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A passive house with photovoltaic, heat pump, and Stirling engine.

An energy-balance model

Department of Mechanical and Materials Engineering
Bachelor's thesis

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29.4.2024
Turku

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Subject: Mechanical Engineering
Author: Eero Virtanen
Title: A passive house with photovoltaic, heat pump, and Stirling engine
Supervisor: Ph.D. Andrey Mityakov
Number of pages: 29 pages
Date: 29.4.2024

The purpose of this thesis is to analyse a way of heating a passive house with a thermal energy source instead of electricity, while still taking advantage of the high coefficients of performance typical for heat pumps. To achieve this, a thermal energy balance model of a passive house with photovoltaic electricity generation, a heat pump for temperature control and a Stirling engine to directly power the heat pump is created. The thesis will focus only on the heating, but not the cooling of a passive house and therefore example calculations are made for a cold climate. The thesis was heavily inspired by “CO2 Stirling Heat Pump for Residential Use” (2008) by M. Berchowitz et al.

From the analysis it is found that even in a non-optimal configuration in a cold climate, the heating system achieves an average coefficient of performance of almost 2. Therefore, the addition of a Stirling engine heat pump should be able to halve the amount of fuel needed for heating and has potential for even better numbers. The performance is based on the usage of an air-source heat pump to transfer heat. A notable improvement is achievable by changing over to a ground-source solution.

Even though there are significant shortcomings in the mathematical model, rough energy consumption numbers are calculated. They show that the solution presented should be able to satisfy most if not all the requirements of the passive house standard. The model is also clearly divided into heats produced by different phenomena, making it easy to improve upon in the future. The accuracy of used equations is analysed qualitatively.

Key words: passive house, Stirling engine, residential heating, free piston Stirling engine. free piston Stirling engine heat pump

List of used abbreviations:

COP	Coefficient of Performance
FPSE	Free Piston Stirling Engine
FPSHP	Free Piston Stirling Heat Pump
HPVHPSE	a passive House with PhotoVoltaic, Heat Pump, and Stirling Engine
HVAC	Heating, Ventilation, and Air Conditioning
PH	Passive House
PER	Primary Energy Ratio
PHI	Passive House Institute

PHPP	Passive House Planning Package

List of used symbols:

A_{env}	total area of the building envelope	$[m^2]$
A_{exp}	area of the building envelope that can be exposed to the sun	$[m^2]$
COP_{Carnot}	coefficient of performance of Carnot Heat Pump	$[1]$
COP_{HP}	coefficient of performance of Heat Pump	$[1]$
c_{pa}	specific heat of dry air in constant pressure	$[\frac{J}{kg*K}]$
c_{pw}	specific heat of water vapor	$[\frac{J}{kg*K}]$
h_{in}	specific enthalpy of indoor air	$[\frac{J}{kg}]$
h_{out}	specific enthalpy of outdoor air	$[\frac{J}{kg}]$
h_s	heat surface transfer coefficient	$[\frac{W}{m^2*K}]$
h_{we}	heat of evaporation of water	$[\frac{J}{kg}]$
k_{COP}	COP of the heat pump relative to the Carnot heat pump	$[1]$
k_η	efficiency of the FPSE relative to the Carnot engine	$[1]$
$\dot{m}$	mass flow rate	$[\frac{kg}{s}]$
Q_{FPSHP}	useful heat delivered by the FPSHP	$[W]$
Q_{env}	heat lost through the building envelope	$[W]$
Q_{fuel}	heat delivered to the FPSHP	$[W]$
Q_{int}	heat produced inside the house	$[W]$
Q_{solar}	heat transfer from the sun	$[W]$
Q_{vent}	heat lost due to ventilation	$[W]$

S	solar radiation constant	$[\frac{W}{m^2}]$
$T_{Cold,e}$	temperature of cold side of FPSE	$[K]$
$T_{Cold,HP}$	temperature of cold side of Heat Pump	$[K]$
$T_{Hot,e}$	temperature of hot side of FPSE	$[K]$
$T_{Hot,HP}$	temperature of hot side of Heat Pump	$[K]$
T_{in}	temperature inside the building	$[K]$
T_{out}	ambient temperature outside the building	$[K]$
t	air temperature in Celsius	[℃]
U	U-value	$[\frac{W}{m^2 * K}]$
U_{total}	Total U-value for the whole house	$[\frac{W}{m^2 * K}]$
$\dot{V}$	volume flow rate	$[\frac{m^3}{s}]$
x_{hum}	humidity ratio	[1]
η_{Carnot}	efficiency of Carnot engine	[1]
η_{engine}	efficiency of FPSE	[1]
η_{re}	efficiency of heat regeneration	[1]
τ_{HP}	temperature ratio of Heat Pump	[1]
τ_e	temperature ratio of FPSE	[1]
λ	thermal conductivity	$\left[\frac{W}{m * K}\right]$
ρ	density of air	$[\frac{kg}{m^3}]$

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1 Introduction

Keeping the inside of a building comfortable is a problem that has been solved many times over: Add or take out heat until the temperature is comfortable, and make sure that there is enough ventilation to ensure good air quality and even temperatures in different parts of the building. The question nowadays is not how an area can be conditioned. Instead, the challenges arise regarding efficiency, climate effects and ultimately costs.

Unlike many other engineering applications, building heating and especially the costs related to it still get a lot of attention in news outlets and public discussion. An example from the Finnish public media company Yle, written during the 2023-2024 Winter, can be seen in [1]. The heating of a building affects people’s comfort, their living costs and is a huge environmental factor, as shown by the fact that in 2022, 66 % of the total energy consumption of households in Finland was used for the heating of spaces [2].

Diversification is a good way to balance energy usage and production. Usually this refers to varying ways of generating and using electricity. Instead of looking at electric heating, the solution presented in this thesis allows for efficient heating using thermal energy from various sources. To achieve this, the idea of a passive house with photovoltaic solar panel electricity generation, a heat pump, and a Stirling engine (HPVHPSE) is explored. The solar panels are used only for electricity required by appliances etc., and air conditioning is achieved with a free-piston Stirling engine heat pump.

First, different methods of energy flow in the house and some background information about passive houses will be introduced. Secondly, some mathematical models will be utilised to represent the different phenomena in an energy balance equation. Finally, an example calculation will be made to showcase the potential of the HPVHPSE in a cold climate.

Multiple texts referenced in this thesis use the definition of a thermal or building envelope, which is defined as the part of the building surrounding the conditioned inside area, separating the inside of the building from the outside elements.

During the preparation of this work the author used ChatGPT by OpenAI to check and improve English language expressions. After using the tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

2 Literature review

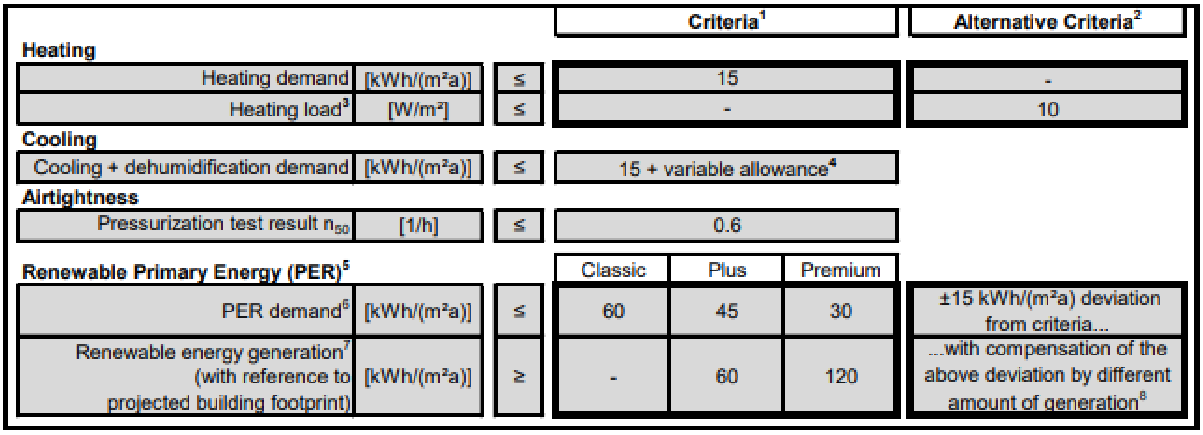
The aim of this literature review is to gain an overall understanding of the idea and requirements for a Passive House (PH), and why the PH with photovoltaic, heat pump, and Stirling engine (HPVHPSE) could be a suitable solution.

Interest towards energy-saving buildings started to increase in the 1970s. For example, during 1973-1979, the ECONO-house complex was built in Otaniemi, Finland. In addition to a complex solution around the utilisation of the internal volume and heat capacity of the building, considering the peculiarities of location and climate, the building used a special ventilation system, in which the air was heated by solar radiation inside the windows. The heat accumulation was facilitated by special vented windows and blinds. Other ways of solar collection were also utilised, providing energy savings. The specific heat consumption of the ECONO-house was only half of similar buildings built during the 1970s. Similar trials of more efficient building models popped up around the world during the 1970s and 1980s.[3]

2.1 Passive House standard

The German PH Institute (PHI), founded in 1996 by Dr Wolfgang Feist, has defined standard criteria for PHs. The purpose of the standard is said to be to define a house to be comfortable to live in while achieving “an extremely high level of energy efficiency “. According to the PHI, high efficiency is vital to minimising costs and the climate effects of living. The PHI often throws around the number that PHs need only 10% of the energy for heating when compared to average houses. [4]

The requirements are not climate specific, meaning that they are harder to achieve in harsher climates. Older versions of the standard do mention easier criteria for northern climates, but this is not the case in the newest, January 2023, version. The PHI also offers the EnerPHit and Low Energy Building standards for improvement of older buildings and for buildings that cannot achieve the PH Criteria, respectively. In this thesis, I will only focus on the PH standard. [4]



			Criteria[1]			Alternative Criteria[2]
Heating						
Heating demand	[kWh/(m^{2}a)]	≤	15			-
Heating load[3]	[W/m^2]	≤	-			10
Cooling						
Cooling + dehumidification demand	[kWh/(m^{2}a)]	≤	15 + variable allowance[4]			
Airtightness						
Pressurization test result n_{50}	[1/h]	≤	0.6			
Renewable Primary Energy (PER)[5]			Classic	Plus	Premium	
PER demand[6]	[kWh/(m^{2}a)]	≤	60	45	30	±15 kWh/(m^{2}a) deviation from criteria...
Renewable energy generation[7] (with reference to projected building footprint)	[kWh/(m^{2}a)]	≥	-	60	120	...with compensation of the above deviation by different amount of generation[8]

Figure 1: PH Criteria reprinted from [4].

The Criteria for the PH standard can be seen in Figure 1. It should be noted that the areas that the standard refers to are defined as treated floor area, meaning the heated living area of the house, with the exception of the area for renewable energy generation being the vertical projection of the thermal envelope onto the ground. [4]

Another notable factor that is not clear from only Figure 1 is the PHI's definition of renewable primary energy ("PER demand" in the figure). It differs from a traditional primary energy value of the house in that it assumes the energy used in the house to be 100% renewable electricity, meaning that there will be storage and conversion losses due to the variance of solar and wind energy, for example. The primary energy is therefore artificially scaled to be bigger than the actual primary energy requirement of the house. The renewable primary energy amount refers to total energy used in the building, not just heating, and it can be compensated for by generating renewable energy. For the HPVHPSE, this means the photovoltaic energy generation can be used to compensate for the renewable "PER demand" of the house to achieve the various levels of the standard. [4]

Throughout the entire document, whenever there are calculations to be made, the PH Institute refers to their Excel-based PH Planning Package (PHPP), where one can make the calculations according to the standard [4]. For example, the factors to translate the energy used in a building to renewable primary energy are provided only in the PHPP. The PHPP is a paid product that the PHI sells, and the specific way that calculations are made is not public knowledge. Thus, the standard should be treated critically, and will only be used as a rough guideline to determine what is expected of a PH in this thesis.

2.2 About the idea of a passive house

Regarding the reasons of why energy consumption of houses is important, it makes almost no difference if a house passes a specific standard or threshold. The focus should be on making buildings as efficient as possible and continuously improving. On the other hand, standards are good targets to aim for, and make it simpler for a consumer to understand differences between houses.

A PH doesn’t have to be a smart house. A PH is not required to have advanced heating, ventilation, or air conditioning (HVAC) systems, but it is instead defined only by the energy consumption, like shown in the PHI’s criteria in Figure 1.

In Figure 2, different climate zones are referenced on a map. Even though this thesis will focus on PHs in cold climates, energy efficiency can be improved in all climates, but in varying ways. While in warm climates, the thermal insulation of walls or roofs isn’t as important due to the lower temperature differences between the house and its environment, very hot climates benefit from good insulation to improve the efficiency of cooling down the house. Some climates also offer special challenges related to controlling the humidity. [5]

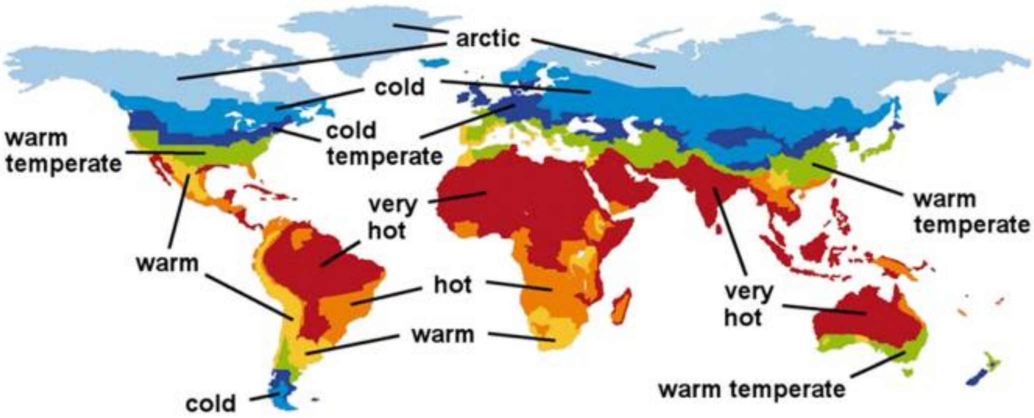


Figure 2: Map of the climate zones referred to in this thesis. Adapted from [5].

Cooling and humidity control will not be the addressed in this thesis, as I will focus on the cold climate, where the main challenge is keeping the house warm enough.

Overall, it should be kept in mind that the aim and idea of a PH is to be comfortable, economically viable and efficient, and these benefits are not defined only by achieving specific standards. Additionally, the measures required vary extensively depending on the climate.

2.3 HPVHPSE and its possible advantages

It is clear that there will always be heat losses during mechanical power generation, whatever method is used. The idea of the HPVHPSE is that the power generation could be done at the plot of the PH, so that the rejected heat from the Stirling engine can be utilized to heat the house instead of it going to waste, as it traditionally does during energy generation and conversion.

The free-piston Stirling engine (FPSE) has been proven to be a reliable and mechanically simple tool for power generation. A differentiating feature for any Stirling engine is a lack of internal combustion and therefore exhaust emissions. The energy source for a Stirling engine is a temperature difference between two distinct regions, which can be produced by any external heat source. The thermal energy can then be converted into mechanical work by the engine. The free-piston-variant (shown in Figure 4) has no need for crankshafts because the cycle is sustained using carefully tuned springs, which decreases the mechanical complexity and allows for a relatively small size. [6–8]

From a thermodynamic standpoint, an ideal Stirling engine works according to the ideal Stirling cycle shown in figure 3. The Stirling cycle is a closed thermodynamic cycle, which has the same efficiency as the Carnot cycle, when talking about an ideal case. [8]

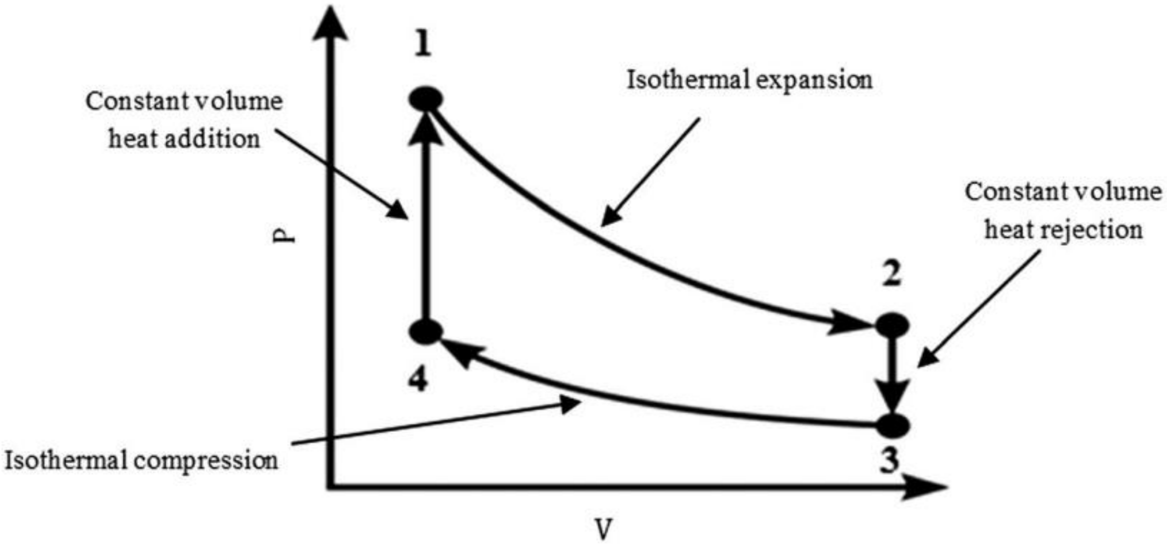


Figure 3: Ideal Stirling cycle reprinted from [8].

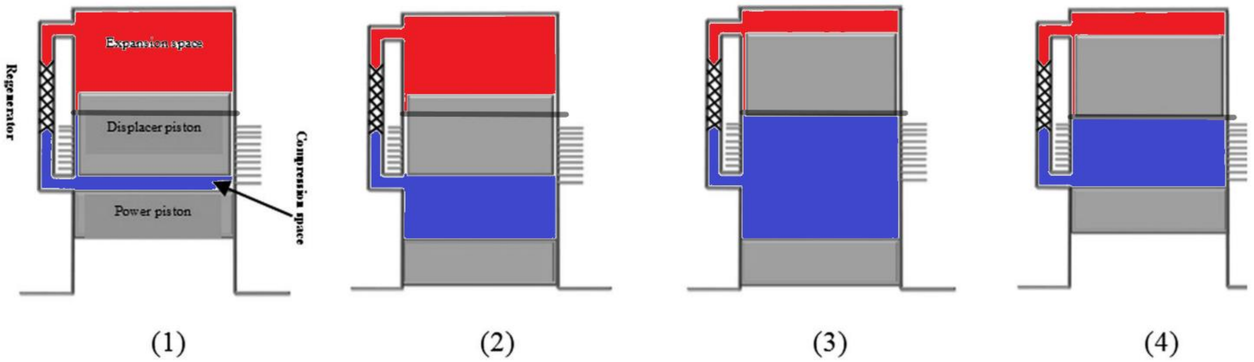


Figure 4: The movement of pistons inside the FPSE. Adapted from [8].

Notice that the numbers in Figures 3 and 4 correspond to each other. In figure 4, as noted by the colours, the hot side of the engine is on the top, and the cold side on the bottom where cooling fins are drawn. The top piston (pistons are coloured grey) is called the displacer piston. Its main function is to displace air inside the engine. The bottom piston is the power piston, as it is the piston used to do mechanical work. The working gas can move between the hot and cold sides through a heat exchanger.[8]

Still referring to figures 3 and 4, during the process from position 1 to 2, the gas is heated on the hot side of the engine, which leads to isothermal expansion as the power piston moves down into the position seen in 2. The process from 2 to 3 has the displacer piston push the air from the hot side towards the cold side. The total volume is constant, and heat is rejected through the cooling fins. The lower pressure caused by heat rejection then leads to the power piston compressing the gas isothermally in process from 3 to 4. Finally, the displacer piston pushes air back to the hot side to be heated to start the cycle all over again. Power is made due to the internal pressure being higher when the power piston moves downwards, and lower when the power piston moves upwards. [8]

In [7], Berchowitz et al. explore the possibility of using a Free-Piston Stirling Heat Pump (FPSHP) to improve the efficiency of conditioning a residential house, and also determine the importance of different influencing factors for the coefficient of performance (COP) and the primary energy ratio (PER) of the system. In the paper, performance of real heat pumps and Stirling engines is given as a factor of the efficiency of ideal, Carnot machines. [7]

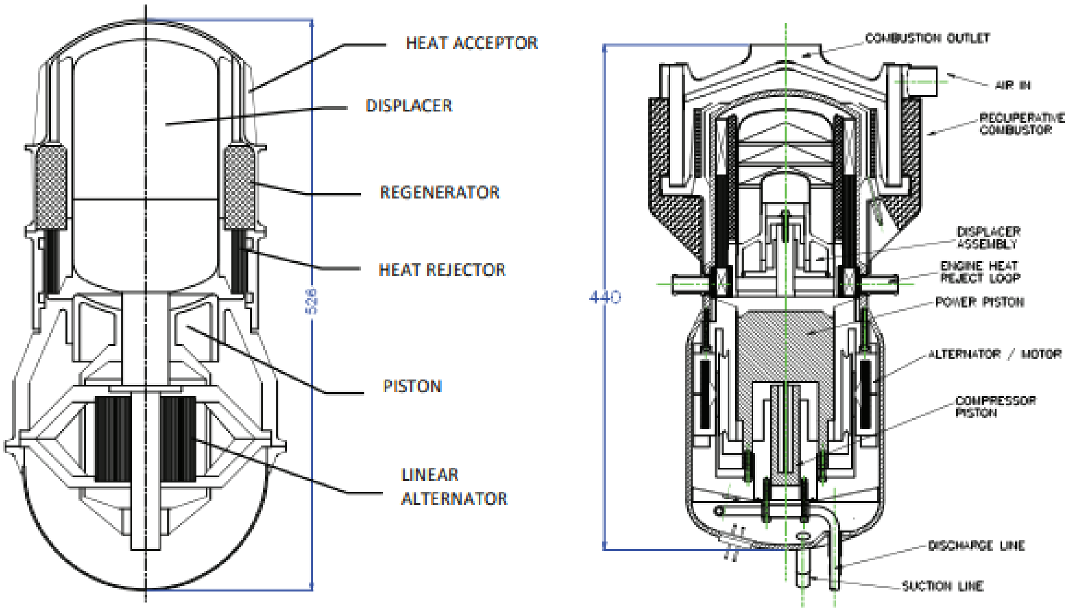


Figure 5: A traditional Free-piston Stirling engine (left) and a Free-piston Stirling heat pump (right). Reprinted from [7].

In Figure 5, there is a both a traditional FPSE with a linear alternator and a Free-piston Stirling heat pump (FPSHP). The FPSE can be used to create electricity, but the losses will consist of both rejected heat and heat losses in the alternator. In contrast, in the FPSHP, the kinetic energy can be used to directly run a heat pump without converting the energy to electricity first, meaning that a larger portion of the energy goes to the heat pump, which often have COP of over 3 [9]. The rejected heat can be used for house heating in both the FPSE and the FPSHP with a theoretical COP of only 1. The difference in COPs means that power supplied to the heat pump should be maximised to achieve more useful heat transfer.

The main technical challenge of making an FPSHP used to be that the working gases for the engine and the heat pump needed to be mechanically separated. In the solution presented by Berchowitz et al., the working gas is carbon dioxide for both components. It is also allowed to mix freely between the engine and heat pump. This decreases the Stirling engine efficiency by around 10 %, but makes the design simpler and less prone to malfunctions. [7]

The most important parameter that effects the energy ratios of the FPSHP is determined to be the heat pump temperature ratio. This means that the temperature inside the building envelope should be as close as possible to the heat source temperature. Thus, it is determined that a ground source heat pump is a superior alternative to an air source heat pump, especially in northern climates. [7]

The whole point of the FPSHP is to be able to use thermal energy instead of electricity for more flexibility in terms of the energy source. The temperature difference required for a Stirling engine could be created by any heating method, like biofuels, natural gas, solar or even electrical ways of heating. One futuristic use case could be the usage of hydrogen gas as a heat source. In practice, this could be done if today’s natural gas grids were converted into a hydrogen supply system according to [10], for example.

3 Analysis of the HPVHPSE

In this chapter, we will define the different methods of heat gains and losses associated with a HPVHPSE, based on existing literature.

3.1 Defining the phenomena

3.1.1 Energy losses through the building envelope

The energy losses through the insulation of the house are often quantified using the thermal transmittance U-value $[\frac{W}{m^2 * K}]$ [11]. The value gives the rate of heat flows through a surface per Kelvin of heat difference. Once the U-value and area of a surface of the building envelope is known, one can calculate the estimated heat flux through the envelope by a temperature difference on different sides of the wall.

As the U-value is defined by material properties and a temperature difference, it ignores the changes of convection or in other words, wind speed. According to [11], U-values for "elements having thermally homogenous layers" can be calculated by the thermal conductivity $\lambda \left[\frac{W}{m * K}\right]$, the material thickness, and a heat surface transfer coefficient h_s $[\frac{W}{m^2 * K}]$, which takes into account both convective and radiative heat transfer.

The U-values of entire building walls, for example, are affected by irregularities such as windows, doors, and possible air leaks. Different variations are often accounted for by adjusting the U-value of a surface to better represent the heat transfer.

3.1.2 Ventilation losses

The authors of [12] determined that good air quality can be achieved in PHs with airtight construction in accordance to the PH Standard and by having a fresh air supply of 20 to 30 cubic meters per hour per person. This additionally requires good air circulation within the building [12].

As the insulation of PH building envelopes gets better, the relative importance of minimizing ventilation losses increases. Because a certain amount of ventilation is obligatory and cannot be eliminated, optimisation of ventilation heat losses is imperative to maximise efficiency. In PHs, ventilation losses have been estimated to be more than 50% of total lost thermal energy [13].

Regenerative heat exchangers can be used to transfer heat from the warm exhaust air to the cold fresh in cold climates. Aktershev et al. note that a “regenerative heat exchanger for a ventilation system with a periodic change in the air flow direction” can regenerate over 90% of the ventilation losses back into the PH, when compared to no ventilation regeneration. [14]

3.1.3 Thermal bridges

Thermal bridges are discontinuities in the building envelope caused by fasteners, supporting structures, or other components with different thermal conductivity compared to the insulation used in the thermal envelope. Šadauskienė et al. [15] have concluded that point-type, meaning bolts and other similar fasteners, thermal bridges may influence the U-value of a wall by 30% on average. In most applications, instead of calculating the effect of every thermal bridge, the excess heat transfer can be taken into account by adjusting the U-value of the specific part of the building envelope.

The effect of thermal bridges on the HPVHPSE should be minimised, as PHs have been defined to be designed so that there aren’t any significant heat bridges [4,5]. Despite this, it is impossible to build a liveable house without some thermal bridges disrupting the continuity of the insulation around the thermal envelope.

3.1.4 FPSHP heating and cooling

The FPSHP heats up the house in two different ways. Firstly, the Stirling engine supplies mechanical energy to the heat pump, which can transfer heat with a specific coefficient of performance. Secondly, the waste heat from the Stirling engine can also be used for heating purposes.[7]

Technically, a Stirling cycle could also be utilized in the other direction to turn mechanical energy into a heat differential between the hot and cold sides of the engine, but this is not achieved in practice due to the integration of the heat pump in [7]. Additionally, in this configuration, the phenomenon would not be useful for house heating, even if it was possible.

If there is a need for cooling during the Summer, the heat pump cycle in the FPSHP can be reversed to cool down the conditioned area instead of heating it up. Despite a total need for cooling, the waste heat of the Stirling engine can still be utilized to produce hot water for the house.[7]

3.1.5 Heat produced internally in the house

The people living in the house and electrical equipment produce useful heat internally in the house, which needs to be considered. For example, in a model described in [16], heat gains were described to be 80W per adult, 60W per adolescent, and a time average of 144W from the electrical devices in a "Jangster de Lux" type single-family PH. These values are based on measurements by the PHI made in 2001 [17]. As the measurements are old, they should not be assumed to hold true in modern conditions. This is influenced by the transition from incandescent bulbs to LEDs, for example.

3.1.6 Passive solar and photovoltaic energy gains

Harnessing the heat of the sun is one of the ways to improve PH efficiency. In a 250-day experiment of a typical family home in Ottawa, Canada, researchers were able to achieve a solar fraction of over 50% for space heating, meaning that 50% of the solar energy received by the house could be used for heating. Despite this, the implementation wasn't practical, as the system used to avoid overheating and to store and to distribute excess heat consumed more energy than was gained from the sun. [18]

The authors of [18] also note that attempts to utilise passive solar gains without any complicated energy transfer systems usually lead to one of two possibilities: either the solar gains lead to overheating, or their effect is negligible. This is very typical for any kind of solar power, as the amount of energy received varies a lot over time and is difficult to predict.

Due to the challenges with passive solar, any special solar collection system won't be used in the HPVHPSE. Due to good insulation, solar energy hitting the building's roof or walls shouldn't have a large impact on the energy balance. Therefore, the main thing to consider might be solar gains through windows, as is done in the PHPP [4]. Different windows have varying G-values, usually between 0,2 and 0,7, which describe the fraction of solar heat that is transmitted through the windows into the conditioned area[19]. Another option would be to roughly model the total energy received on the outside of the envelope and assume that some fraction of it gets through to increase the inside temperature.

The photovoltaics (PV) in the house transform sunlight into electricity. In the HPVHPSE this energy cannot be used to run the heat pump as it is directly connected to the Stirling engine. Instead, other options should be considered: The electricity could be used to run appliances and other electric devices in the house, and in cases of excess electricity production it could be used to heat up the hot side of the Stirling engine or be output into the electric grid. The photovoltaic generation can also fill requirements to achieve higher levels of the PH standard.

In cases in the Nordics where PV energy isn’t stored at the production site, vertical bifacial PVs have been found to be a good option to prevent overloading of the energy grid at generation peaks. The importance of this increases as more and more photovoltaic systems are introduced to a grid. Overall, the energy production of solar panels is defined by the technology used, the orientation of the panels and the amount of solar irradiance.[20]

The problem with PV generation is that it varies depending on the amount of sunlight, which often leads to a need for some kind of energy storage system. An example of this kind of system can be found in [21].

3.1.7 Comfortable living conditions

To simplify calculations, the usual temperature values assumed by the PHI for comfortable living conditions in a PH is 20°C in the winter with a maximum of 25°C in the summer, with the summer maximum humidity ratio being 12 g/kg [5]. Multiple adaptive and passive comfort models exist to better define indoor comfort for humans [22–24], but as comfort is very subjective, and the essence of the houses is to be comfortable for the very people who live in them, no single model can be used to define maximum comfort.

An exception to not using comfort models in analysis of PHs was made by Schnieders et al. in 2015, where a range of comfortable values of humidity and temperature were defined. It is still notable that the comfort models are not being applied in the summer part of the simulations, and that the authors “do not want to depend on the validity of this idea” for the model. [25]

The personal feeling of comfort for people living in the PH is more dependent on the way that the system is controlled, rather than the energy usage. Simplified assumptions will be used also in this thesis, as I will only be looking at the energy consumption.

3.2 Defining the model

In this part, a numerical energy-balance model will be defined for the HPVHSE. Equations will be determined for the various phenomena introduced in the previous chapter using literature and certain assumptions. The model itself will not be restricted to only the cold climates as this will be taken into account during the choices made for example calculations.

The aim is not to make an accurate model, but a rough approximation to evaluate the possible benefits of the HPVHSE.

3.2.1 General assumptions

For the simplicity of this model, excess energy storage in terms of batteries for electricity or thermal storage will not be considered.

The values used for calculations should be constant, average values. The model will not be dynamic.

The conditioned area inside the house will be assumed to be in a steady state and in thermal equilibrium. Ventilation, convection, or any other heat transfer phenomena inside the thermal envelope will not be taken into account.

Simplified assumptions for comfort and thus the inside temperature will be used, as we will only be looking at the energy consumption instead of a temperature control system. Humidity will be ignored.

A single-family PH of typical size will be studied. The geometry will be defined as a box-like shape with only right angles, a length, width, and a height.

Other, phenomena-specific assumptions will be mentioned when applied in the next subchapter.

3.2.2 Equations for the heat gains in the HPVHPSE

First, I will introduce the equation for the primary energy ratio for heating utilising FPSHP. In this case, the primary energy ratio is defined as

$$PER_{FPSHP} = \frac{Net\ heat\ delivered}{Input\ Energy} = \frac{Q_{FPSHP}}{Q_{fuel}}. \ (1)$$

In [7], the primary energy ratio of an FPSHP for heating is defined as

$$PER_{FPSHP,heating} = 1 + k_{\eta} * \frac{\tau_e - 1}{\tau_e}\left(k_{COP} * \frac{\tau_{HP}}{\tau_{HP} - 1} - 1\right), \ (2)$$

where k_{η} is a constant of proportionality that takes also into account the efficiency of the fuel burner or other heating system for the Stirling engine. It represents how much of the ideal maximum efficiency of a Carnot engine the real Stirling engine can provide:

$\eta_{engine} = k_{\eta}\eta_{Carnot}$ (3a)

Similarly, k_{COP} represents how much of the ideal maximum coefficient of performance of a Carnot heat pump the real heat pump achieves:

$COP_{HP} = k_{COP}COP_{Carnot}$ (3b)

τ represents a heat ratio between the hot and cold sides of either the engine or the heat pump.

$\tau_e = \frac{T_{Hot,e}}{T_{Cold,e}}$ (4)

$\tau_{HP} = \frac{T_{Hot,HP}}{T_{Cold,HP}}$ (5)

In warm climates, there might be a simultaneous need for both cooling and heating. For a case where all of the engine reject heat is used for residential water heating, the heat pump is utilized for cooling and the heat pump reject heat is not recovered, the primary energy ratio of an FPSHP is as follows: [7]

$PER_{FPSHP,cooling} = 1 + k_{\eta} * \frac{\tau_e - 1}{\tau_e}\left(k_{COP} * \frac{1}{\tau_{HP} - 1} - 1\right)$ (6)

For the passive solar gains, a very rough approximation will be made, as the modelling of these gains is very challenging.

We have data for a solar average radiation $S\ [\frac{W}{m^2}]$ from [26].The radiation is measured as the total radiation that hits a horizontal surface during a time period. If we assume that on average, one fourth of the total possible area of the PH receives this solar radiation fully, and that the absorption factor of the paint used is 0,5, meaning that half of the energy is absorbed and the other half reflected back, we can approximate

$Q_{solar} = \frac{S * A_{exp}}{8}$, (7) where A_{exp} is the area of the PH envelope that is exposed to the sun, meaning the walls and the roof. This is in no way an accurate calculation, but it should be functional for the purpose of this thesis.

To account for the internal heat sources, an average value of Q_{int} will be used. It will be a sum of the heat produced by the occupants of the house and heat emitted from different appliances inside the house.

The photovoltaic system will not be used for heating or cooling in the HPVHPSE, so it will not be a part of the thermal energy balance model.

3.2.3 Equations for the heat losses in the HPVHPSE

To get a total U-value U_{total} $[\frac{W}{m^2 * K}]$ for the entire PH, we can take a weighted average of the U-values of the different areas of the building envelope, where the weight factors are the areas where the specific values are applicable:

$U_{total} = \frac{\sum(A_n U_n)}{\sum A}$ (8)

Then, the total energy conducted through the envelope Q_{env} will be

$Q_{env} = U_{total} * A_{env} * (T_{in} - T_{out})$, (9)

where A_{env} is the total area of the thermal envelope, T_{in} is the internal temperature of the house, and T_{out} is the ambient temperature. This assumes the ambient temperature to be constant on all sides, also in the ground under the house.

A simplified method to determine ventilation losses Q_{Vent} for a building according to [13] is

$Q_{vent} = \dot{m}(h_{in} - h_{out})(1 - \eta_{re})$. (10)

$\dot{m}$ is the mass flow that exits the building, which is assumed to be equal to the mass flow into the building, and η_{re} is the efficiency of the regenerative heat exchanger. The specific enthalpies of outdoor and indoor air, h_{out} and h_{in}, could be calculated as the sum of the thermal energy of dry air and the water vapour by

$h = c_{pa} * t + x_{hum} * (c_{pw} * t + h_{we})$, (11) where h is the total specific enthalpy, c_{pa} is the specific heat of dry air, $x_{hum} = \frac{m_{water}}{m_{air}}$ is the humidity ratio, c_{pw} is the specific heat of water and h_{we} is the evaporation heat of water. t is then the temperature in Celsius, and the zero point of enthalpy can be chosen to be 0 Celsius since we are only interested in the enthalpy differences. When done this way, the total enthalpy would be calculated by multiplying h by the total mass of dry air. Therefore, also the mass and volume flows should be numbers referencing only dry air.[27]

As is noted in earlier chapters, the scope of this thesis does not include considering humidity, so calculations will be made with an assumed enthalpy difference between the inside and outside air instead of using equation (11).

As equation (10) refers to a ventilation mass flow $\dot{m}$, but most sources [12] refer to volume flows $\dot{V}$ required for comfort, we can calculate $\dot{m}$ by

$$\dot{m} = \rho * \dot{V}, \quad (12)$$

assuming the density of air ρ to be constant.

Although PHs should be built so that thermal bridges are avoided [4,5], they are still a significant factor regarding heat transfer through the thermal envelope of a PH. The exact effects of varying geometries are quite complex to determine [15] and are beyond the scope of this thesis, so we will neglect the effects of thermal bridges for this model. If needed, thermal bridges can still be accounted for by adjusting the U-value of the house for more accurate calculation results.

3.2.4 Energy balance

To keep the HPVHPSE at a constant temperature, heat gains and losses need to be equal. As this thesis focuses on a cold climate, where the FPSHP will be only used for heating, we can define an energy balance referring to equations (1-2), (7) and (9-10):

$$Q_{FPSHP} + Q_{int} + Q_{solar} = Q_{env} + Q_{vent} \quad (13)$$

To solve for the input energy or energy consumption Q_{fuel} needed to heat the house, which is the defining variables for the performance of the HPVHPSE, we need to know all the variables mentioned in the defining equations. These variables should all be averages or constants over the time that a calculation is considering; For example, monthly or yearly averages could be suitable. All of the needed variables are $T_{Hot,e}$, $T_{Cold,e}$, $T_{Hot,HP}$, $T_{Cold,HP}$, k_η, k_{COP}, S, A_{exp}, U-values and their corresponding areas, A_{env}, T_{in}, T_{out}, Q_{int}, η_{re}, h_{out}, h_{in}, ρ, and $\dot{V}$.

Inserting equations (1-2), (7), (9-10) and (12) into (13) and solving for Q_{fuel} yields

$$Q_{fuel} = \frac{Q_{env} + Q_{vent} - Q_{int} - Q_{solar}}{PER_{FPSHP,heating}}$$

$$= \frac{U_{tot}A_{env}(T_{in} - T_{out}) + \rho * \dot{V}(h_{in} - h_{out})(1 - \eta_{re}) - Q_{int} - \frac{S * A_{exp}}{8}}{1 + k_\eta * \frac{\tau_e - 1}{\tau_e}\left(k_{COP} * \frac{\tau_{HP}}{\tau_{HP} - 1} - 1\right)}. \quad (14)$$

3.3 Example calculations

In this subchapter, equation (14) will be utilized to calculate a yearly average value for Q_{fuel} for the HPVHPSE.

The geometry of the house will be defined to be a rectangularly shaped two-story single-family home with dimensions of 10m*6m*5m and thus a simplified living area of 120m^2. The window area is assumed to be 10m^2. Geographically, the house is assumed to be in a cold climate, referencing Figure 2.

The U-values for different areas of the HPVHPSE are shown in Table 1. The values are recommendations for cold climates from [5] and are in accordance with the PHPP planning package. For simplicity, the U-values of the walls, roof and floor are assumed to be the same.

Table 1: U-values and corresponding areas

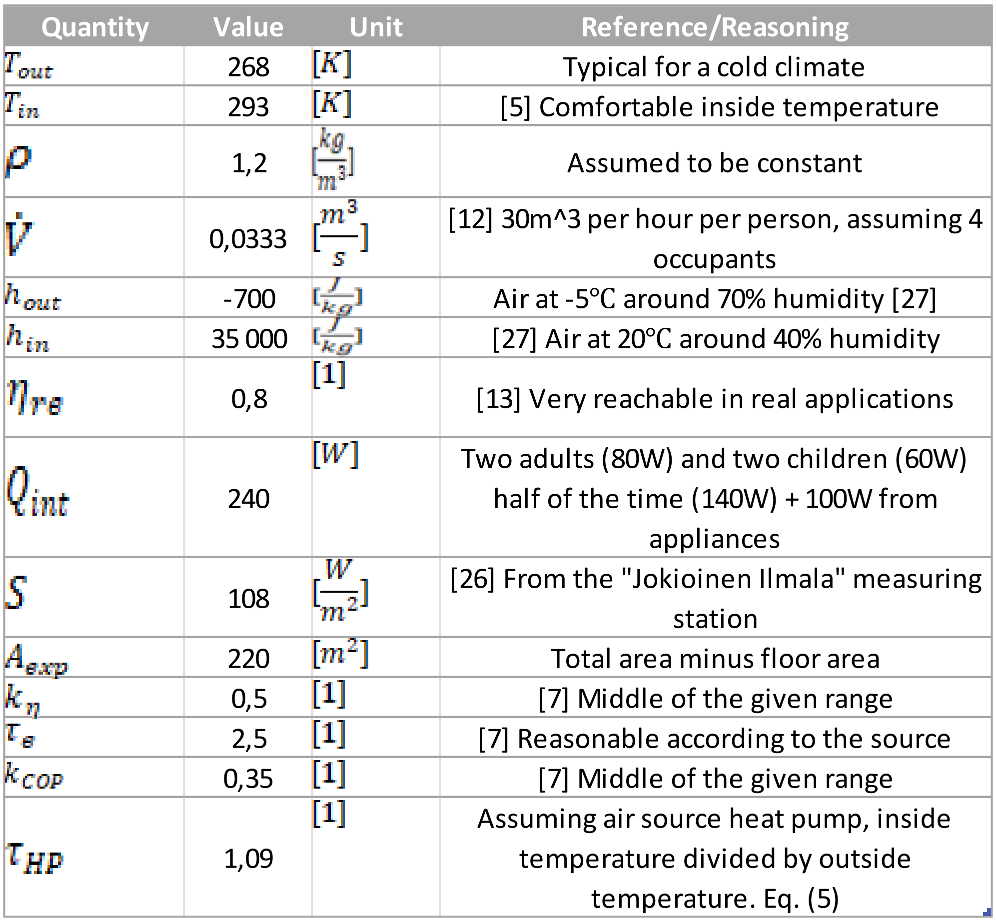
	Roof	Windows	Walls	Floor
U-values [W/(m^2*K)]	0,12	0,65	0,12	0,12
Area [m^2]	60	10	150	60
A_{env} [m^2]	280			

Using equation (8), it can be determined that

$$U_{total} = \frac{A_{Roof}U_{Roof}+A_{Windows}U_{Windows}+A_{Walls}U_{Walls}+A_{Floor}U_{Floor}}{A_{env}} = 0{,}1389\,\frac{W}{m^2*K}.$$

Other values, their reasonings and references can be found in table 2.

Table 2: The rest of the variables used in calculations.



Quantity	Value	Unit	Reference/Reasoning
T_{out}	268	$[K]$	Typical for a cold climate
T_{in}	293	$[K]$	[5] Comfortable inside temperature
ρ	1,2	$[\frac{kg}{m^3}]$	Assumed to be constant
$\dot{V}$	0,0333	$[\frac{m^3}{s}]$	[12] 30m^3 per hour per person, assuming 4 occupants
h_{out}	-700	$[\frac{J}{kg}]$	Air at -5°C around 70% humidity [27]
h_{in}	35 000	$[\frac{J}{kg}]$	[27] Air at 20°C around 40% humidity
η_{re}	0,8	$[1]$	[13] Very reachable in real applications
Q_{int}	240	$[W]$	Two adults (80W) and two children (60W) half of the time (140W) + 100W from appliances
S	108	$[\frac{W}{m^2}]$	[26] From the "Jokioinen Ilmala" measuring station
A_{exp}	220	$[m^2]$	Total area minus floor area
k_{η}	0,5	$[1]$	[7] Middle of the given range
τ_e	2,5	$[1]$	[7] Reasonable according to the source
k_{COP}	0,35	$[1]$	[7] Middle of the given range
τ_{HP}	1,09	$[1]$	Assuming air source heat pump, inside temperature divided by outside temperature. Eq. (5)

Substituting the values from tables 1 and 2 into the equations specified below, we get the yearly averages of heat losses:

$$(9)\colon Q_{env} = 972{,}3W$$

$$(10) \text{ and } (12)\colon Q_{vent} = 274{,}1W$$

The yearly averages of passive heat gains are listed similarly:

$$\text{Assumed to be constant: } Q_{int} = 240W$$

$$(7)\colon Q_{solar} = 2970W$$

And finally, the average PER for the HPVHPSE over a year:

$$(2)\colon PER_{FPSHP,heating} = 1{,}972$$

The solar heat gains according to this calculation would be almost three times the amount of energy losses, leading the building to be energy-positive even without an FPSHP or other conditioning systems, which is not realistic in cold-climate PHs [25]. The reasons for this are the inaccuracy of the way that solar gains are modelled, and the fact that seasonality isn't considered in the yearly averages; The solar gains are lowest during the winter, when the need for heating is the highest, and inversely the gains are highest during the summer, which should lead to overheating without a cooling load from the FPSHP.

For example, the PHPP, which is used in the design of PHs, only takes into account the solar gains through windows instead of the whole building envelope, which leads to more realistic results [4]. The equations used aren't public and I do not have access to the planning package, so their calculations cannot be replicated for this thesis.

If we assume the worst-case scenario in terms of passive energy and let solar gains be zero ($Q_{solar} = 0$), we can finish the analysis by calculating the yearly average of Q_{fuel} from equation (14).

$$Q_{fuel} = \frac{Q_{env} + Q_{vent} - Q_{int} - Q_{solar}}{PER_{FPSHP,heating}} = 510{,}3W$$

As $PER_{FPSHP,heating}$ already considers losses for a burner in the value for k_η, the value of Q_{fuel} should be interpreted as the heat energy released by the fuel used in the FPSE heating method.

To calculate the heating load mentioned in the PH criteria, we can use equation (13). Note that $Q_{solar} = 0$:

$$Q_{FPSHP} = Q_{env} + Q_{vent} - Q_{int} - Q_{solar} = 1006{,}4W$$

Divided by the total living area of 120m^2, we can determine the steady-state average heating load to be $\frac{1006{,}4W}{120m^2} = 8{,}39\,\frac{W}{m^2}$, which is under the $10\,\frac{W}{m^2}$ requirement set by the PHI, seen in Figure 1. This result is to be expected, as this thesis neglects thermal bridges and overall assumes quite ideal conditions for the losses, while using u-values suggested by the PHI for practical deployment in PHs. On the other hand, correctly modelling solar gains would make this number even smaller.

For clarity, here is the definition given by the PHI for heating load: “The heating load is the heat emitted by the heating system which must be supplied to the heated rooms in order to maintain the desired indoor temperature even under unfavourable conditions (cold outdoor temperatures/ no solar irradiation).” They also add that in the criteria, the number used is “The steady-state heating load calculated in the PHPP Loads for heating up after temperature setbacks are not taken into account.” To sum up, the yearly average number calculated in this example might not be directly comparable to the requirement of $10\,\frac{W}{m^2}$, as it is not clear how it is exactly calculated.

The most important takeaway from this should be that the heat balance of the HPVHPSE is in the right ballpark when compared to the PH criteria. The specifics of achieving the standard do not really matter.

Contrarily to the energy calculations, the way of calculating the $PER_{FPSHP,heating}$ factor should be accurate as long as the efficiency factors k_η and k_{COP} are accurately determined. This shows that the FPSHP can achieve similar performance coefficients to electric heat pumps, while allowing the input energy to be heat instead of electricity. As is concluded in [7], the main improvement potential lies in coupling the FPSHP to a ground source instead of an air source, leading to a smaller τ_{HP}. Note that this example calculation was done assuming an air source for the FPSHP.

Even in this non-optimal case, the FPSHP achieves a PER of almost two, meaning that it will at least halve the required fuel for heating when compared to a traditional boiler with some losses and thus a PER of a bit under 1.

3.4 Discussion

Referring to the quality of modelling presented in this thesis, the general assumptions made are appropriate and should not lead to great error in the calculations. The equations used for the heat transferred by the FPSHP, losses measured with U-values, and ventilation losses are based on reliable sources and should also be accurate. Moreover, all the main phenomena related to heat transfer in the HPVHPSE are mentioned, even if some of the models are inaccurate/non-existent.

The biggest potential for mathematical improvement is in the modelling of solar gains and heat bridges. The solar gain equation presented gives results that do not correspond with real-world results and are based on a totally different philosophy when compared to the way of calculating in the PHPP (looking only at windows in the PHPP vs the whole envelope in this thesis). Due to the challenges with modelling these phenomena, they had to be assumed to be zero in the final calculation to get some rough results. Additionally, the value used for internal gains from occupants and appliances could be made more accurate by finding or measuring better data, but it is quite similar to the values used in the sources[4,5].

Analysis related to the FPSHP’s performance should be accurate, as it is based on [7].

Overall, to achieve trustworthy results from an improved version of the model presented here, more research is required. One possible option would be to look at how heat transfer numbers are acquired in practical cases, and to do some experiments. This model should be easy to improve upon as the different heat transfer methods are separated and the basis of every equation is clearly stated.

4 Conclusions

It can be concluded that compared to traditional heating, the FPSHP has potential to at least halve the fuel needed for heating by taking advantage of the high COPs of heat pumps, even in a cold climate. This is applicable to any house, not just the extremely well insulated passive houses. One challenge not taken into account here is supplying and dividing the energy evenly in the building, and air-source heating can struggle with these things.

The HPVHPSE defined in the example calculation could be a possible technological solution of making a PH but would require some special modifications to the PH standard’s requirements, as they use the assumption of renewable electricity as the energy source.

Despite the inaccuracies, the calculations show potential to achieve the numbers that fit some of the PH standard’s prerequisites. Due to the good PER of the FPSHP, it can be said that since PHs can already be built using traditional electric heat pumps, a PH with a FPSHP should also be viable.

Useful applications of a FPSHP would be in areas where fuel is for some reason easier or financially more beneficial to transport to the location, compared to electricity. As an example, the HPVHPSE could be useful in areas where there are problems with electricity supply. Still, no real-world examples of using a Stirling heat pump to heat a house were found during the writing of this thesis, meaning that practical problems might still arise.

Directions of future research could be practical implementations and comparison of the potential of different fuels to heat the FPSHP. The FPSE itself is a proven concept, so its reliability or functionality shouldn’t be a problem. Instead, problems might arise from the combining with a heat pump and accurate temperature control in the FPSHP. Economic analysis is also required, as the solution would need to be financially viable in order to be implemented more widely.

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