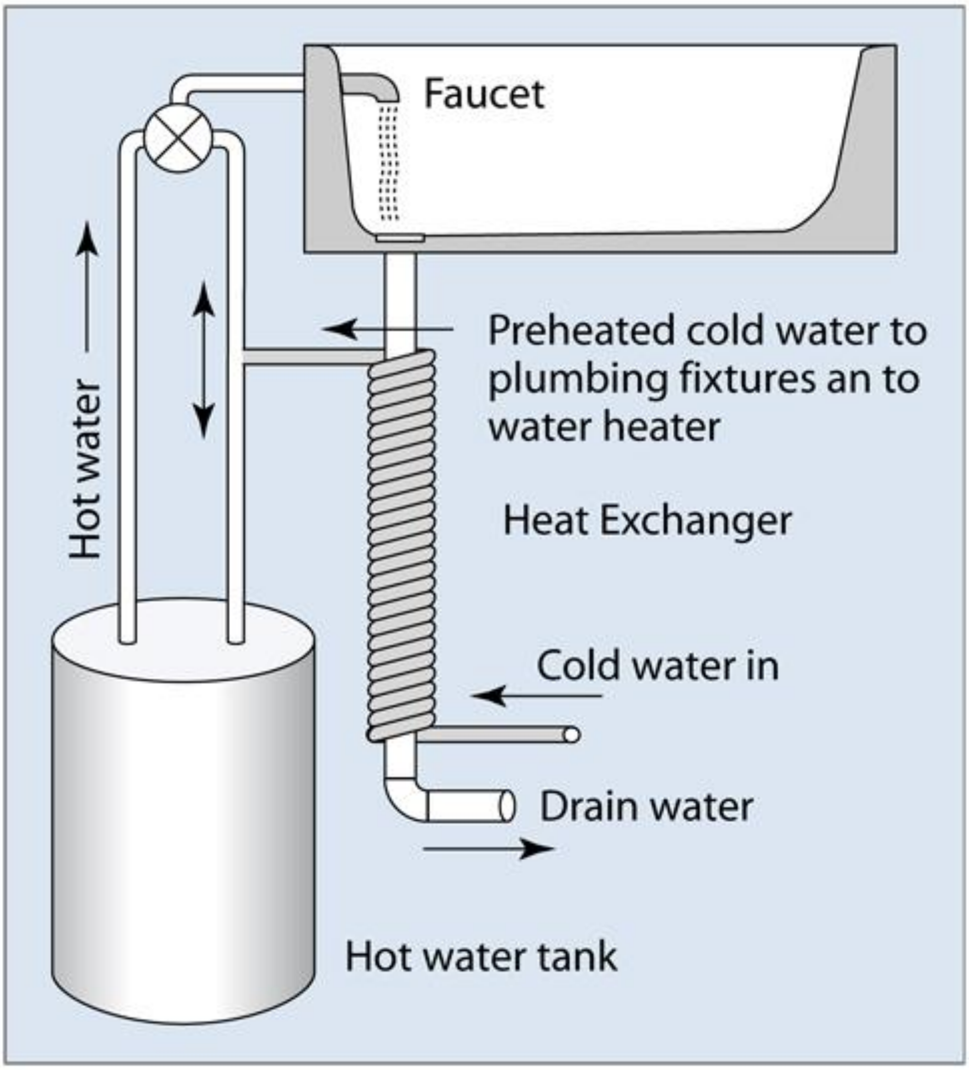


FIGURE 7. Drain water heat recovery /15/

As the construction of a passive house meets a few barriers in Finland because of the cold climate, it must be noted that reaching the Passivhaus Standard requirements can be complicated. Heating demands in cold periods can't be compensated only by means of thick insulation layers in the building's structure or perfect air-tightness. Therefore additional space heating system is necessary in winter time, although with a very low heating input. Low heating demands is the reason why the heating system can't be a regular hydronic heating with heat emitters in each room, otherwise the building will be overheated. So, renewable heat sources are preferred since they support the idea of sustainable building, which is the passive house, and also can be the best solution when not so much heating energy is needed.

3 RENEWABLE HEATING SOURCES

3.1 Ground source heat pump (GSHP)

GSHP is an installation which uses ground heat as its source of energy for space heating and domestic hot water (DHW) in all kinds of buildings. Although the surface temperature of the ground varies throughout the year depending on the heat gains from the sun, snow cover, precipitations, etc., in the depth of about 10 m the temperature of the ground remains constant independent of the climate. So this renewable energy source never depends on weather or climate conditions, what makes it universal both in warm and cold climates. But GSHP is sufficient when the soil properties allow the equipment to be installed in a proper way. /16/.

GSHP doesn’t need much energy and the output energy can be up to four times more than the input. A typical GSHP consists of 3 main parts: a ground loop of pipes filled with a refrigerant, heat pump itself and a pipe distribution system inside the building. The main principle of its work is that it runs the heat from the lower to a higher temperature, using the vapour compression refrigeration cycle, but reverse. It usually comes in 2 different types: closed-loop and open-loop systems. And the loop can be installed vertically or horizontally. The closed-loop system is installed in the ground while the closed-loop system is installed directly to the ground water either in two drilled wells or in an underground pond. Choosing the right system depends on the ground and the location of the building site. The principle of functioning of GSHP that delivers heat to DHW and ventilation system is shown in figure 8.

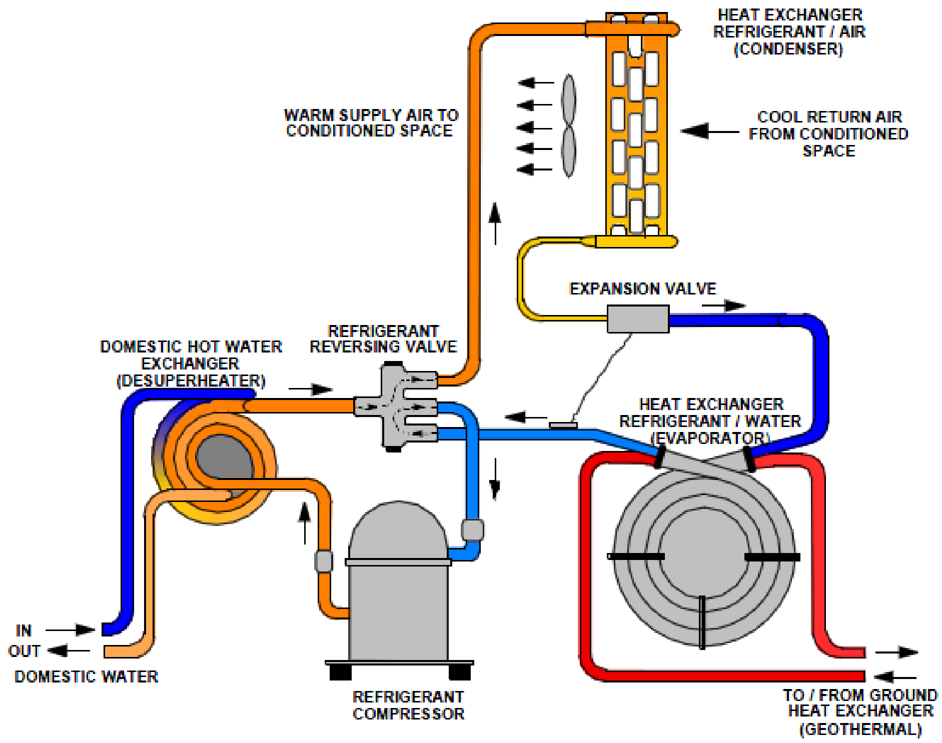


FIGURE 8. GSHP in heating cycle /17/

The first step of the heat pump cycle is when ground loop heat exchanger (evaporator) delivers heat from the ground to the fluid which is running inside the loop. Usually the fluid is a refrigerant, anti-freeze, or water. Then inside the compressor the pressure of the fluid increases and thereby the temperature is rising. This heating energy is transferred into the building for heating purposes. Then the refrigerant returns to the beginning of the cycle through the expansion valve, and the process repeats again. /18/.

GSHP can serve either as a heating source in winter (collects heat from the ground) or as a cooling machine in summer (rejects excessive heat to the ground).

The system efficiency is expressed through the Coefficient of Performance (COP) which shows how many times the output heat is more than the input electrical energy for the GSHP /17/.

Besides the low energy costs of GSHP system, it also doesn't need much maintenance, therefore it has low maintenance costs as well. "The payback period of GSHPs for residential application typically ranges between <10 and 20 years, varying with capital investment costs and a region's fuel prices, and relative fuel price increases "/16/. It is estimated that GSHP can decrease energy consumption up to 25-50%. In the summer the heating of DHW with waste heat from ventilation will be free while in the winter it will be half of the ordinary price. In comparison there are illustrated 3 different types of heating systems in concern to their economy aspect. It is shown in table 5.

TABLE 5. Comparison of various types of heating systems

Compare	Safety	Installation Cost	Operating Cost	Maintenance Cost	Life-Cycle Cost
Combustion-based	A Concern	Moderate	Moderate	High	Moderate
Air-Source heat pump	Excellent	Moderate	Moderate	Moderate	Moderate
GHP	Excellent	High	Low	Low	Low

GSHP can also heat the household water by adding the desuperheater to the heat pump unit. Desuperheater is a heat exchanger which uses the superheated gases that come out of the compressor to heat water. Then this water is delivered to a hot water tank. But in winter there can be needed additional heating of water because the desuperheater can not to be enough. Though nowadays manufacturers offer a triple system, which provides heating, cooling and DHW with a separate heat exchanger. /19/.

It can operate for the whole heating system of a building: space heating, ventilation, and DHW, when equipped with a desuperheater. Besides, it can function as a cooling system in hot summer days. Low operation costs and energy consumption, long life-cycle, universality for every weather conditions, - these are the benefits of GSHP.

3.2 Direct heat storage solar system

This system consists of the thermal solar collector which is operating for direct heat storage. It collects the heat directly to the wall of the dwelling. This solar collector consists of a thin solar absorbtion layer with a phase change material (PCM) covered with a transparent cover. PCM has a melting temperature of 29 °C, and it's the main part of a solar collector which is used for heat storage. "When the PCM undergoes the phase change, it can absorb or release a large amount of energy (~190 kJ/kg) as latent heat" /20/. This DHW solar system generates and stores heat for the purpises of space heating. The wall of a dwelling receives solar heat during daytime and stores it for the night. During the night PCM cools down and solidifies and releases heat which is used for space heating. The main principle of this system is to keep the wall warm with the temperature over 20 °C. The structure of the solar panel is shown in figure 9.

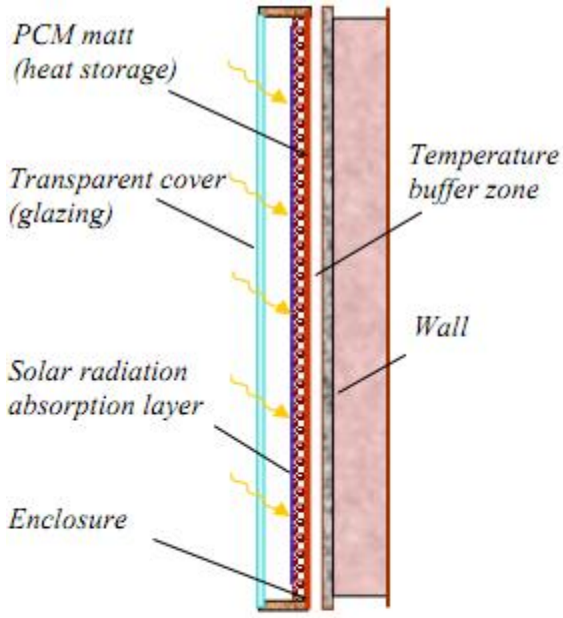


FIGURE 9. Cross section of the DHS collector /20/

The advantages of this system are the following. Firstly there is no any fluid circulation system or additional equipment as heat exchangers, etc. so consequently it has low system costs and it is simple to install. And, in summer it prevents the building from overheating, thus reduces energy demands for cooling. In the case of the passive house it maintains minimal heat losses through the building's structure in addition to the insulation and air-tightness.

3.3 Solar combi-system

The Solar combi-system combines DHW preparation and space heating. This active solar heating system actually consists of the following parts: solar thermal collectors, a hot water storage tank, a secondary water circuit, a DHW heating system, and an air ventilation or heating system. This system is most efficient for the regions with cold climate and large amount of sunny days during the year. /21/. According to the data of Finnish Meteorological Institute, the average duration of sunshine in Helsinki is 1867 hours per year /22/. The typical Finnish schemes of the system's operation is shown in figure 10.

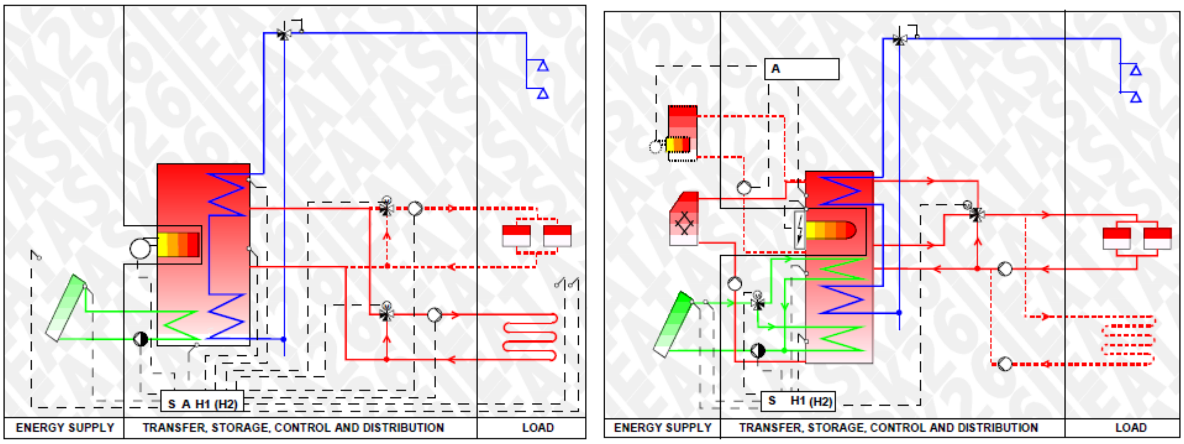


FIGURE 10. Typical solar combi-system /22/

Figure is divided in three parts. On the left side of the figure there are the energy sources, which are the solar collector and the auxiliary energy supply system. In the middle there is a hot water storage tank with heat exchangers and the control system. On the right side there are DHW and space heating distribution systems. Usually such a system consists of 5-10 m^2 of solar collectors and 200-300 liters storage tank which is built into a unit that includes all the equipment for the operation of the whole system: valves, pumps, expansion tanks, control system, etc.

The hot water storage tank is heated by a solar collector with the help of auxiliary energy supply system. The solar combi-system has to supply heating energy both for DHW and for space heating. DHW usually needs temperatures higher than 50 °C, while space heating needs lower temperatures, especially in the case of a passive house.

The solar collector loop usually uses anti-freeze or water. The flow of liquid is driven by a pump, and usually the flow rates are about 0,15 – 1,2 l/min/m^2 /22/. The liquid from the solar collector is distributed through a heat exchanger spiral at the bottom of a storage tank or through an external heat exchanger which is connected to a storage tank by pipes. The space heating distribution system is a controlled radiator system with thermostats or underfloor heating system. This system can be applied either for high heating demands in a building or for low like in passive houses. "In summer an immersed electric heater can supply additional heat to the hot water allowing the boiler to be turned off"/22/. This system can also be combined with air conditioning unit.

"Some studies show that in spite of the low efficiency of the solar combi-systems, the payback time is acceptable due to the fairly high saving of fuel in cold climates"/23/. In cold climate the payback of this system is about 2 years.

Solar combi-systems can be universal. The heat exchanger can be either water-to-water for providing hydronic heating system or water-to-air for heating up the ventilation air. So this system fits the passive house heating demands and decreases energy consumption by using renewable solar energy, although it can have high operation costs since there is pipe distribution system with all its components.

4 HEATING SYSTEMS FOR A PASSIVE HOUSE

Since heating loads of the passive house are very low, the ordinary heating system is not needed, therefore the heating system should be simplified. It is possible if the outer walls and windows have the temperature close to the room air temperature. "Two criteria are to be considered: thermal comfort requirements in regard to radiation asymmetry and the space heating load"/6/. There is a wide variety of heat generation sources being used in passive houses around the world. They are presented in table 6.

Final energy source / system	Conversion / heat generator
Electricity	Compact heat pump unit Air/soil/water–based heat pump Direct electricity (Joule heating)
Fossil fuel	Gas: low temperature /condensing boiler technology (natural gas, liquefied gas) Oil: low temperature /condensing boiler technology, district/on-site heating
Combined heat and power generation	Small CHP Fuel cell District/local heating with/without cogeneration
Regenerative energy sources	Biomass heating/cogeneration Solar thermal system /photovoltaic firewood, wood chips, pellets Liquefied and gaseous biofuels

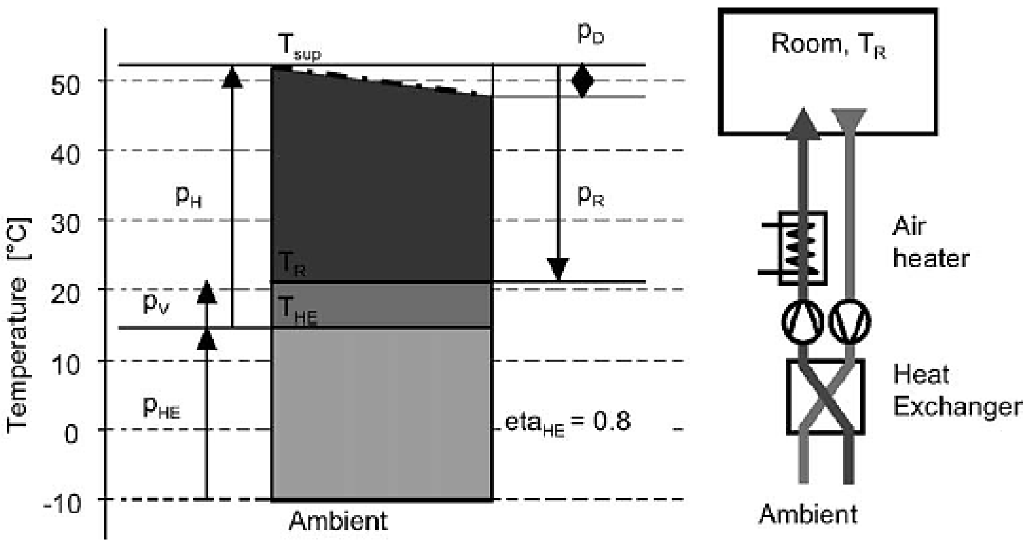
TABLE 6. The main final energy sources that can be used for heat generation in passive houses /7/

In this thesis work 3 different heating systems for a passive house are going to be examined. All the structural features described above are taken into account. Each heating system uses renewable energy sources listed earlier. Each alternative includes the solution for space heating, ventilation, and DHW. But firstly the main principles of each heating system solution for a passive house will be described.

4.1 Ventilation air heating system

As the passive house needs low amount of heating energy, space heating can be provided by ventilation supply air without any additional water heating system.
According to Passivhaus Standard heating demands can be compensated with ventilation air heating but it is not a requirement.

As it was mentioned above the ventilation system must be equipped with a heat recovery unit with high efficiency. Also there should be a backup system for heating the ventilation air. "Space heating demand in a passive house is typically met through passive solar gains (40 – 60 %), internal heat gains (20 - 30%) and the remainder (10 - 40%) needs to be provided from auxiliary heating systems"/2/. Usually the energy sources for this system are biomass, gas and electricity from renewable sources. The air heater is installed right after the heat recovery unit. "Heat may also be delivered via the condenser of an exhaust air heat pump"/6/. The heat delivered to the dwellings and consequently the demanded heating power is shown in figure 11.



p_{HE} heat transfer from heat exchanger

p_H heating power of air heater

p_V part of heating power compensating "ventilation losses"

p_R heat delivered to room by air

p_D heat delivered through duct case (to room)

T_{HE} Air temperature after heat exchanger

T_{sup} Supply air temperature

T_R Room air temperature

FIGURE 11. Heat delivered to the room and required heating power /6/

The heat delivered to the room by air p_R should compensate heat losses due to transmission and infiltration in each room. And, also there are ventilation losses as well which have to be taken into account. So, the heating power of the air heater p_H has to cover heat losses due to transmission, infiltration, and ventilation losses. The supply air temperature of the air which is meant for space heating is limited to 50 °C and when the air heater is off (during the non-heating season) the supply air temperature should be about 17 °C. /6/. With these temperatures it is quiet enough to cover the space heating demands of a passive house. This can be seen in figure 12.

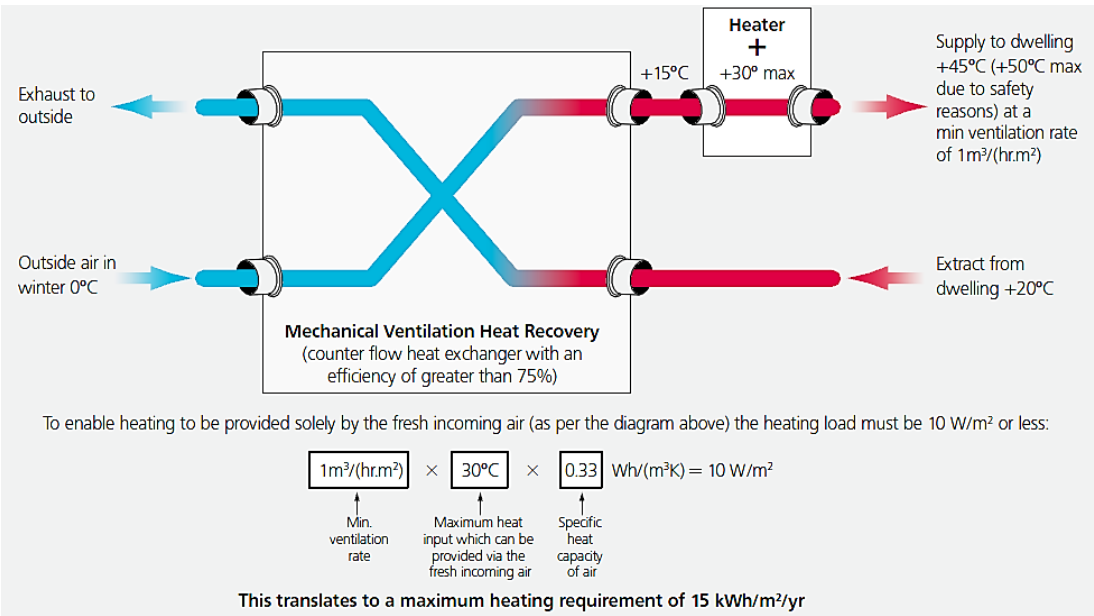


FIGURE 12. Space heating with ventilation air /24/

For a passive house the heating losses can’t be calculated only on the base of designing outdoor temperature. Solar heat gains are sufficient too and have to be taken into account as well. Obviously, the minimum of heat losses occur during the days with high insolation. And, to the contrary, the largest heat losses result from the cold moderate days with overcast sky. They can also occur during the cold and sunny days as well, or there can even be larger heating losses.

“Heat is distributed within the dwelling by the forced air flow due to the ventilation system, by transmission through internal walls, and by convective flows if internal doors are open”/6/. As the heat losses are very low in a passive house, heat transfer between the rooms via transmission through inner walls has the biggest impact on air distribution. And when the doors are open, it increases the air distribution as well. For example, if the air flow rate is about 30 m^3/h with maximum air temperature of 50 °C, it can cover 300 W of heat demands. And if the heat losses of a certain room are smaller than this, the excessive heat can be delivered to another rooms. So the distribution of heat between rooms is not a problem in a passive house, even if the supply air is delivered only into the “clean” spaces. The whole building will be heated anyway due to air distribution via transmission through the inner walls and via convection in the case when the doors are open.

In order to avoid heat losses through ventilation ducts, some parts of the duct system must be insulated. If there is no additional heating coil in the system, the duct areas with warm supply air leading through unheated areas as well as with colder exhaust air leading through heated areas, should be insulated. The temperature drop depending on the duct length and duct air temperature with and without insulation is shown in figure 13.

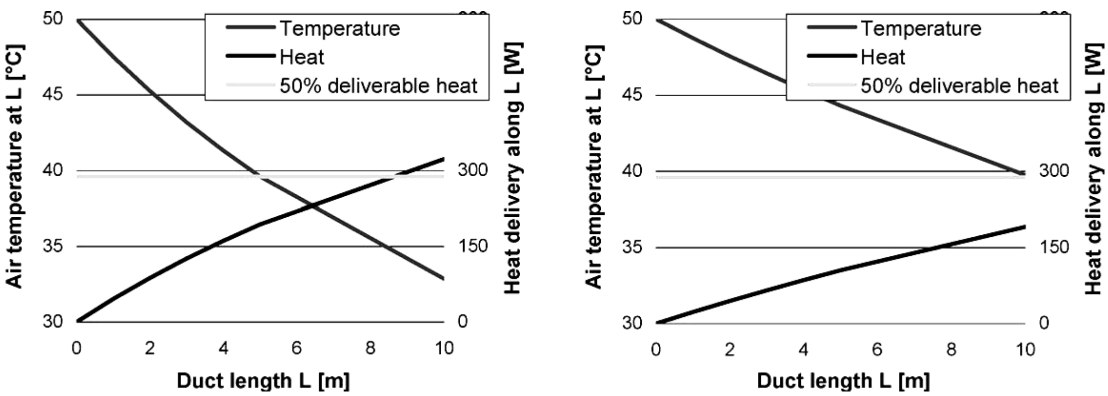


FIGURE 13. Example for the temperature drop along the duct and heat transfer to the room through the duct casing of a supply air channel. Left – duct without insulation. Right – duct with 1 cm insulation with conductivity 0,04 W/mK /6/

Concerning thermal comfort air heating system shows very good results. According to the EN ISO 7730:1995 standard, the vertical temperature gradient should not be more than 3 K on the height from 0,1 m to 1,7 m above the floor level. In dwellings with ventilation air heating this gradient is less than 1 K. It is also should be noted that the risk of draught is very low as well. The percentage of persons dissatisfied (PPD) in this case is below 15 % that is acceptable. /6, p. 1199./

So in this first alternative of the heating system for a passive house the heating source is solar collectors which provide heat for DHW and space heating with ventilation air. The water-to-air heat exchanger is connected to a water storage tank. Also there should be a backup heating source for heating the ventilation air. The best heating source for a backup system is electrical heat pump.

The water-to-air heat exchanger is a unit integrated right into the supply air outlet of the ventilation system. The radiator inside the unit is heated by the hot water which comes out of the hot water storage tank which receives heat from the solar collectors by-turn. When the building is in need of extra heat, the water from the water tank starts to circulate in the water-to-air heat exchanger. The inside air temperature is controlled by a thermostat. Whenever the house reaches the needed inside air temperature, the air stops to be heated. The water-to-air heat exchanger unit is shown in figure 14. And the principle scheme of the whole heating system by the first alternative is shown in figure 15.

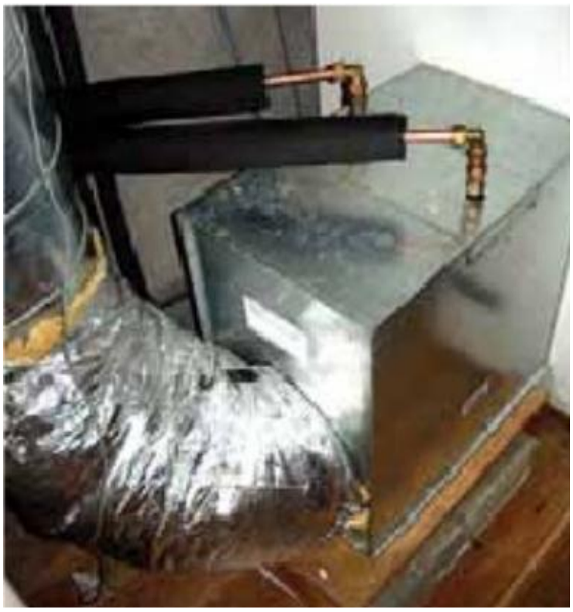


FIGURE 14. Water-to-air heat exchanger unit /2/

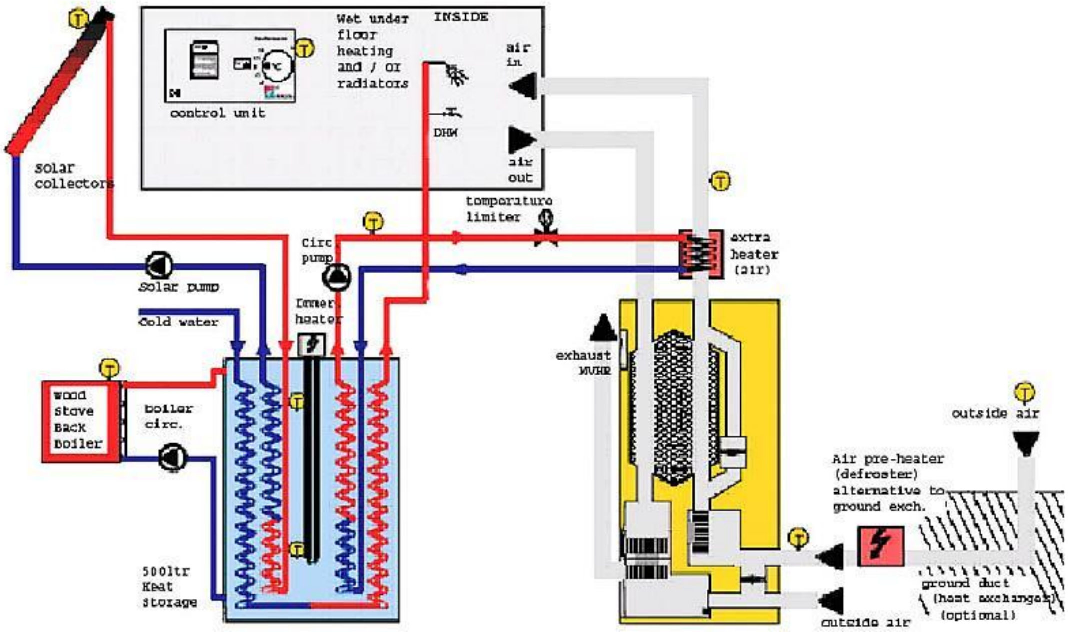


FIGURE 15. Heating system including solar water heating and ventilation air heating /25/

4.2 Underfloor heating system

Underfloor heating can be a good alternative to cover low heating demands in a passive house since it uses low temperature heat distribution.

In the case of underfloor heating the heat emitter is the whole floor itself but not the ordinary radiator placed by the wall. So the heat distribution is from the floor upwards, that reduces the risk of draughts and keeps vertical temperature gradient acceptable. The type of heat distribution of underfloor heating system is radiation and convection. All this provides the prefect thermal comfort for the occupants.

There can be two types of such kind of heating: electrical, using conductive wiring, or hydronic, using piping with water inside and pumps which force the hot water to flow /26/. It is more convenient and reasonable in our case to use hydronic underfloor heating for not to install different energy sources for space heating and DHW.

As every room has its own heat losses, different spacings of the underfloor heating system should be designed for each dwelling. The floor covering material should be taken into account when designing the underfloor heating system, since its resistance has an influence on the heat output of the system. An example of how the floor material affects the heat output is shown in table 7.

TABLE 7. The affect of floor coverings on the heat output /27/

Floor Covering	Floor covering Resistance W/ m²k	Mean Water Temperature	OUTPUT @200 mm pipe spacing Watts m²	OUTPUT @ 300 mm pipe spacing Watts m²
Tile	0.00	35° C	68	52
Carpet (light duty)	0.10	35° C	44	36
Floorboards	0.15	35° C	38	32

The distribution temperatures in underfloor heating systems usually are 30 – 45 °C, that result in the floor surface temperature of about 26 °C /28/. The ideal heat source for such type of heating system is GSHP. The highest COP of heat pump can be reached with flow temperatures of about 35 °C, that exactly corresponds to the underfloor heating temperatures.

So in the second alternative the heating source is GSHP, which provides heat for the underfloor heating system, DHW, and ventilation system. The heat pump transfers water to the hot water storage tank from which the hot water flows to the main heating appliances. The maximum temperature of water in the storage tank is usually about 50 °C. But the temperature needed in the water storage tank must be not less than 60 °C in order to prevent the growth of Legionella. So, for water heating the desuperheater should be added as the power of the heat pump is not enough for providing adequate temperatures for DHW. “A desuperheater is a refrigerant hot gas-to-water heat exchanger that is installed between the compressor and the reversing valve of a space conditioning heat pump”/28/. With the desuperheater temperatures of about 70 °C can be achieved. As the operation of the desuperheater depends on the heat pump (i.e. when the house reaches the desired space temperature, the desuperheater turns off along with the heat pump), therefore an auxiliary heating source is needed. The possible types of auxiliary heaters are described earlier./28/. The heating coil of ventilation system gets heat from the hot water storage tank as well. The operation of the second alternative for the heating system is presented in figure 16.

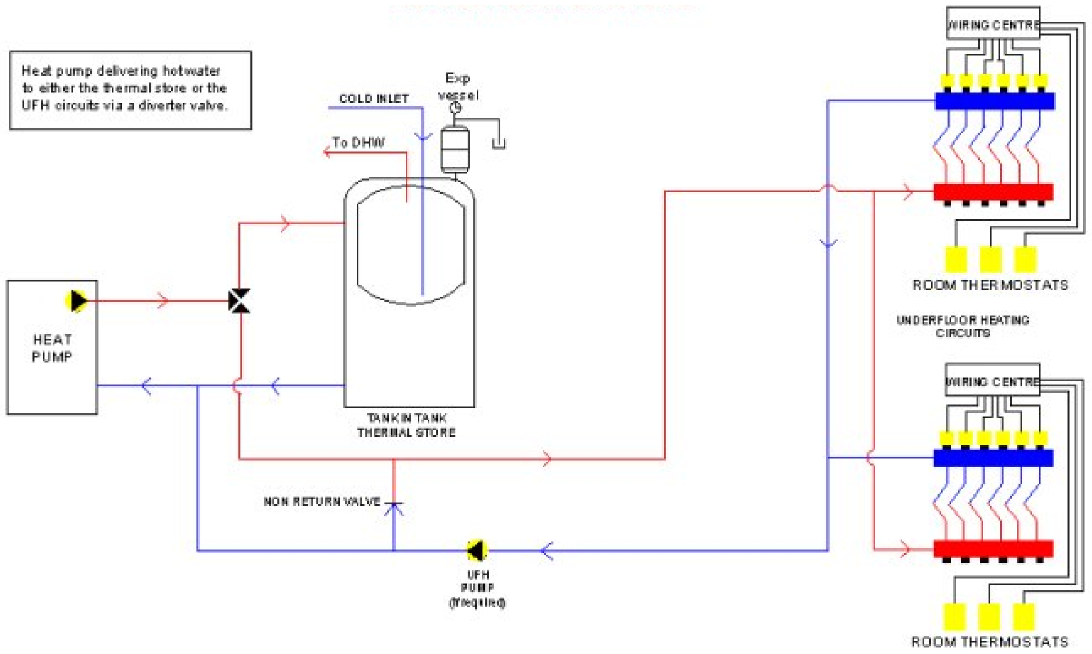


FIGURE 16. Heat pump with thermal store and underfloor heating zone /29/

4.3 Pellet stove and solar combi system

The third alternative is not to design any space heating system in a passive house but to manage it with a pellet stove, placed in a living room, for example.

The fuel for such kind of stove is pellets. It is a sawdust based product pressed into the form of a pellet. /30/. When burnt pellets leave few particle emissions, that's why this type of fuel is considered clean and environmental friendly. It fits perfectly to a passive house idea of a sustainable building. And the stove itself is made of heavy cast iron or steel which conduct and radiate heat off them.

Pellet stoves usually are very efficient (up to 80 – 90%) and have a high BTU content, i.e. high value of energy content. They also don't need a chimney but a small hole to ventilate the flue gases outdoors. Most stoves are equipped with an internal fan which doesn't allow the heat to be kept inside the stove. /30/.

In the case of the passive house a pellet stove can also provide extra heat for a DHW along with solar collectors. It is very sufficient especially when the hot water tank provides heat for the ventilation air. "If there is a need to back up the mechanical heat recovery ventilation (MHRV) the stored hot water will be used to re-heat the fresh air"/2/. A stove approximately of 3 kW heat output can be enough for both space heating and DHW needs in a passive house. Otherwise there is a risk of overheating since the passive house has very low heat losses./2/. They can be controlled by thermostats, which control how many pellets should be out inside the heating chamber, and can have a variable heat output. So "they are ideal for providing top-up heating in low energy houses, where the actual amount of fuel required is minimal"/31/. The principle of operation of the pellet stove is shown in figure 17.

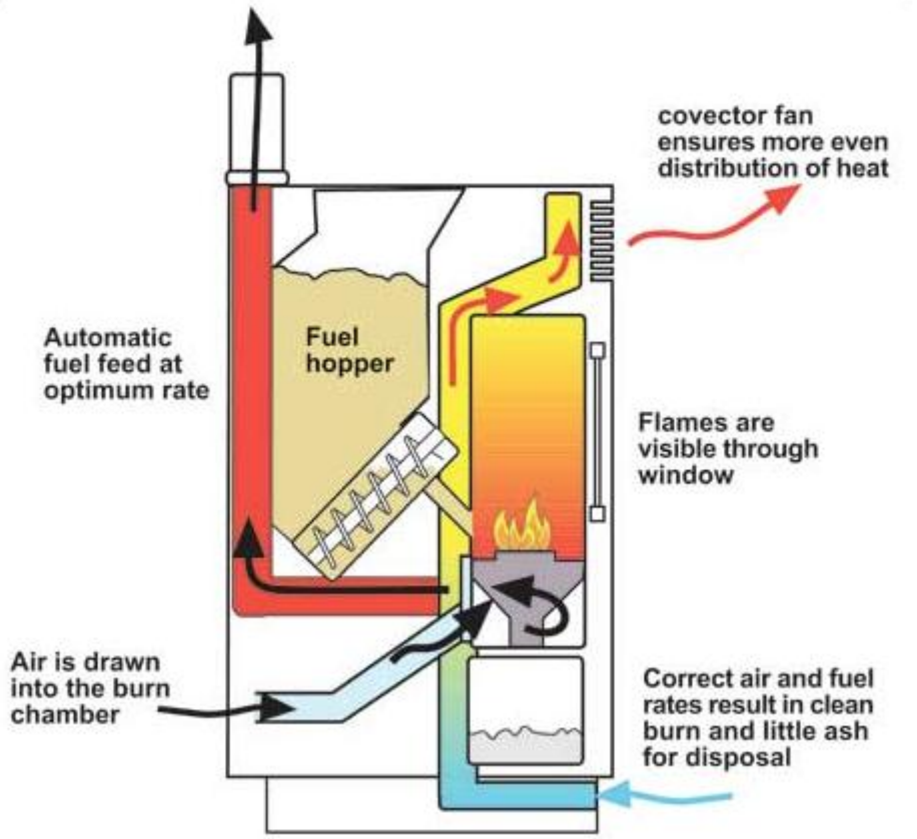


FIGURE 17. Cutaway diagram of a typical pellet stove /31/

The typical pellet stove consists of a hopper, screw feed, heating element, electronic control, suction and convection fans, and a combustion chamber. The hopper usually needs about 25 kg of pellets, that provide heat for 2 – 5 days. The ash is collected in an ash pan, and it usually is 2% of all the fuel volume burnt./31/.

It should be taken into account that the passive house is very air-tight, therefore there should be extra combustion air added for the stove. "Air required for combustion is drawn in through are relatively small diameter duct and expelled through the flue"/31/.

So in this system a pellet stove operates as a space heating source as well as an auxiliary heating source for DHW and ventilation air. It can be used whenever needed during the coldest days in winter, that is very cost effective.

Each of the three alternatives can have its advantages and disadvantages. But the scope of this thesis work is to estimate which of these is the most efficient and reasonable from different points of view. The most important issue is their cost efficiency which depends on the energy demands of each system and their operating costs. On this base it can be estimated in which time there will be a payback of the system. Also the heating system should meet the requirements of Passivhaus Standard and cover the heat losses of the passive house without letting it to overheat. And thirdly it should manage the cold climate challenges.

5 AN EXAMPLE OF A PASSIVE HOUSE

In this thesis work a research comparing three different heating systems for a passive house was made. In order to accomplish an objective comparison, it was necessary to put each system in same conditions, i.e. to attach them to a certain example of a passive house, which already exists. I've chosen a passive house in Lindås near Göteborg, Sweden. The choice was that because the climate conditions in Sweden are quiet similar to that of Finland, so it was built taking into account the specifics of cold climate conditions. And also there could be found a lot of exact information and initial data about this particular house for the further calculations which will be presented further. The view on the district with passive houses in Lindås is shown in figure 18.

FIGURE 18. Twenty terrace houses in four rows /32/

5.1 Influence of solar radiation and glazing

The house is built with south-oriented façade with large windows to get more solar gains. Balconies and eaves make a sufficient shading to protect the house from summer solar overheating. /32/.

The values concerning insolation and window glazing are listed below /33/:

- Average daily insolation: horizontal = 2,84 kWh/m^2
- Average daily insolation: vertical = 2,81 kWh/m^2
- Clearness index = 0,43 Kt
- Window area total = 42 m^2
- Window area: south = 40 m^2
- Window area: north = 2 m^2
- South glazing-to-floor ratio = 33%.

The windows have three panes with two metallic coats and krypton or argon fill. Energy transmittance of the windows is 50%, and light transmittance is 64 – 68%. /34/. This is leading to the following heating losses in the house (mid unit), considering solar gains. The results are presented in figure 19.

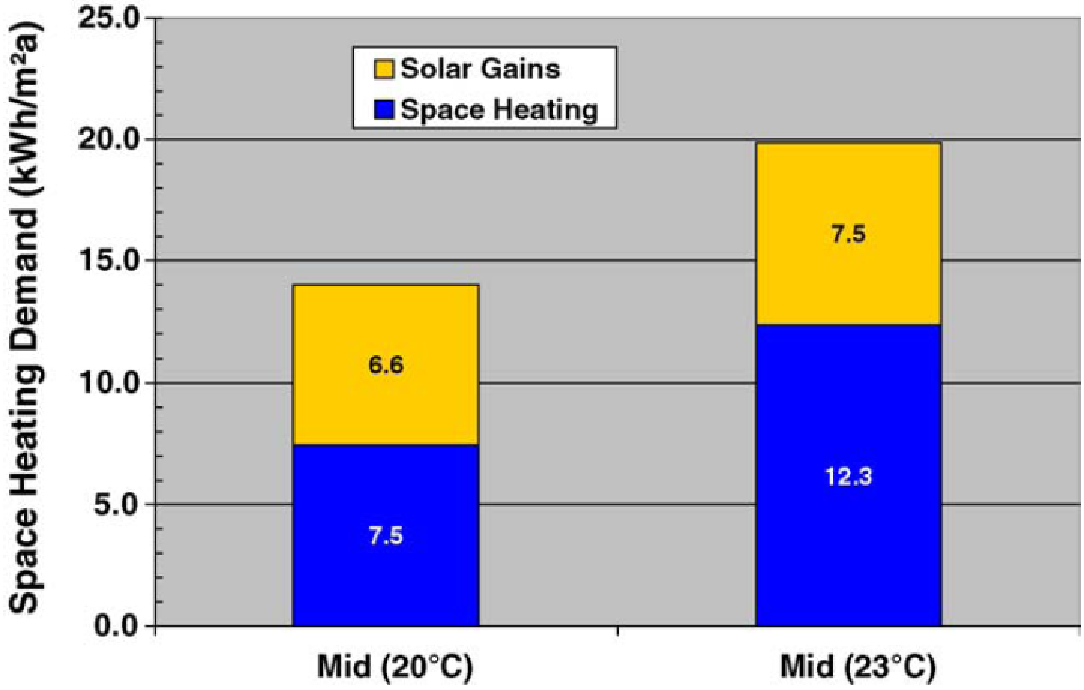


FIGURE 19. Space heating demand and solar gains for a mid unit heated to 20 and 23 °C /32/

As it can be noticed that solar gains cover approximately half of the heating demands of the house. The situation is different for a peak load. The results for peak load are shown in figure 20.

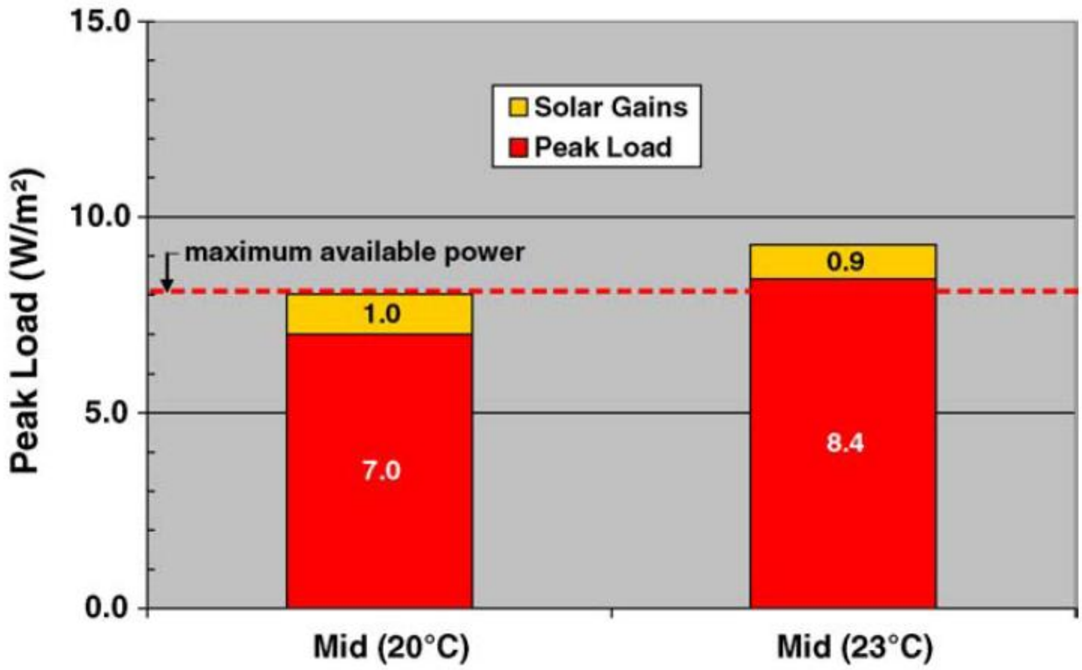


FIGURE 20. Peak load and solar gains for a mid unit heated to 20 and 23 °C /32/

The line represents the maximum available power for the electric resistance heating in the supply air. “The peak occurs usually in early morning after a cold night when potential solar gains stored in the building mass already have been used”/34/.

5.2 The building envelope

The house has a living area of 120 m^2 (mid unit) and 124 m^2 (end unit) and has two stories. All the exterior walls are highly insulated as well as the roof and floor. The building envelope consists of: external wall with frame construction with insulation layer of 430 mm, roof made of masonite beams with insulation thickness of 480 mm, and floor of concrete slab with 250 mm of insulation./34/. The structure of the building envelope is shown in figure 21.

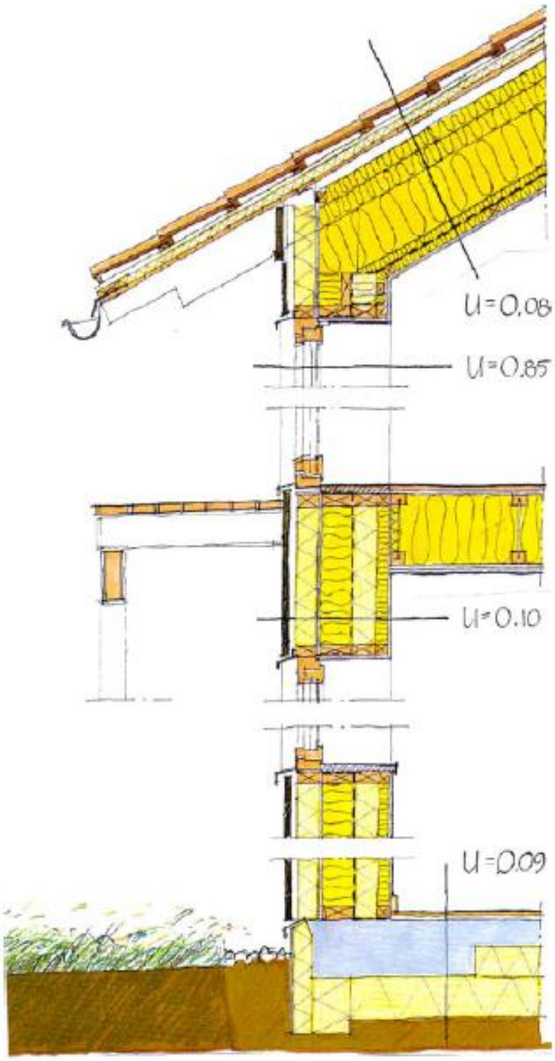


FIGURE 21. Cross-section of the building envelope /32/

The air-tightness at 50 Pa was measured as 0.3 l/s per m^2. The U-values for all the components of the structure are shown in table 8.

TABLE 8. U-values of the building envelope /32/

Building envelope	*U*-value (W/m^2 K)
Exterior walls	0.10
Roof	0.08
Ground floor	0.11
Windows, average	0.85
Door	0.80
Average, building envelope	0.16

Other important values of the house parameters per unit are the following /33/:

- Volume = 330 m^3
- Footprint = 66 m^2
- Heated floor area = 120 m^2
- Ceiling area = 66 m^2
- External wall area = 170 m^2.

5.3 Space heating and ventilation

Space heating is provided by heating the ventilation air with heat recovery unit. The efficiency of heat recovery unit is 80%. In summer it can be turned off, using automatic bypass. Also heating demands are covered by heat gains from the occupants and household appliances. Heat gains from the occupants are about 1200 kWh/a, and those from the electric appliances are about 2900 kWh/a. And the rest of the heating demands are covered with electric resistance heating of the supply ventilation air. It has a power of 900 W per unit, approximately 8 W/m^2. /34/. The air change rate is 0.5 h^{-1} at 50 Pa. /33/.

5.4 Domestic hot water

The water is heated by solar collectors installed on the roof, with a covering area of 5 m^2. It is then stored in a 500 l storage tank which is additionally heated by an electric immersion heater.

5.5 Energy demands

The energy consumed was monitored after the house was already built. It turned out to be more than that calculated before. The energy demands vary a lot: between 45 and 97 kWh/m^2a, and the average is 68 kWh/m^2a. This energy includes energy for space heating, domestic hot water, and electricity. Annual heating demand for ventilation is 9 kWh/m^2a /33/. The energy use for all these needs is shown in table 9.

TABLE 9. Monitored energy use /32/

Monitored energy use (kWh/m^2 a)	
Heating of space and ventilation air (electricity)	14.3
Domestic hot water heating; electricity	15.2
Fans and pumps	6.7
Lighting and household appliances	31.8
Delivered energy demand	68.0
Domestic hot water heating; solar energy	8.9
Total monitored energy demand	76.9

So there was assumed that the exact house is situated in Helsinki, Finland. And each heating system was inspected having been applied to this house. Some of these values were used for the calculations.

6 ENERGY NEEDS FOR HEATING IN THE PASSIVE HOUSE IN HELSINKI

One of the criteria for comparing the three systems is energy needs of a building with each of the systems. The final value is consumption of purchased energy of a building, which includes energy needs for heating, cooling, and also electrical energy needs for heating, ventilation, cooling, lighting, and electrical appliances. The calculations are based on National Building Code of Finland, Part D5 “Calculation of power and energy needs for heating in buildings". The calculations were carried out with Microsoft Excel, and the results are presented in the appendices.

The consumption of purchased energy of buildings:

$$E_{purchased} = Q_{heating} + W_{heating} + W_{ventilation} + Q_{cooling} + W_{cooling} + W_{appliances} + W_{lighting} \quad (1)$$

where:

E_{purch} - building's consumption of purchased energy, kWh/(m^{2}a)

$Q_{heating}$ - heat energy consumption of the heating system, kWh/(m^{2}a)

$W_{heating}$ - electric energy consumption of the heating system, kWh/(m^{2}a)

$W_{ventilation}$ - electric energy consumption of the ventilation system, kWh/(m^{2}a)

$Q_{cooling}$ - heat energy consumption of the cooling system (district cooling), kWh/(m^{2}a)

$W_{cooling}$ - electric energy consumption of the cooling system, kWh/(m^{2}a)

$W_{appliances}$ - electric energy consumption of household or consumer appliances, kWh/(m^{2}a)

$W_{lighting}$ - electric energy consumption of the lighting system, kWh/(m^{2}a).

6.1 Energy consumption of a heating system

Energy needs for heating include energy consumption of space heating, heating the ventilation heating, heating of DHW, excluding the energy needed for DHW heating using solar collectors.

The net energy need for space heating:

$$Q_{heating\ spaces,\ net} = Q_{space} - Q_{int.\ heat} \quad (2)$$

$$Q_{heating\,spaces} = \frac{Q_{heating\,spaces,net}}{\eta_{heating\,spaces}} + Q_{distribution,out} \quad (3)$$

where:

$Q_{heating,spaces,net}$ - net energy need for space heating, kWh/a

$Q_{distribution,out}$ - heat loss into a non-heated room during heat distribution, kWh/a

$\eta_{heating,spaces}$ - heating system efficiency in heating spaces, -

$$Q_{heating} = \frac{Q_{heating\,spaces} + Q_{heating,iv} + Q_{DHW} - Q_{solar}}{\eta_{production}} \quad (4)$$

where:

η_{prod} efficiency of heating energy production in heating spaces, ventilation, and domestic hot water

Q_{solar} domestic hot water produced using solar collectors

6.1.1 Energy needs for space heating

Energy needs for space heating consist of heat losses of a building envelope, through air leakages, heating of the supply and make-up air in a space.

Energy need for space heating is calculated according to formula /5/.

$$Q_{space} = Q_{conduct} + Q_{air\ leakage} + Q_{supply\ air} + Q_{make\text{-}up\ air} \quad (5)$$

where:

Q_{air} - leakage air leakage heat loss, kWh

Q_{supply} - air heating of supply air in a space, kWh

$Q_{make\text{-}up\ air}$ - heating of make-up air in a space, kWh

$$Q_{conduct} = Q_{exterior\ wall} + Q_{ceiling} + Q_{floor} + Q_{window} + Q_{door} + Q_{thermal\ bridges} \quad (6)$$

It should be estimated that $Q_{thermal\ bridges}$ is approximately equal to zero, because in passive houses heat losses due to thermal bridges are very low.

Heat losses for each component of the building structure, i.e. exterior walls, ceiling, windows, and exterior doors:

$$Q = \Sigma U_i A_i (T_{ind} - T_{outd}) \Delta t / 1000 \quad (7)$$

where:

Q - conduction heat loss through a building component, kWh

U_i - thermal transmittance factor for a building component, $W/(m^2K)$

A_i - floor area of a building component, m^2

T_{ind} - indoor air temperature, °C

T_{outd} - outdoor air temperature, °C

Δt - time period length, h

1000 - factor for converting the denomination to kilowatt hours.

Energy $Q_{air\ leakage}$ for heating air flowing in and out of buildings due to leaks:

$$Q_{air\ leakage} = \rho_i \cdot c_{pi} \cdot q_{v,air\ leakage} (T_{ind} - T_{outd}) \Delta t / 1000 \quad (8)$$

where:

Q_{air} - leakage energy required to heat air leakage, kWh

ρ_i - air density, 1.2 kg/m^3

c_{pi} - specific heat capacity of air, 1 000 Ws/(kgK)

$q_{v,\ air\ leakage}$ - air leakage flow, m^3/s

$$q_{v,air\ leakage} = \frac{q_{50}}{3600 \cdot x} A = \frac{0,3 \cdot 3,6}{3600 \cdot 24} 302 = 0,004\ m^3/s \quad (9)$$

where:

q_{50} - air leakage number of the building shell, $m^3/(h\ m^2)$

A - surface area of the building shell (including floor), m^2

x - factor, which is: 35 for one-storey buildings; 24 for two-storey buildings; 20 for three and four-storey buildings, and 15 for five-storey buildings or higher

3600 - factor which converts air flow from unit m^3/h to unit m^3/s

6.1.2 Energy needs for heating the supply air in a space

The heating of supply air in a space:

$$Q_{iv,supply\ air} = \rho_i\ c_{pi}\ t_d\ t_V\ q_{v,supply}\ (T_{ind} - T_{sp})\ \Delta t/1000 \quad (10)$$

where:

$Q_{iv,supply\ air}$ – energy required to heat supply air for a space, kWh

$q_{v,supply\ air}$ - supply air flow, m^3/s

t_d - ventilation system's mean daily running time ratio, h/24h

t_v - ventilation system's weekly running time ratio, days/7 days (day=24 h)

The net heating energy need for ventilation:

$$Q_{iv} = \rho_i \cdot c_{pi} \cdot t_d \cdot t_V \cdot q_{v,supply}(T_{ib} - T_{recov})\Delta t/1000 \quad (11)$$

where:

Q_{iv} - net heating energy need for ventilation, kWh

$q_{v,\ supply}$ - supply air flow, m^3/s

T_{ib} - inblown air temperature, °C

T_{recov} - temperature after heat recovery device, °C

As the heating energy for ventilation is provided by solar energy, it is not taken into account.

The supply air temperature after heat recovery:

$$T_{recov} = T_{outd} + \eta_{t,a}\ (T_{ind} - T_{outd}) \quad (12)$$

Supply air flow rate

For calculating the supply air flow rate $q_{v,supply}$ in the house there were used the regulations of National Building Code of Finland, Part D2 “Indoor Climate and Ventilation of Buildings”. According to D2, the supply air flow rate is 6 l/s per person in dwelling rooms (in this case living rooms and bedrooms). The layouts of the house are shown in figure 22.

As the ventilation system is running year round, therefore ventilation system’s mean daily and weekly running time ratios t_d and t_V are equal to one each.

FIGURE 22. Layouts of the house /33/

As the house is for 3 families with 2 adults and 2 children, it can be assumed that each unit is occupied with 4 persons, 12 persons overall.

$q_{v,supply}$ (main floor) = (6 l/s · 4)·3 = 72 l/s;

$q_{v,supply}$ (upper floor) = (15 l/s + 10 l/s + 10 l/s)·3 = 105 l/s;

$q_{v,supply}$ = 72 l/s + 105 l/s = 177 l/s = 0,177 m^3/s.

6.1.3 Heat loads

Heat load energy recovered for heating:

$$Q_{int.heat} = \eta_{heat} Q_{heat\ load} \quad (13)$$

where:

$Q_{int.heat}$ - building's heat load energy recovered for heating, kWh

η_{heat} - degree of heat loads recovered by month, -

$Q_{heat\ load}$ - a building's heat load, i.e. heat energy released into a building by means other than regulating devices, kWh

Heat loads from different activities:

$$Q_{heat\ load} = Q_{person} + Q_{electric} + Q_{solar} + Q_{DHW,circ} + Q_{DHW,tank} \quad (14)$$

where:

Q_{person} - heat energy emitted by a person, kWh

$Q_{electric}$ - heat loads released into a building from lighting and electrical appliances, kWh

Q_{solar} - solar radiant energy coming into the building through windows, kWh

$Q_{DHW,circ}$ - loss from domestic hot water circulation, kWh/a

$Q_{DHW,tank}$ - loss from domestic hot water storage, kWh/a

From the initial data:

Q_{person} = 1200 kWh/a;

$Q_{electric}$ = 2900 kWh/a.

Solar radiant energy entering the building through windows:

$$Q_{solar} = \Sigma G_{radiant,horizontal} F_{direction} F_{transmittance} A_{win}\, g = \Sigma G_{radiant,vertical} F_{transmittance} A_{win}\, g \quad (15)$$

where:

Q_{solar} - solar radiant energy entering the building through the windows, kWh/month

$G_{radiant,\ horizontal}$ - total solar radiant energy on a horizontal surface per area unit, kWh/(m^2unit)

$G_{radiant,\ vertical}$ - total solar radiant energy on a vertical surface per area unit, kWh/(m^2unit)

$F_{direction}$ - conversion factor for converting the total solar radiant energy on a horizontal surface to total radiant energy on a vertical surface by compass direction,-

$F_{transmittance}$ - total correction factor for radiation transmittance, -

A_{win} - surface area of a window opening (including frame and casing), m^2

g - transmittance factor for total solar radiation through a daylight opening, -.

The total correction factor for radiation transmittance:

$$F_{transmittance} = F_{frame}\ F_{curtain}\ F_{shade} \quad (16)$$

where:

$F_{transmittance}$ - total correction factor for radiation transmittance, -

F_{frame} - frame factor, -

$F_{curtain}$ - curtain factor, -.

F_{shade} - correction factor for shades, -.

Frame factor F_{frame} can be assumed 0,75 as no detailed data was provided. Curtain factor $F_{curtain}$ = 0,8 according to table 5.1 /35/

The correction factor for shades F_{shade}:

$$F_{shade} = F_{environment}\ F_{top\ shade}\ F_{side\ shade} \quad (17)$$

where:

F_{shade} - correction factor for shades, -

$F_{environment}$ - correction factor for horizontal shades in the environment (e.g. terrain, surrounding buildings, and trees), -

F_{top} - shade correction factor for shade provided by horizontal structures above a window,-

F_{side} - shade correction factor for shade provided by vertical structures on the side of a window,-.

The correction factor for the environment is equal to 1 as there are no environment shades on the site. The correction factor for top shade $F_{top\ shade}$ during heating season is 0,8 and 0,85 for north and south oriented windows respectively. And the correction factor for side shade $F_{side\ shade}$ during heating season is 0,98 and 0,85 for north and south oriented windows respectively. /35, table 5.3 and 5.4/

Then F_{shade} for north and south oriented windows respectively:

$F_{shade} = 1 \cdot 0,8 \cdot 0,85 = 0,68$

$F_{shade} = 1 \cdot 0,98 \cdot 0,85 = 0,83$

The total correction factor for radiation transmittance for north and south oriented windows respectively:

$F_{transmittance} = 0,75 \cdot 0,8 \cdot 0,68 = 0,41$

$F_{transmittance} = 0,75 \cdot 0,8 \cdot 0,83 = 0,50$

The circulation pipe heat loss:

$$Q_{DHW,circ} = \frac{W_{DHW,circ}}{1000} L_{DHW} t_{DHW} 365 + W_{DHW,heating} n_{heating\,device} \quad (18)$$

where:

$W_{dhw,\,circ}$ - specific power of DHW circulation pipe heat loss, W/m

L_{dhw} - length of the DHW circulation pipe, m

t_{dhw} - running time of the domestic hot water circulation pump, h/day

$W_{dhw,\,heating}$ - specific power of heaters connected to the circulation pipe for domestic hot water, W/pc.

$n_{heating\ device}$ - number of heaters connected to the circulation pipe for domestic hot water, pcs.

The specific power of the circulation pipe $W_{DHW,circ}$ is assumed 40 W/m. The specific length of the circulation pipe L_{DHW} is 0,043 m/m^2 /35, table 6.5/. Running time of domestic hot water circulation pump t_{DHW} is 24 h, as the pump runs permanently.

According to initial data the specific power of a an electric immersion heater connected to the circulation pipe of DHW $W_{DHW,heating}$ is 15,2 $kWh/m^2 \cdot 360$ m = 5472 kWh/a.

Then the circulation pipe heat loss:

$$Q_{DHW,circ} = \frac{40}{1000}(0{,}043 \cdot 360) \cdot 24 \cdot 365 + 5472 \cdot 1 = 10896\ kWh/a$$

Heat loss from domestic hot water storage $Q_{DHW,tank}$ is 850 kWh/a assuming that the hot water storage tank is insulated with 100 mm insulation /35, table 6.3b/.

The degree of heat loads recovered:

$$\eta_{heat} = \frac{1-\gamma^{a}}{1-\gamma^{a+1}} \quad (19)$$

where:

η_{heat} - degree of heat loads recovered by month, -

γ - heat load to heat loss ratio, -

a - is a numerical parameter, -

$$a = 1 + \frac{\tau}{15} \tag{20}$$

where:

τ - building's time constant, h

$$\tau = \frac{C_{build}}{H} \tag{21}$$

where:

C_{build} - building's interior effective thermal capacity, Wh/K

H - building's specific heat loss (total specific heat loss due to conduction, heating of air leakage, make-up air, and supply air in a space), W/K

The specific heat loss H of the house:

$$H = \frac{Q_{space}}{(T_{ind} - T_{outd})\Delta t} 1000 \tag{22}$$

Building's interior effective thermal capacity $C_{build,spec}$ is 70 Wh/(m^{2}K) /35, table 5.5/. Then

C_{build} = 70 Wh/(m^{2}K) · 180 m^2= 12600 Wh/k.

The ratio γ between $Q_{heat\ load}$ and heat loss Q_{space}:

$$\gamma = \frac{Q_{heat\ load}}{Q_{space}} \tag{23}$$

Heating system efficiency in heating spaces $\eta_{heating\ spaces}$ for ventilation heating is 0,89 /35, table 6.1/. $Q_{distribution,out}$ is equal to zero as there is no on-site heat production and no heat is distributed out.

6.1.4 Energy needs for heating DHW

The energy consumption for heating domestic hot water from heat production to water point according to initial data:

$Q_{heating,DHW}$ = (15,2 + 8,9) kWh/m^{2}a · 360 m^2 = 8676 kWh/a

Heating domestic hot water with solar energy according to initial data:

$Q_{solar,\ DHW}$ = 8,9 kWh/m^{2}a · 360 m^2 = 3204 kWh/a.

As in the first alternative the house needs heating energy for ventilation and domestic hot water, then the heating system energy consumption is:

$$Q_{heating} = Q_{heating,spaces} + Q_{heating,DHW} - Q_{solar,DHW} \quad (24)$$

6.1.5 Electric energy consumption

Electric energy consumption of the heating system $W_{heating}$ according to initial data is:

$W_{heating}$ = 14,3 kWh/m^{2}a · 360 m^2 = 5148 kWh/a.

Electric energy consumption of household or consumer appliances and lighting $W_{appliances\ and\ lighting}$ according to initial data:

$W_{appliances\ and\ lighting}$ = 31,8 kWh/m^{2}a · 360 m^2 = 11480 kWh/a. /35/

7 HEATING POWER FOR THE PASSIVE HOUSE IN HELSINKI

In order to choose certain equipment for the three heating systems the heating power for the house should be calculated. According to the heating power the equipment is chosen by its heat output. The calculations are based on National Building Code of Finland, Part D5 “Calculation of power and energy needs for heating in buildings”. The power is calculated according to the design temperatures.

Heating power need of a building:

$$\Phi_{heating} = \frac{\Phi_{room\ heating}}{\eta_{room\ heating}} + \frac{\Phi_{supply\ air\ battery}}{\eta_{supply\ air}} + \frac{\Phi_{DHW}}{\eta_{DHW}} \quad (25)$$

where:

$\Phi_{heating}$ building’s heating energy need, W

Φ_{room} heating room heating power need, W

$\Phi_{supply\ air}$ battery heating power need for a ventilation supply air after-heater battery, W

Φ_{dhw} power required to heat domestic hot water, W

η_{room} heating efficiency of a room heating system under design conditions, -.

$\eta_{supply\ air}$ efficiency of a ventilation supply air heating system under design conditions, -

η_{dhw} efficiency of a domestic hot water heating system under design conditions, -.
All the efficiency values can be assumed to be 0,9.

7.1 Heating power need for space heating

The heating power required to heat the spaces consists of heat losses through the building envelope, air leakages, heating power to heat suuply and make-up air.
The heating energy need for heating spaces:

$$\Phi_{space} = \Phi_{cond} + \Phi_{air\ leakage} + \Phi_{\ supply\ air} + \Phi_{make\text{-}up\ air} \quad (26)$$

where:

Φ_{space} - heating power required to heat spaces, W

$\Phi_{conduct}$ - conduction heat loss through the building shell, W

$\Phi_{air\ leakage}$ - air leakage heat loss, W

Φ_{supply} - air power for heating supply air in a space, W

$\Phi_{make\text{-}up\ air}$ - power for heating make-up air in a space, W

Heating power for conduction:

$$\Phi_{conduct} = \Phi_{exterior\ wall} + \Phi_{ceiling} + \Phi_{floor} + \Phi_{window} + \Phi_{door} + \Phi_{thermal\ bridges} \quad (27)$$

The heat losses of building components are calculated for each component, i.e. for exterior walls, ceiling, floor, windows, exterior doors:

$$\Phi = \Sigma U_i A_i \ (T_{ind} - T_{outd,\ design}) \quad (28)$$

$\Phi_{exterior\ wall} = 0{,}1\ W/m^2K \cdot 236\ m^2 \cdot (21 - (-26))°C = 1109{,}2\ W$

$\Phi_{ceiling} = 0{,}08\ W/m^2K \cdot 198\ m^2 \cdot (21 - (-26))°C = 744{,}5\ W$

$\Phi_{floor} = 0{,}11\ W/m^2K \cdot 198\ m^2 \cdot (21 - (-26))°C = 1023{,}7\ W$

$\Phi_{window} = 0{,}85\ W/m^2K \cdot 42\ m^2 \cdot (21 - (-26))°C = 1677{,}9\ W$

$\Phi_{door} = 0{,}8\ W/m^2K \cdot 12\ m^2 \cdot (21 - (-26))°C = 451{,}2\ W$

$\Phi_{thermal\ bridges}$ is assumed to be zero, as thermal bridges in a passive house are minimal.

$\Phi_{conduct} = 1109{,}2 + 744{,}5 + 1023{,}7 + 1677{,}9 + 451{,}2 = 5006{,}5$ W.

The power required for heating air leakages:

$$\Phi_{air\ leakage} = \rho_i c_{pi} q_{v\ air\ leakage}(T_{ind} - T_{outd,design}) \quad (29)$$

where:

$\Phi_{\ air\ leakage}$ - power required for heating air leakages, W

T_{ind} - indoor air temperature, °C

$T_{outd\ design}$ - design outdoor air temperature, °C

$\Phi_{air\ leakage}$ = 1,2 kg/m^3 · 1000 Ws/(kgK) · 0,004 m^3/s · (21 – (-26)) °C = 225,6 W.

Power required for heating supply air in a space:

$$\Phi_{supply\ air} = \rho_i c_{pi} q_{v,\ supply\ air} (T_{ind} - T_{ib}) \quad (30)$$

where:

$\Phi_{supply\ air}$ - power required for heating supply air in a space, W

$\Phi_{supply\ air}$ = 1,2 kg/m^3 · 1000 Ws/(kgK) · 0,177 m^3/s · (21 – 18) °C = 637,2 W.

The power required for heating make-up air $\Phi_{make\text{-}up\ air}$ is assumed to be zero as passive house is extremely air-tight.

Φ_{space} = 5006,5 + 225,6 + 637,2 = 5869,3 W.

7.2 Heating power need for ventilation system

The heating power required for the ventilation system of the whole building:

$$\Phi_{vent} = \rho_i c_{pi} q_{v,supply}(T_{ib} - T_{recov,design}) \quad (31)$$

where:

Φ_{vent} - power of ventilation heater battery, W

$T_{recov,\ design}$ - temperature after heat recovery device, °C

The supply air temperature after heat recovery:

$$T_{recov,design} = T_{outd,design} + \eta_{t,design} (T_{ind} - T_{outd,design}) \quad (32)$$

where:

$\eta_{t,design}$ - supply air temperature ratio in heat recovery under design conditions

$T_{recov,design}$ = -26 + 0,8 (21 – (-26)) = 11,6 °C

Φ_{vent} = 1,2 kg/m^3 · 1000 Ws/(kgK) · 0,177 m^3/s · (18 – 11,6) = 1359,4 W.

7.3 Heating power need for DHW

The power required for heating domestic hot water:

$$\Phi_{DHW} = \rho_v c_{pv} q_{v,\ dhw}(T_{dhw} - T_{cw}) + \Phi_{DHW,circloss} \quad (33)$$

where:

Φ_{dhw} - power required for heating domestic hot water, kW

ρ_v - water density, 1 000 kg/m^3

c_{pv} - specific heat capacity of water, 4.2 kJ/kgK

$q_{v,\ dhw}$ - maximum normal flow of domestic hot water, m^3/s

T_{dhw} - domestic hot water temperature, °C

T_{cw} - domestic cold water temperature, °C

$\Phi_{dhw,circloss}$ - power required by the DHW circulation pipe, kW

The heating power need for the circulation pipe heat loss:

$$\Phi_{cw,\ circloss} = \rho_v c_{pv} q_{v,\ dhw,\ circ} (T_{dhw} - T_{dhw,\ circ,\ return}) \tag{34}$$

where:

$\Phi_{dhw,circloss}$ - power required by the DHW circulation pipe, kW

$\Phi_{dhw,circloss}$, - spec specific power required by DHW circulation pipes, kW/m^2

A - net heated area of a building, m^2

$q_{v,\ dhw,\ circ}$ - designed flow of domestic hot water in circulation pipes, m^3/s

T_{dhw} - domestic hot water temperature, °C

$T_{dhw,\ circ}$, - return temperature of the return water in the DHW circulation pipe, °C

$\Phi_{cw,\ circloss}$ = 1000 kg/m^3 · 4,2 kJ/kgK · 0,0005 m^3/s · 5 °C = 10,5 W

Φ_{DHW} = 1000 kg/m^3 · 4,2 kJ/kgK · 0,0026 m^3/s · 50 °C + 10,5 W = 556,5 W

$$\Phi_{heating} = \frac{5969{,}3W}{0{,}9} + \frac{1359{,}4W}{0{,}9} + \frac{556{,}5W}{0{,}9} = 8771{,}3W$$. /35/

8 ECONOMICAL CALCULATIONS

For comparing the profitability of the three heating systems, capital and operational costs should be estimated for each of them. Capital costs include the prices of the equipment that makes the difference for each heating system and its installation costs. Operational costs consist of maintenance costs, costs of the electricity consumed and the costs of fuel in the case of the pellet stove. Also there should be taken into account the bank loan interest of Finland, that is 2.21 % /36/. Economical calculations were made on the basis of the bachelor’s thesis of Kaydalova N. and Kryukov V. /37/.

8.1 The costs of the ventilation air heating system

Capital costs:

$$C = c_{hc} + c_{sc} + c_{he} + c_{ih} + c_i \quad (35)$$

where:

c_{hc} – the price of the heating coil for ventilation air heating – 1067 € /38/

c_{sc} – the price of the solar collectors – 2826 € /39/

c_{he} – the price of water-to-air heat exchanger – 195 € /40/

c_{ih} – the price of the backup immersion heater – 143 € /41/

c_i – installation costs, which are assumed as 15% of the solar collectors price – 424 €.

C = 1067 + 2826 + 195 + 143 + 424 = 4655 €

Operational costs can be assumed as 3% of capital costs:

O = 0,03 · 4655 = 140 € per year.

8.2 The costs of underfloor heating system

The heat pump chosen according to the heating demands of the building is AHS-G-8I - AHS ground source heat pump 8 kW.

Capital costs:

$$C = c_{uh} \cdot A_h + c_{hp} + c_{ghe} \cdot L + c_{dsh} + c_i \quad (36)$$

where

c_{uh} – the price of the underfloor heating per m^2 of space – 35 €/m^2 /42/

A_h – heating area, m^2

c_{hp} – the price of the ground source heat pump – 8320 € (including the installation costs) /43/

c_{ghe} – the price of the ground heat exchanger – 3 €/m

L – length of the ground heat exchanger, m, that can be calculated according to the formula:

$$L = \frac{Q_a \cdot 0,6}{q_s}, \quad (37)$$

where:

Q_a – annual energy consumption, kWh

0,6 - share of energy got from the ground according to COP1 = 2,5

q_s - specific heat flow through 1 meter of the pipe ≈ 50 kWh/m

$$L = \frac{14000 \cdot 0{,}6}{50} = 168 \text{ m}$$

c_{dsh} – the price of desuperheater – 539 € /44/

c_i – installation costs, which are assumed as 15% of the price of the underfloor heating – 1932 €

C = 35 · 368 + 8320 + 3 · 168 + 539 + 1932 = 24175 €

Operation costs:

$$O = m + c_e \tag{38}$$

where:

m – maintenance costs, that can be assumed 3% from the capital costs – 667 €

c_e – the price of the electricity, €, that can be calculated according to the formula:

$$c_e = \frac{Q_a \cdot p_e}{\eta_{a.hp}}, \tag{39}$$

where:

p_e – the price of energy consumed – 4,49 c/kWh /45/

$\eta_{a.hp}$ – annual efficiency of ground source heat pump – 3,5 /35/

$$c_e = \frac{14000 \cdot 4{,}49}{3{,}5} = 180 \text{ €}$$

O = 667 + 180 = 847 € per year.

8.3 The costs of the pellet stove heating system

The pellet stove chosen according to the heating demands of the building is SIV pellet stoves NB-PS 3-6 kW.

Capital costs:

$$C = c_{ps} + c_{sc} + c_{he} + c_i \tag{40}$$

where:

c_{ps} – the price of the pellet stove – 1451 € /46/

c_{sc} – the price of the solar collectors – 2826 € /39/

c_{he} – the price of water-to-air heat exchanger – 195 € /40/

c_i – installation costs, which are assumed as 15% of the solar collectors price – 424 €.

C = 1451 + 2826 + 195 + 424 = 4896 €

Operational costs:

$$O = m + c_{fuel} \, , \qquad (41)$$

where:

m – maintenance costs, which can be assumed as 3% of the capital costs – 147€

c_{fuel} – cost of the fuel during one year, that can be calculated according to the formula:

$$c_{fuel} = \frac{Q_a \cdot c_p}{\eta_{a.s}} \, , \qquad (42)$$

where:

Q_a – annual energy consumption (for space heating)

c_p – the price of the pellets – 51,8 €/MWh /47/

$\eta_{a.s}$ – annual efficiency of the pellet stove – 0,6 /35/

$$c_{fuel} = \frac{7{,}727 \cdot 51{,}8}{0{,}6} = 667\ €$$

O = 147 + 667 = 814 €.

The final calculations are made according to the annuity model /48, p. 656 - 658/. The annuity factor:

$$P = \frac{i}{1-(1+i)^{-n}} \, , \qquad (43)$$

where:

i – bank loan interest, -

n – lyfe cycle of the system, years

So annuity factor P will be 0,064 for the systems using solar collectors as a heating source, and 0,054 for the system using GSHP. And payment per year is a sum of capital costs multiplied with the annuity factor and operational costs. /37, p. 33 - 35/ The results of the economical and energy calculations are shown in table 10.

TABLE 10. Economical and energy comparison of the three heating systems

Heating system	Capital costs, €	Life cycle, years	Q_a, kWh	$E_{purchased}$, kWh	Energy price, €/MWh	Operational costs, €/year	Payment per year, €
Ventilation air heating	4655	20	26546	43178	44,9	140	438
Underfloor heating	24175	25	14000	30624	44,9	847	2152
Pellet stove	4896	20	7727	41290	51,8	814	1127

9 CONCLUSION

This work has examined the possible alternatives of heating systems for a passive house in Finland. All the systems were designed to take into account the cold climate conditions in Finland. The alternative energy sources were chosen in accordance with the current market offers.

As all these systems meet the requirements of the Passivhaus standard, are efficient and are designed according to low energy needs of the building, the main criteria for comparing should be the economic issue. It can be seen from the table above that the lowest costs are of the ventilation air heating system. It is 5 times cheaper than the underfloor heating system with GSHP, and 2,5 times cheaper than the pellet stove with a solar combi system, according to the payment per year. Though in the case of ventilation air system the energy demands are the highest, the capital costs of the system are the lowest. High energy demands can be explained by relatively high electricity consumption, as it requires higher temperatures for ventilation air.

Underfloor heating system turned out to be the most expensive as it is not simple to install, and hydraulic underfloor heating along with GSHP have high capital and installation costs, though GSHP seemed to be profitable for the passive house, since it produces 2,5 times more heat than it consumes electricity.

Pellet stove could be a good alternative. But the annual payment for this system depends also on the price of pellets. Besides, the stove can’t control the temperature inside the building properly, and the house can easily overheat, even though it can be used only during the coldest winter days.

Thus, the best heating system for a passive house situated in the cold climate of Finland is ventilation air system, based on the solar collectors heating source. This system is quiet easy to install, it doesn’t require any piping system. Also it is the cheapest and efficient. It was originally the heating system for the first passive houses in Central Europe, though it fits to the cold Nordic climate as well. Besides exactly this system was installed in the passive house, that was built in Lindås, Sweden, which was used as an example in this thesis work.

The result of this work is that it was proved that it is possible to meet the Passivhaus Standard requirements in the cold climate conditions and to build a passive house according to its definition in the Passivhaus Standard and meeting the requirements of NBC of Finland. Also there is no need to install any other heating system, but to use all the heat storage methods in the highest extent. Then it is possible to use ventilation air space heating, which remains the best solution for a passive house anywhere in Europe.

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APPENDIX 1(2).

Energy needs for heating with ventilation air heating system

	T_{outd}	Δt	$Q_{exterior\ wall}$	$Q_{ceiling}$	Q_{floor}	Q_{window}	Q_{door}
January	-3,97	744	42,2	294,3	404,6	663,2	178,3
February	-4,5	672	40,7	271,4	373,2	611,8	164,5
March	-2,58	744	41,1	277,9	382,1	626,3	168,4
April	4,5	720	35,5	188,2	258,7	424,1	114,0
May	10,76	744	31,2	120,7	165,9	272,0	73,1
June	14,23	720	28,5	77,2	106,2	174,0	46,8
July	17,3	744	26,4	43,6	60,0	98,3	26,4
August	16,05	744	27,3	58,3	80,2	131,5	35,4
September	10,53	720	31,1	119,4	164,2	269,1	72,4
October	6,2	744	34,6	174,4	239,8	393,1	105,7
November	0,5	720	38,4	233,8	321,5	526,9	141,7
December	-2,19	744	40,9	273,3	375,8	615,9	165,6
Total per year		8760,0	417,8	2132,5	2932,2	4806,2	1292,4

	$Q_{conduct}$	$Q_{air\ leakage}$	$Q_{iv,supply\ air}$	T_{recov}	Q_{space}	$G_{radiant,vertical\ (N)}$
January	1582,6	89,2	2434,7	16,0	4106,5	6,2
February	1461,7	82,3	2245,8	15,9	3789,7	17,3
March	1495,9	84,2	2299,2	16,3	3879,2	40,3
April	1020,6	57,0	1556,9	17,7	2634,5	43,9
May	662,9	36,6	998,5	18,0	1698,0	57,8
June	432,7	23,4	638,8	18,0	1094,9	70,6
July	254,6	13,2	360,8	18,0	628,6	66,3
August	332,7	17,7	482,7	18,0	833,0	50
September	656,2	36,2	987,9	18,0	1680,4	32,9
October	947,7	52,9	1443,1	18,0	2443,6	17,9
November	1262,3	70,8	1934,4	16,9	3267,5	7,2
December	1471,5	82,8	2261,1	16,4	3815,5	4,2
Total per year	11581,2	646,2	17643,8		29871,3	

APPENDIX 1(2).

Energy needs for heating with ventilation air heating system

	$G_{radiant,vertical\ (S)}$	Q_{solar} (N)	Q_{solar} (S)	Q_{solar}	Q_{heat} load	H	τ	a	γ
January	12,9	2,5	129	131,5	543,5	221,0	57,0	4,8	0,1
February	41,4	7,1	414	421,1	833,1	221,2	57,0	4,8	0,2
March	89,5	16,5	895	911,5	1323,5	221,1	57,0	4,8	0,3
April	107,3	18,0	1073	1091,0	1503,0	221,8	56,8	4,8	0,6
May	116	23,7	1160	1183,7	1595,7	222,9	56,5	4,8	0,9
June	101,6	28,9	1016	1044,9	1456,9	224,6	56,1	4,7	1,3
July	115,5	27,2	1155	1182,2	1594,2	228,3	55,2	4,7	2,5
August	100,4	20,5	1004	1024,5	1436,5	226,2	55,7	4,7	1,7
September	100,5	13,5	1005	1018,5	1430,5	222,9	56,5	4,8	0,9
October	37	7,3	370	377,3	789,3	221,9	56,8	4,8	0,3
November	16,8	3,0	168	171,0	583,0	221,4	56,9	4,8	0,2
December	11,8	1,7	118	119,7	531,7	221,1	57,0	4,8	0,1
Total per year		170,0	8507,0	8677,0	13621,0				

	η_{heat}	$Q_{int.\ heat}$	$Q_{heating\ spaces,\ net}$	$Q_{heating}$ spaces	$Q_{heating}$	$E_{purchased}$
January	1,00	543,5	3563,0	4003,4	4459,4	5845,4
February	1,00	832,6	2957,0	3322,5	3778,5	5164,5
March	1,00	1318,5	2560,7	2877,2	3333,2	4719,2
April	0,97	1457,3	1177,3	1322,8	1778,8	3164,8
May	0,85	1358,4	339,6	381,5	837,5	2223,5
June	0,69	1007,7	87,2	97,9	553,9	1939,9
July	0,39	623,7	4,9	5,5	461,5	1847,5
August	0,56	804,9	28,1	31,5	487,5	1873,5
September	0,89	1267,3	413,1	464,1	920,1	2306,1
October	1,00	786,9	1656,7	1861,4	2317,4	3703,4
November	1,00	582,8	2684,7	3016,5	3472,5	4858,5
December	1,00	531,7	3283,8	3689,6	4145,6	5531,6
Total per year		11115,4	18755,8	21074,0	26546,0	43178,0

APPENDIX 2(1).

Energy needs for heating with underfloor heating with GSHP

	T_{outd}	Δt	$Q_{exterior\ wall}$	$Q_{ceiling}$	Q_{floor}	Q_{window}	Q_{door}
January	-3,97	744	42,2	294,3	404,6	663,2	178,3
February	-4,5	672	40,7	271,4	373,2	611,8	164,5
March	-2,58	744	41,1	277,9	382,1	626,3	168,4
April	4,5	720	35,5	188,2	258,7	424,1	114,0
May	10,76	744	31,2	120,7	165,9	272,0	73,1
June	14,23	720	28,5	77,2	106,2	174,0	46,8
July	17,3	744	26,4	43,6	60,0	98,3	26,4
August	16,05	744	27,3	58,3	80,2	131,5	35,4
September	10,53	720	31,1	119,4	164,2	269,1	72,4
October	6,2	744	34,6	174,4	239,8	393,1	105,7
November	0,5	720	38,4	233,8	321,5	526,9	141,7
December	-2,19	744	40,9	273,3	375,8	615,9	165,6
Total per year		8760,0	417,8	2132,5	2932,2	4806,2	1292,4

	$Q_{conduct}$	$Q_{air\ leakage}$	$Q_{iv,supply\ air}$	T_{recov}	Q_{iv}	Q_{space}	$G_{radiant,vertical\ (N)}$
January	1582,6	89,2	474,1	16,0	315,1	1671,8	6,2
February	1461,7	82,3	428,2	15,9	299,7	1543,9	17,3
March	1495,9	84,2	474,1	16,3	271,2	1580,1	40,3
April	1020,6	57,0	458,8	17,7	45,9	1077,6	43,9
May	662,9	36,6	474,1	18,0	0,0	699,5	57,8
June	432,7	23,4	458,8	18,0	0,0	456,1	70,6
July	254,6	13,2	474,1	18,0	0,0	267,8	66,3
August	332,7	17,7	474,1	18,0	0,0	350,3	50
September	656,2	36,2	458,8	18,0	0,0	692,4	32,9
October	947,7	52,9	474,1	18,0	0,0	1000,5	17,9
November	1262,3	70,8	458,8	16,9	168,2	1333,1	7,2
December	1471,5	82,8	474,1	16,4	258,8	1554,3	4,2
Total per year	11581,2	646,2	5581,9		1359,0	12227,5	

APPENDIX 2(2).

Energy needs for heating with underfloor heating with GSHP

	$G_{radiant,vertical}$ (S)	Q_{solar} (N)	Q_{solar} (S)	Q_{solar}	$Q_{heat\ load}$	H	τ	a	γ	η_{heat}
January	12,9	2,5	129	131,5	543,5	90,0	140,0	10,3	0,3	1,00
February	41,4	7,1	414	421,1	833,1	90,1	139,8	10,3	0,5	1,00
March	89,5	16,5	895	911,5	1323,5	90,1	139,9	10,3	0,8	0,97
April	107,3	18,0	1073	1091,0	1503,0	90,7	138,9	10,3	1,4	0,71
May	116	23,7	1160	1183,7	1595,7	91,8	137,2	10,1	2,3	0,44
June	101,6	28,9	1016	1044,9	1456,9	93,6	134,7	10,0	3,2	0,31
July	115,5	27,2	1155	1182,2	1594,2	97,3	129,5	9,6	6,0	0,17
August	100,4	20,5	1004	1024,5	1436,5	95,1	132,5	9,8	4,1	0,24
September	100,5	13,5	1005	1018,5	1430,5	91,9	137,2	10,1	2,1	0,48
October	37	7,3	370	377,3	789,3	90,9	138,7	10,2	0,8	0,98
November	16,8	3,0	168	171,0	583,0	90,3	139,5	10,3	0,4	1,00
December	11,8	1,7	118	119,7	531,7	90,1	139,9	10,3	0,3	1,00
Total per year		170,0	8507,0	8677,0	13621,0					

	$Q_{int.\ heat}$	$Q_{heating\ spaces,\ net}$	$Q_{heating\ spaces}$	$Q_{heating}$	$E_{purchased}$
January	543,5	1128,3	1446,5	2169,5	3555,5
February	832,4	711,5	912,1	1635,1	3021,1
March	1283,7	296,4	380,0	1103,0	2489,0
April	1067,3	10,3	13,2	736,2	2122,2
May	699,4	0,1	0,1	723,1	2109,1
June	456,1	0,0	0,0	723,0	2109,0
July	267,8	0,0	0,0	723,0	2109,0
August	350,3	0,0	0,0	723,0	2109,0
September	692,2	0,2	0,3	723,3	2109,3
October	773,6	227,0	291,0	1014,0	2400,0
November	582,9	750,2	961,8	1684,8	3070,8
December	531,7	1022,6	1311,0	2034,0	3420,0
Total per year	8081,0	4146,5	5316,0	13992,0	30624,0

APPENDIX 3(1).

Energy needs for heating with a pellet stove

	T_{outd}	Δt	$Q_{exterior\ wall}$	$Q_{ceiling}$	Q_{floor}	Q_{window}	Q_{door}
January	-3,97	744	42,2	294,3	404,6	663,2	178,3
February	-4,5	672	40,7	271,4	373,2	611,8	164,5
March	-2,58	744	41,1	277,9	382,1	626,3	168,4
April	4,5	720	35,5	188,2	258,7	424,1	114,0
May	10,76	744	31,2	120,7	165,9	272,0	73,1
June	14,23	720	28,5	77,2	106,2	174,0	46,8
July	17,3	744	26,4	43,6	60,0	98,3	26,4
August	16,05	744	27,3	58,3	80,2	131,5	35,4
September	10,53	720	31,1	119,4	164,2	269,1	72,4
October	6,2	744	34,6	174,4	239,8	393,1	105,7
November	0,5	720	38,4	233,8	321,5	526,9	141,7
December	-2,19	744	40,9	273,3	375,8	615,9	165,6
Total per year		8760,0	417,8	2132,5	2932,2	4806,2	1292,4

	$Q_{conduct}$	$Q_{air\ leakage}$	$Q_{iv,supply\ air}$	T_{recov}	Q_{iv}	Q_{space}	$G_{radiant,vertical\ (N)}$
January	1582,6	89,2	474,1	16,0	315,1	2145,9	6,2
February	1461,7	82,3	428,2	15,9	299,7	1972,1	17,3
March	1495,9	84,2	474,1	16,3	271,2	2054,1	40,3
April	1020,6	57,0	458,8	17,7	45,9	1536,4	43,9
May	662,9	36,6	474,1	18,0	0,0	1173,6	57,8
June	432,7	23,4	458,8	18,0	0,0	914,8	70,6
July	254,6	13,2	474,1	18,0	0,0	741,9	66,3
August	332,7	17,7	474,1	18,0	0,0	824,4	50
September	656,2	36,2	458,8	18,0	0,0	1151,2	32,9
October	947,7	52,9	474,1	18,0	0,0	1474,6	17,9
November	1262,3	70,8	458,8	16,9	168,2	1791,9	7,2
December	1471,5	82,8	474,1	16,4	258,8	2028,4	4,2
Total per year	11581,2	646,2	5581,9		1359,0	17809,3	

APPENDIX 3(2).

Energy needs for heating with a pellet stove

	$G_{radiant,vertical\ (S)}$	Q_{solar} (N)	Q_{solar} (S)	Q_{solar}	$Q_{heat\ load}$	H	τ	a	γ	η_{heat}
January	12,9	2,5	129	131,5	543,5	115,5	109,1	8,3	0,3	1,00
February	41,4	7,1	414	421,1	833,1	115,1	109,5	8,3	0,4	1,00
March	89,5	16,5	895	911,5	1323,5	117,1	107,6	8,2	0,6	0,99
April	107,3	18,0	1073	1091,0	1503,0	129,3	97,4	7,5	1,0	0,89
May	116	23,7	1160	1183,7	1595,7	154,0	81,8	6,5	1,4	0,71
June	101,6	28,9	1016	1044,9	1456,9	187,7	67,1	5,5	1,6	0,61
July	115,5	27,2	1155	1182,2	1594,2	269,5	46,8	4,1	2,1	0,45
August	100,4	20,5	1004	1024,5	1436,5	223,9	56,3	4,8	1,7	0,56
September	100,5	13,5	1005	1018,5	1430,5	152,7	82,5	6,5	1,2	0,76
October	37	7,3	370	377,3	789,3	133,9	94,1	7,3	0,5	1,00
November	16,8	3,0	168	171,0	583,0	121,4	103,8	7,9	0,3	1,00
December	11,8	1,7	118	119,7	531,7	117,6	107,2	8,1	0,3	1,00
Total per year		170,0	8507,0	8677,0	13621,0					

	$Q_{int.\ heat}$	$Q_{heating\ spaces,\ net}$	$Q_{heating\ spaces}$	$\eta_{production}$	$Q_{heating}$	$E_{purchased}$
January	543,5	1602,4	1704,6	0,76	3257,5	4643,5
February	832,7	1139,4	1212,1	0,75	2644,3	4030,3
March	1310,3	743,8	791,3	0,72	2170,0	3556,0
April	1340,3	196,1	208,6	0,68	1440,7	2826,7
May	1126,0	47,6	50,6	0,61	1347,1	2733,1
June	886,8	28,0	29,8	0,56	1430,2	2816,2
July	724,5	17,4	18,5	0,56	1410,0	2796,0
August	798,2	26,2	27,8	0,56	1426,7	2812,7
September	1083,1	68,1	72,5	0,61	1382,9	2768,9
October	785,4	689,2	733,2	0,69	2180,1	3566,1
November	582,9	1209,0	1286,2	0,73	2818,2	4204,2
December	531,7	1496,7	1592,2	0,75	3151,1	4537,1
Total per year	10545,6	7263,7	7727,3		24658,7	41290,7