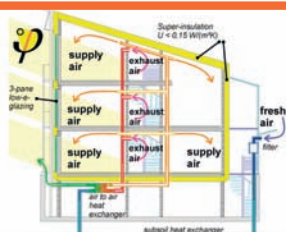


An energy efficient building for the Arctic climate

Is a passive house sensible solution for Greenland?



Petra Vladykova

PhD Thesis

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Preface

This thesis is submitted for the Ph.D. degree to the Department of Civil Engineering at the Technical University of Denmark.

The study described in the thesis has been carried out from August 2007 to April 2011. It should be noted that a leave of absence for a total of 8.5 months has occurred during the process of working on the thesis. The funding for this Ph.D. is from the Technical University of Denmark.

The work has been conducted at BYG - Section for Building Physics and Services, Department of Civil Engineering, Technical University of Denmark. The supervisors were Head of Section Professor Carsten Rode (BYG DTU), Associate Professor Toke Rammer Nielsen (BYG DTU) and M.Sc. Søren Pedersen (Passivhus.dk, Passivhus.fi).

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Kongens Lyngby, April 15, 2011.

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- A special thanks to my family, Michal and all my friends for their support.

List of appended papers

This thesis is based on analyses which are described partly in the body of the thesis and in the following articles which are the basis of this dissertation. The enclosed publications are papers presented at international conferences and papers accepted in, or submitted to, scientific journals.

Appended papers

- Paper I Passive houses for the Arctic Climates
Petra Vladykova, Carsten Rode, Toke Rammer Nielsen, Søren Pedersen
Published in the 1st Norden Passivhus Conference, Trondheim, Norway, 2009
- Paper II The potential and need for energy savings in standard family detached and semi-detached wooden houses in arctic Greenland
Søren Peter Bjarløv, Petra Vladykova
Published in the Journal of Building and Environment, 2010
- Paper III Low-energy house in Arctic climate - 5 years of experience
Petra Vladykova, Carsten Rode, Jesper Kragh, Martin Kotol
Accepted in the Journal of Cold Regions Engineering, 2011
- Paper IV Passive houses in the Arctic. Measures and alternatives
Petra Vladykova, Carsten Rode, Toke Rammer Nielsen, Søren Pedersen
Published in the 13th International Conference on Passive House, Frankfurt am Main, Germany, 2009
- Paper V The energy potential from the building design's differences between Europe and Arctic
Petra Vladykova, Carsten Rode
Published in the 9th Nordic Symposium on Building Physics, Tampere, Finland, 2011
- Paper VI The study of an appropriate and reasonable building solution for Arctic climates based on a passive house concept
Petra Vladykova, Carsten Rode
Submitted to the Journal of Cold Regions Engineering, 2011

Abstract

The Arctic is climatically very different from a temperate climate. In the Arctic regions, the ambient temperature reaches extreme values and it has a direct large impact on the heat loss through the building envelope and it creates problems with the foundation due to the permafrost. The solar pattern is completely different due to the limited availability in winter, yet, in summer, the sun is above horizon for 24 hours. Furthermore, the sunrays reach the vertical opaque elements at shallow angles. The great winds and storms have large effects on the infiltration of buildings and they heavily influence the infiltration heat loss through the building envelope. The wind patterns have large influences on the local microclimate around the building and create the snowdrift and problems with thawing, icing and possible condensation in the building envelope. The humidity in the interior is driven out through the building envelope in the winter due to the pressure difference, strong winds and low water ratio in the outdoor air. The Arctic is also defined by different conditions such as building techniques and availability of the materials and energy supply.

The passive house uses the basic idea of a super energy efficient house in which the normal hydronic heating system can be omitted. The savings in investment for a traditional hydronic heating system are spent on energy conserving components such as increased insulation in a super airtight building shell, super efficient windows to produce the net positive solar gain, and a ventilation system with very efficient heat recovery. To design a passive house in the way it is defined by Wolfgang Feist, the founder of the Passivhaus Institute, its annual heat demand should not exceed $15 \text{ kWh}/(\text{m}^2\cdot\text{a})$ and its total primary energy demand should not exceed $120 \text{ kWh}/(\text{m}^2\cdot\text{a})$ in which the building envelope allows limited air change of 0.6 h^{-1} at 50 Pa pressurization. The living area of the building is well defined according to the standard conditions as a net area and the heat of $10 \text{ W}/\text{m}^2$ can just be supplied by post-heating of fresh air after the heat recovery unit which ensures a satisfactory indoor air quality. A passive house also takes advantage of free gains such as solar heat, the heat from its occupants and their activities, and the domestic appliances, and other sources.

The hypothesis in this dissertation is testing the possibility of a new usage of an extreme energy efficient building in the Arctic. The purpose of this Ph.D. study is to determine the optimal use of an energy efficient house in the Arctic derived from the fundamental definition of a passive house, investigations of building parameters including the building envelope and systems, and investigations of boundary situations in the Arctic regions.

The object of the study is to analyse current passive house standards used in the temperate climate through the energy performance of a passive house in the cold climates. In theory, it is possible to completely fulfil the fundamental definition of a passive house in the Arctic and therefore to save the cost of traditional heating, but that would incur high costs for the building materials and the provision of technical solutions of extremely high standards which would take too many years to pay back in the life time of a building. The fundamental definition which applies to all climates can be realized in the Arctic regions at very high costs using fundamental design values and the building technologies available in the Arctic.

Based on the investigations, the optimal energy performing building is derived from a passive house concept. The passive house optimisation follows the main design rule in the Arctic and this is focused on minimizing the heat loss before maximizing the heat gains followed by the optimisation of the essential building elements and the implementation of the necessary equipments in the cold regions such as a highly efficient ventilation system with heat recovery. Furthermore, the implementation of a passive house concept in a cold climate needs to be based on sensible solutions regarding material use, and, on a practical level, using available technologies and resources. The adaptation of a passive house in the Arctic needs to take into account also different socioeconomic conditions, building traditions and use of buildings, survival issue, sustainability and power supply, among others. In the Arctic, the energy efficient house based on a passive house concept offers a sustainable solution to the operation of the building with regarding the heating and the consumption of electricity, but, the energy, money investment and CO₂ footprint needed to build such a house would be demanding. Yet, using these energy efficient buildings, there is an opportunity to improve indoor climate, health and security towards extreme climate for the inhabitants in the Arctic areas. Furthermore, the development and usage of extremely energy efficient buildings in the Arctic can lead to new experiences with extremely well-insulating building components, airtight constructions and well-functioning ventilation systems.

Resume

Arktis er klimatisk meget forskellig fra et tempereret klima. I de arktiske områder, når den omgivende temperatur ekstreme værdier, hvilket har stor indflydelse på varmetabet gennem klimaskærmen, som skaber problemer under fundamentet på grund af permafrosten. Solens mønster er helt anderledes på grund af den begrænsede anvendelighed om vinteren, men om sommeren står solen over horisonten 24 timer i døgnet. Endvidere bestråler solen lodrette uigennemskinnelige elementer i lave vinkler. De stærke vinde og storme påvirker infiltration af bygninger meget og har stor indflydelse på varmetabet gennem klimaskærmen. Vindens mønstre har store indflydelse på det lokale mikroklima omkring bygningen og skabe snedrive, samt problemer med optøning, isdannelse og mulig kondens i klimaskærmen. Fugtigheden indendørs drives ud igennem klimaskærmen om vinteren grundet trykforskellen, kraftig vind, samt et lavt vandindhold i luften udenfor. Arktis er også defineret ved forskellige forhold som byggeteknikker og tilgængeligheden af materialer og energiforsyning.

Passivhuse princippet benytter den grundlæggende idé med et super energieffektivt hus, hvor det normale vandbaserede varmeanlæg kan udelades. Bespareserne opnåede ved investering i et traditionel vandbaseret varmesystem bruges på energibesparende komponenter såsom øget isolering, super lufttæt klimaskærm, energi effektive vinduer til opnåelse af solvarme, og et ventilationssystem med en meget effektiv varmegenvinding. At designe et passivhus ud fra metoden defineret af Wolfgang Feist, grundlæggeren af Passivhaus Institut, må husets årlige varmebehov ikke overstige $15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$, og det samlede primære energibehov må ikke overstige $120 \text{ kWh}/(\text{m}^2 \cdot \text{a})$. Luftsiftet for huset skal ligeledes begrænses til $0,6 \text{ h}^{-1}$ ved et overtryk på 50 Pa. Beboelsesarealet er veldefineret i henhold til normen som et nettoareal, og varmen på $10 \text{ W}/\text{m}^2$ kan leveres af opvarmet frisk luft, igennem varmegenvinding enheden der sikrer en tilfredsstillende indendørs luftkvalitet. Et passivhus benytter også fordelene i de gratis gevinster, såsom solvarme, intern varmetilskud fra personer og husholdningsapparater, samt andre kilder.

Hypotesen opsat i denne afhandling er at teste muligheden for en ny anvendelse af en ekstrem energieffektiv bygning i det Arktiske. Formålet med denne Ph.D. afhandling er at bestemme den optimale udnyttelse af et energieffektivt hus i Arktis med udgangspunkt i den grundlæggende definition af et passivhus, undersøgelser af bygnings parametre herunder klimaskærmen og systemer, og undersøgelser af de afgrænsede situationer i de arktiske områder.

Formålet med undersøgelsen er at analysere aktuelle passivhus standarder, som anvendes i tempererede klimaer, gennem den energimæssige ydeevne af et passivt hus under arktiske forhold. Det er i teorien muligt at opfylde de grundlæggende definitioner af et passivhus i Arktis og dermed spare udgifterne til traditionel opvarmning, men dette ville medføre store omkostninger i form af byggematerialer, levering af tekniske løsninger af meget høj standard, hvilket ville tage mange år at tilbagebetale i relation til bygningens levetid. Den grundlæggende definition, der gælder i alle klima zone kan realiseres i de arktiske regioner med meget store omkostninger ved benyttelse af grundlæggende design værdier, samt de bygningsteknologier der er til rådighed i Arktis.

Baseret på undersøgelser, stammer den optimale energimæssige bygning fra passivhus konceptet. Passivhus optimering følger de vigtigste design regler i Arktis, og det er fokuseret på at minimere

varmetabet før varmen tilskuddet maksimeres efterfulgt af en optimering af de væsentligste bygningsdele, samt gennemførelsen af det nødvendige ekvipering, som et meget effektivt ventilationsanlæg med varmegenvinding, i de arktiske regioner. Desuden skal gennemførelsen af et passivhus koncept i arktisk klima være baseret på fornuftige løsninger med hensyn til materialeforbrug, og på det praktiske plan, ved hjælp af tilgængelige teknologier og ressourcer. Der skal ligeledes tages højde for forskellige socioøkonomiske forhold, byggeskik og brugen af bygninger, bæredygtighed og strømforsyning, ved tilpasningen af et passivhus i Arktis. Et energieffektive hus i arktisk som er baseret på et passivhus koncept tilbyder bæredygtig løsning for driften af bygningen med hensyn til opvarmning og forbrug af el, men dette vil være meget krævende at bygge sådan et hus grundet energien, den økonomiske investering og CO₂-aftrykket. Men ved at bygge disse energieffektive bygninger, er der mulighed for at forbedre indeklima, sundhed og sikre beboerne mod ekstrem vejr i de arktiske egne. Desuden kan udviklingen og brugen af ekstremt energieffektive bygninger i Arktis føre til nye oplevelser med ekstremt godt isolerende bygningsdele, lufttæt konstruktioner og velfungerende ventilationsanlæg.

Symbols and abbreviations

A_{gross}	Gross heated area	[m ²]
A_i	Surface area	[m ²]
A_{TFA}	Treated floor area	[m ²]
A_w	Window area	[m ²]
C_{AIR}	Heat capacity of air	[Wh/(m ³ ·K)]
O	Oil consumption	[litres]
D	Number of days	[-]
\varnothing	diameter of insulated pipe	[mm], [m]
e	Ratio of total floor area to footprint area	[-]
f_T	Temperature factor	[-]
g, g-value	Solar energy transmittance	[-]
G	Solar radiation on vertical surfaces	[kWh/(m ² ·a)]
Gh	Global radiation horizontal	[kWh/(m ² ·a)]
Gk	Global radiation on tilted surface	[kWh/(m ² ·a)]
HDH	Heating degree hours	[KKh/a]
HDD	Heating degree days	[Kd/a]
λ	Thermal conductivity	[W/(m·K)]
l_i	Length of outer thermal bridges	[m]
n	Infiltration at normal pressure	[h ⁻¹]
η_{HR}	Efficiency of heat exchanger system	[-]
$n_{\text{infiltration}}$	Infiltration air change rate	[h ⁻¹]
n_V	Effective air change rate	[h ⁻¹]
$n_{V,\text{System}}$	Average air change rate	[h ⁻¹]
n_{50}	Air change rate at 50 Pa	[h ⁻¹]
η	Efficiency	[%], [-]
q_{50}	Leakage rate at 50 Pa	[l/s m ²]
Q_T	Transmission heat loss	[kWh]
Q_V	Ventilation heat loss	[kWh]
Q_{inf}	Infiltration heat loss	[kWh]
Q_I	Internal heat gains	[kWh]
Q_S	Solar gains	[kWh]

ψ	Linear heat coefficient	[W/(m·K)]
r_i	Shading factor	[-]
ρ	Air density (1.2 kg/m ³)	[kg/m ³]
S_i	Solar radiation on vertical surface	[kWh/m ²]
T_{supply}	Temperature of the supply air after the heat exchanger	[°C]
$T_{extract}$	Extract air temperature	[°C]
$T_{amb,j}, T_{ambient}$	Average monthly temperature	[°C]
$T_{avg,a}$	Average annual ambient temperature	[°C]
T_{base}	Base temperature	[°C]
T_i	Interior design temperature	[°C]
$T_{outdoor,design}$	Temperature of outdoor design day	[°C]
$T_{supply,air}$	Maximum supply air temperature	[°C]
U_i , U-value	Thermal transmittance	[W/(m ² ·K)]
V	Volume of a building	[m ³]
V_{net}	Internal volume of a building	[m ³]
V_V	Volume of air	[m ³]
V_{RAX}	Reference volume of the ventilation system	[m ³]
$V_{1,2}$	Climate scenarios, temperature difference	[°C]
V_{50}	Air flow at 50 Pa	[l/s], [m ³]
w_{50}	Air change rate at 50 Pa	[l/s m ²]

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1 Introduction

1.1 Energy use worldwide

The environmental impact from human habitation in buildings has increased dramatically in the last half of the twentieth century in which a higher comfort level in buildings has led to a construction of many buildings which use tremendous amounts of non-renewable sources such as electricity and oil. The energy consumed in the building sector originates from both non-renewable and renewable resources. The non-renewable resources are limited and close to depletion, and natural gas and oil resources may be depleted by the year 2050. Furthermore, coal and uranium will run out in the year 2140 [1]. A natural resource is a non-renewable resource often used in the building sector, i.e. replaced by natural processes and parts of the natural environment and eco-system. The renewable resources are wind power, hydropower, solar energy, geothermal energy, bio fuel and biomass.

Energy use in the world is divided between three major sectors: the transport, building and industry sectors with the following distributions (Fig. 1). In the European Union, residential and office buildings together use up to 25% [2] whilst approximately 40% of the total energy consumption is used in the building sector in developed countries, i.e. USA: 22% in residential and 19% in commercial buildings [3]. The energy consumed in the building sector comprises energy needed to cover heating / cooling, hot water consumption, lighting, electricity and other areas. The amount of energy used per household varies widely and depends on standard of living, climate, and building structures. The average household in a temperate climate has an annual household energy use of total 20,000 kWh/a (Fig. 2) [4].

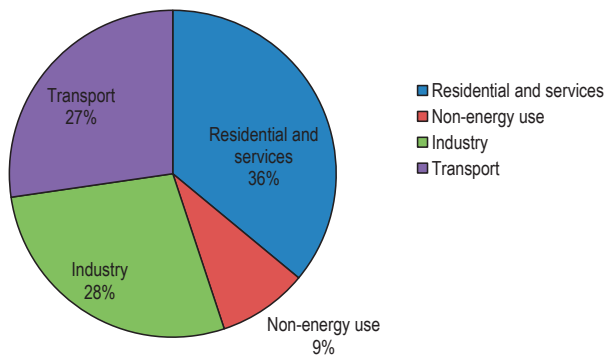


Fig. 1. Primary energy use in EU in 2008 [2]

Reduction of energy demand and energy consumption in buildings is the key factors in reducing the depletion of natural resources and limiting emission pollutants. The desire for a better energy scenario demands more sensible solutions within the building sector, specifically speaking of residential housing, commercial buildings and other buildings offering services. The current average total energy consumption in buildings is 250 kWh/(m²·a) or higher in Germany [5]. As seen

in Fig. 2, the largest amount of consumed energy in a household is related to the heating of the buildings and it is usually more than half of the total consumption. Annual energy used for space heating varies for residential houses in a temperate climate from 100 to 250 kWh/(m²·a) [5].

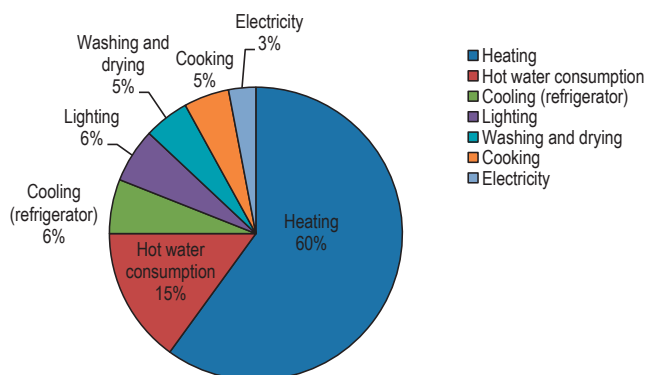


Fig. 2. Energy use in a household in a temperate climate of Germany [4]

Reviewing the national Statistics for countries with a cold climate provides information on energy consumption in these cold countries which varies from 181 kWh/(m²·a) in Norway [6], 213 kWh/(m²·a) in Canada [7], to 416 kWh/(m²·a) in Greenland [8]. The heating consumption is covered by natural resources, e.g. oil based heating system or electricity systems. Renewable resources are being experimented with and they are slowly being adopted to supply this energy through hydropower and wind power, among others. However energy obtained from natural resources is more often used due to availability and it is currently cheaper due to the absence of Value Added Tax.

Those regions with extremely cold climates represent challenges for building construction of energy efficient housing. The building challenges are based on the following criteria: environmental conditions, lifestyles and construction season. The harsh environmental conditions are characterized by prevalent low temperatures, drifting snow and strong wind. In cold climate regions, different lifestyles, which include a wide range of cultures and lifestyles, exist and some of these can generate considerable moisture indoors and often require a high indoor temperature. The short construction season is defined by high transportation costs and difficulties due to the remoteness of the region, the availability of skilled labour and high technology equipment, and high energy costs [9].

Firstly, it is important to bring focus to the bad state of the houses in the Arctic regions, as many houses offer unsuitable living conditions with high energy costs. Thus, it is important to come up with new ideas for highly energy efficient buildings which will improve both existing and new houses. There is a need for super energy efficient houses with a minimum yet reasonable use of energy within the cultural, technical and environmental aspects in the extreme climate of the Arctic. Therefore, the relevance of this study is significant for the Arctic regions.

1.2 Research questions

The Ph.D. project “Passive houses for Arctic climates” deals with the possibility of building a passive house in the extreme climate of the Arctic. Using the fundamental techniques of a passive house in the same way as in Europe and implementing these in the Arctic will lead to an energy reduction, comfortable indoor climate and, furthermore, the CO₂ emissions will be lowered. The thesis offers a perspective on designing a passive house in the Arctic climate including the importance of factors such as energy savings and energy supply. The work on the thesis started with the analytical procedure of asking basic research questions which are used for formulating a problem and mapping the issues in the Arctic. The first three questions have been defined to analyse the possibility of using a passive house definition in the Arctic. The last question describes the outcome of such an analysis, i.e. a super energy efficient house for the Arctic.

1. Can the European definition of a passive house be adapted and applied in the Arctic countries?
2. How will a European passive house perform in Greenland (Arctic)?
3. Could a passive house from the Arctic stimulate the development of low energy building technology in other climates?
4. What would be an energy efficient building for Arctic climates?

In this thesis, the main focus is on residential buildings (detached, semi-detached, and multi-storied), on energy analyses of a new building and also on energy renovation of old buildings. Knowledge concerning the current status of housing in the extreme climate regions is based on personal research performed in Greenland, literature reviews on other Nordic countries and application of the knowledge to the Arctic regions. The research carried out in Greenland consists of the investigation of air tightness using a blower-door, indoor climate using temperature and relative humidity sensors, and monitoring of energy consumption. These investigations were performed on old standard wooden family houses (typehouse 18D) [10], newly built houses, the dormitory Apisseq and the Low-energy house in Sisimiut [11].

1.3 Outline of the thesis

The structure of the thesis follows the methodical approach used in the research and it is graphically represented in Fig. 3:

Technology, Energy, Security, Supply, Temperature stability / Survival

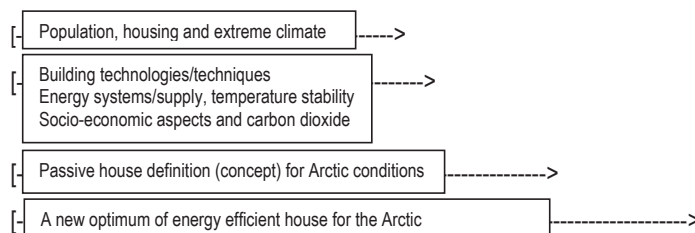


Fig. 3. Analytical methodology with representation of outline for thesis

Chapter 2 studies passive houses in the European climate, including a fundamental definition and implementation of a passive house.

Chapter 3 describes a methodology used in the building optimisation of a passive house concept.

Chapter 4 discusses the extreme climate regions regarding definitions, climate and the Arctic population. Furthermore, the past and current residential buildings and building technologies in the Arctic are described along with energy systems in buildings.

Chapter 5 concerns performance of a fundamental passive house in the Arctic along with the revealing of the main parameters for performance-decisive design.

Chapter 6 concerns the evaluation of design variables for optimising a passive house in the Arctic using different optimisation methods for the design principles of a passive house.

Chapter 7 describes other constraints and challenges for building a passive house in cold climate regions.

Chapter 8 discusses the applicability of a passive house in the Arctic regions and an optimised energy efficient house, based on the adaption of a passive house idea, is described along with recommendations.

Chapter 9 summarizes the conclusions of the thesis.

1.4 Objective of the thesis

The objective of this thesis lies in the research on passive houses and their usability in the extremely cold climate of the Arctic. The research shows that the method of building energy efficient houses in the European climate is different from the one used when building in the Arctic. The work in this thesis focuses on the methods and principles describing how to design an energy efficient house for an extreme climate using the passive house input [12]. The scientific relevance of the thesis lies in the hypothesis of the technical improvement of a passive house and its usage based on scientific method focused on an optimal house for the Arctic with a minimum, yet reasonable, use of energy within the cultural boundaries. The relevance of this project is built on an enhancement of the development of sustainable buildings in those regions where heating consumes a major part of the natural resources.

The development of extreme low energy buildings in general, and passive houses specifically, has lead to new experiences with extremely well-insulating building components, airtight constructions and well-functioning ventilation systems. Using these elements, there is an opportunity to improve indoor climate, health and temperature stability against extreme climate for the inhabitants in the Arctic areas. This study provides a detailed investigation of the consequences of “displacing” a passive house from a temperate to the Arctic climate – what it means to the energy consumption, and what it would demand to still be able to reach the passive house criteria. The basic motivation of the author is not to define something else and call that a “passive house”, but actually to take relevant experiences and implement them in building construction in the Arctic. However, this is merely one approach to find some sensible demands and characteristics for buildings in the Arctic, which is based on the derivation of a passive house; - but it should be named something else.

2 The European passive house

There are many different types of energy efficient houses, e.g. low energy, Minergie®, 0-energy, energy+ houses, active houses, energy star homes, ultra houses and passive houses, and many others. One of the well defined energy efficient buildings is a passive house which is very often built in the temperate climate of Europe and the United States. The passive house originates from the idea of Bo Adamson and Wolfgang Feist. In the late 1980s, Adamson had a project in China concerning the renovation of houses for poor people. These houses were built in areas with limited access to fuel and without conventional heating systems and these houses were called “passive houses”. Adamson’s task was to improve them without making them “active”, i.e. without using active heating represented by a conventional heating system. The concept of a passive house was implemented by Wolfgang Feist from the Passivhaus Institute, Germany [13]. The first passive house to be built was the Kranichstein, Darmstadt, Germany, built in 1991 (Fig.4).



Fig. 4. Passive house Kranichstein, Darmstadt, Germany [14]

A passive house concept is a super insulated and airtight building envelope which utilises solar and internal gain in a way in which it is possible to use low load heating which is delivered by fresh air through the ventilation system with heat recovery. Therefore, costs are saved due to the fact that a traditional heating system is not necessary (Fig.5). The 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%) provided from building systems [15]. The house is further equipped with efficient building services supplied by renewable resources to cover hot water consumption and other necessities. Using a heat recovery system in the ventilation system is a passive technique which only works in the most efficient way if the heating load is very low. The investigation of fundamental techniques and measured experiments led to the establishment of the main criteria for a passive house (fundamental definition).

2.1 Definition of a European passive house

Two versions of a passive house definition exist: a popular definition for a broader and non technical audience and a scientific definition for researchers and building manufactures. The popular definition of a passive house refers to the use of a mechanical ventilation system with highly efficient heat recovery which guarantees good indoor air quality. The scientific definition refers to the limited heating load which can be supplied by minimum required ventilation air; however, the space heating does not have to be supplied through the ventilation systems.

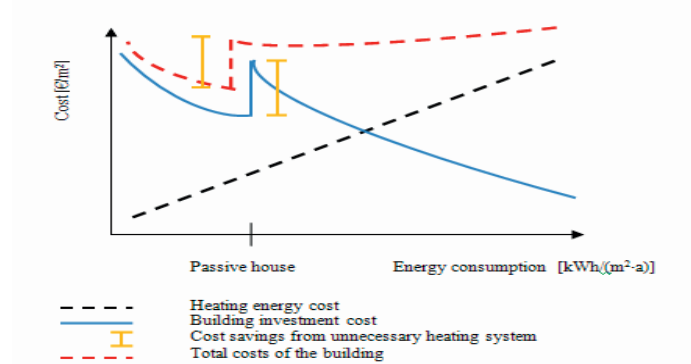


Fig. 5. Passive house savings without conventional hydronic heating system [13]

Passive house requirements can be applied in Central Europe and countries with similar climate. But the rules and underlying principles can apply in all climates. The definition itself does not depend on the climate and holds for 40° to 60° Northern latitudes. For latitudes above 60°, several attempts of a passive house application have been made including an adaptation of the original / fundamental definition of a passive house followed by a changing of the definition based on local conditions.

Main definitions and requirements for a passive house as required for certification (Fig. 6) [13]:

- $\leq 15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ for heating and cooling related to treated floor area (A_{TFA} , [16]), retrofit to passive house standard $\leq 25 \text{ kWh}/(\text{m}^2 \cdot \text{a})$
- $\leq 10 \text{ W}/\text{m}^2$ for heating and cooling load related to treated floor area (A_{TFA})
- total primary energy use $\leq 120 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ related to treated floor area (A_{TFA}) for space heating/cooling, ventilation, hot water demand, electricity for fans and pumps, household appliances and lighting energy
- air tightness $n_{50} \leq 0.6 \text{ h}^{-1}$ at 50 Pa pressure difference, tested by a blower-door

A passive house makes sure that only the usable space is taken into account and this results in more stringent rules regarding the building performance, i.e. it forces designs with a greater surface area to work harder to achieve the standard, taking into account how much energy a building uses. Using the living or useful area within the thermal envelope pushes towards the goal of an energy efficient building form, i.e. maximizing the usable living area as part of the overall strategy of minimizing the surface and heat loss of the building.

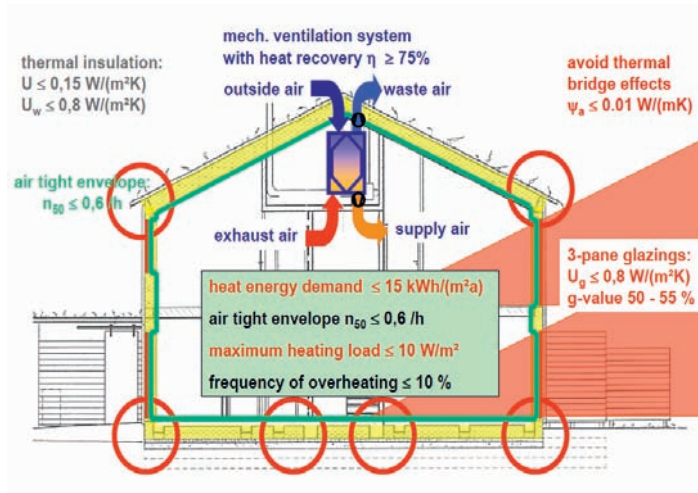


Fig. 6. Passive house qualities - basics [16]

All gains and losses refer to the treated floor area (A_{TFA}) which is calculated based on the German Floor Area Ordinance [16] and refers to the floor area inside the thermal envelope, i.e. often referred to as “carpeted floor area”. The treated floor area includes the floor area of all rooms determined by the clear width between building elements (built-in furniture, baseboards and non-detachable baths or showers, etc.). The floor area of rooms with a height of 2 metres is added completely, the floor area of rooms with a clear height between 1 m and 2 m is added with the half area, and the floor area of rooms with a lower clear height are neglected. Not included within the floor area are chimneys, installation walls, columns, etc, with heights exceeding 1.5 metres and abase area of more than 0.1 m^2 , stairs with more than three steps and their landings. Basements are not regarded as living space and are only accounted for 60% if they are located inside the thermal envelope and have a room height of at least 2 m. All rooms located outside the thermal envelope cannot be added to the treated floor area.

Boundary conditions and computation rules concerning a passive house applicable in a temperate climate:

- calculation with treated floor area (A_{TFA}) represented as “carpeted area” calculated with internal dimensions [16]
- default occupancy $35 \text{ m}^2/\text{person}$ (20 m^2 to 50 m^2)
- solar orientation with minimal glazing to the north, shading to prevent overheating
- frequency of overheating $\leq 10\%$ ($> 25^\circ\text{C}$) EN 15251
- an interior temperature which needs to be homogeneous within the entire house
- internal gain 2.1 W/m^2 from people, household appliances, and lighting
- interior design temperature 20°C (T_i)

Building envelope:

- thermal mass within the building envelope with thermal insulation with U_{envelope} ranging from 0.09 to $0.15 \text{ W/(m}^2\text{K)}$

- thermal bridge free construction with linear heat coefficient $\psi \leq 0.01 \text{ W/(m}\cdot\text{K)}$, balance of negative and positive heat loss through the thermal bridges
- for the thermal local comfort the temperature is distributed evenly on the interior surfaces of the walls to prevent heat loss and mould growth
- triple glazed window $U_{\text{window}} < 0.8 \text{ W/(m}^2\cdot\text{K)}$ with solar energy transmittance $g \geq 0.5$ and door $U_{\text{door}} < 0.8 \text{ W/(m}^2\cdot\text{K)}$, insulated frames, insulating gas between the panes filled with argon or krypton, low emissivity coating on the internal pane, three panes which are separated by low-conductivity spacers
- one continuous airtight layer all around the whole heated building volume, tested by a blower-door in accordance with EN 13829 [17], $n_{50} \leq 0.6 \text{ h}^{-1}$ at 50 Pa

Systems:

- mechanical ventilation system with heat recovery with a minimal electric consumption, an average efficiency of $\eta \geq 75\%$ providing air quality through ventilation rate min 0.3 h^{-1} (average air flow rate $30 \text{ m}^3/\text{person}/\text{hour}$ or national regulation if higher) with regular maintenance
- air temperature supply $< 52^\circ\text{C}$
- air exhaust default values: kitchen $60 \text{ m}^3/\text{h}$, bathroom $40 \text{ m}^3/\text{h}$, shower $20 \text{ m}^3/\text{h}$, WC $20 \text{ m}^3/\text{h}$
- specific fan power $\leq 0.45 \text{ W/(m}^3/\text{h)}$
- domestic hot water demand: 25 litres/person day of 60°C water, cold water temperature 10°C
- compact fluorescent lighting, energy labelled household appliances (A or higher)
- the recommended maximum value for the electricity consumption is $18 \text{ kWh/(m}^2\cdot\text{a)}$ with the recommended specific primary energy demand for household electricity $50 \text{ kWh/(m}^2\cdot\text{a)}$

The following systems can provide supplement heat generation: a biomass combustion unit for biomass fuel, e.g. pellets, logs, and wood chip, with 90% efficiency and 3 - 5 kW output depending on the size of the house, a compact burner, e.g. natural gas, oil, or a compact unit with heat pump. On-site renewable additional systems are solar thermal panels which will cover the hot water consumption, photovoltaic panels which will cover the electricity consumption, rainwater recycling, wind turbine, co-generation, e.g. district heating, earth-to-air heat exchanger, among others.

In accordance with the fundamental definition in the Central European and central US climates ($40^\circ - 60^\circ$ Northern latitudes), the European passive house has the following characteristics regarding the building envelope: $U_{\text{envelope}} < 0.15 \text{ W/(m}^2\cdot\text{K)}$ for ceiling, wall and floor, and $U_{\text{window}} < 0.8 \text{ W/(m}^2\cdot\text{K)}$ with insulated frames and triple pane glazing with low-e coatings and “warm edge” with insulated frames for windows and windows glazing $g \geq 0.5$. The air tightness of the building envelope is $< 0.6 \text{ h}^{-1}$ at 50 Pa pressure difference. The indoor climate, heating and ventilation is provided by the recovery heat from the air with a heat exchanger ($\eta \approx 80\%$). The total primary energy demand must be below $120 \text{ kWh/(m}^2\cdot\text{a)}$, including the hot water consumption $10 - 15 \text{ kWh/(m}^2\cdot\text{a)}$ and the electricity $10 - 15 \text{ kWh/(m}^2\cdot\text{a)}$.

2.2 Implementation of a European passive house

The passive house concept is being implemented worldwide from the Central Europe regions of 40° - 60° northern latitudes, the Nordic regions > 60° and the Mediterranean regions < 40°. For instance, a project called CEPHEUS in 1998-2001 is part of the promotion of Central European passive houses [18]. Another example of a Nordic passive house is the project North-Pass in 2009-2012 [19] and in the Mediterranean regions there is the project named Mediterranean passive houses in 2009 [20]. There are also several attempts to alter the passive house definition to make it possible to build such a house in different climates with larger temperature differences. There are some semi-official definitions which are in the process of being implemented in the following countries: Sweden [21], Norway [22] and Finland. In general, the regulations are often focused on the total consumption or heating consumption respectively based on energy calculation and on the end energy, i.e. all energy consumed in a building, but not including the energy costs included in energy factors, and primary energy which include energy costs for extraction, conversion and transportation of renewable or non-renewable resources. Beside the alteration of space heating demand and heating load, the primary energy with equivalent energy conversion factors, and the calculation of the floor area, are all altered to meet different national requirements.

The passive house concept has been successfully applied in regions with a temperate climate. The above-mentioned projects prove that there is eminent interest for passive houses in the more demanding climates of Scandinavia and elsewhere. The focus is on the applicability of a passive house concept in different climates, and thus, the possibility of energy savings is very attractive for regions with extremely cold or hot climate conditions. Mainly due to very high cost and problems related to a specific climate, often, the passive house concept is being altered to fit such a climate instead of full meaning adaptation. The alternation of a passive house concept in more demanding regions is focused on relating the energy consumption for heating to the average climate temperatures and on increasing the peak of heating load in order to avoid over-dimensioning the building envelope and systems. The strictly calculated treated floor area is also altered to allow for the energy consumption to be spread over substantially thick building elements. In general, the above mentioned projects and alterations have provided valuable background for this thesis and they were used as inspiration.

3 Methods for optimisation

3.1 Background for optimisation methods

Optimisation methods consider one or more *objective function*, *decision variable* and *constraint* as subjects to the limitations in the mathematical operations. The *objective function* is a function expressing a value that can be optimized, i.e. minimized or maximized. The function can be expressed by using mathematical expressions or as a qualitative parameter. *Decision variables* are parameters within a model which one can vary and control. The *constraints* represent limits imposed on decision variables, or functions of these. In theory, the objective function and decision variables can be unconstrained and, thus, be any value. In reality, the objective function or decision variables are often subjects to limitations using a set of constraints. The optimisation problem makes it possible to specify different requirements for the decision variables, as well as for the performance measures. An optimisation method is typically required in order to find a global optimum expressed as either a minimum or a maximum of the objective function. The objective function is subject to upper or lower limits. Finally, there are *boundary conditions* which are the conditions that are set and cannot be changed.

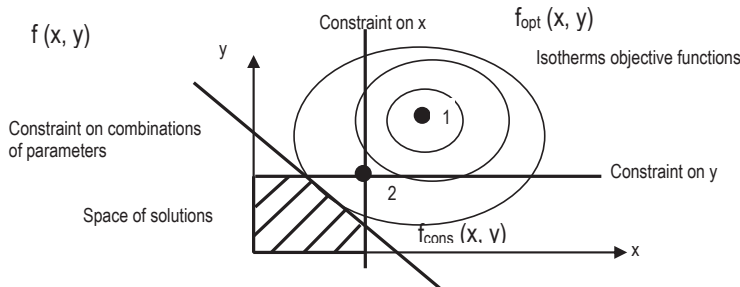


Fig. 7. Illustration of an optimisation problem as a function $f(x, y)$

In Fig. 7, the optimisation is found as a global optimum ("1") representing an optimal value at an unconstrained case. The constraints on the axes ("x" and "y") limit the solution to ("2"). The constraints on the combinations of parameters are further limiting the possible space of solutions. Thus, the optimal solution needs to be found in the area which offers an optimum subject to all constraints (marked as a hatched area in Fig. 7).

There are many possible optimisation methods [23]. The general optimisation methods considered in this study are described as the following:

1. "A single objective" method uses one *measurable objective* which is defined by one objective function and optimised based on different constraints using mathematical operations.
2. A "multi-criteria" method uses several *measurable objectives* which lead to a set of possible solutions defined by mathematical operations.
3. A "qualitative" method which is represented as a *qualitative objective* as it can be difficult to measure and can be expressed as a subjective parameter.

A single objective method uses an optimisation method in which one objective function is optimised using a set of constraint functions. This method improves an objective function to the optimised value which is either a minimum or maximum value. In the multi-criteria method, it is assumed that it is not possible to make a decision which provides optimum values for all decision criteria. Thus, the aim is to improve all objectives as much as possible, by finding a set of solutions in which it is not possible to improve one objective function without deteriorating one or more of the others. Then, that solution is called the Pareto efficient [24]. The qualitative methods are used to identify the constraints which influence the optimisation problem in a subjective way as these can be too overwhelming due to the specific issues. The combination of the above-mentioned methods, objective functions, different decision variables and the set of constraint parameters, along with boundary conditions, provides the base for a building optimisation for a specific climate.

3.2 Optimisation methods for a passive house for the Arctic climate

When it comes to the research, the general approach to building and managing the design process is to divide the process into phases. The processes can be divided into three main phases with the following design tasks: *conceptual design*, *main design* and *detailed design* [25]. In this thesis, the focus is on the “*design principles*” of a building located in extremely cold climate, i.e. the pre-design principles of constructing houses in a specific climate based on the climate characteristics, building boundaries and design solutions, and many other factors.

The following methods are used to optimise the building performance of a passive house for the Arctic climate: a *single objective*, *multi-criteria* and *qualitative* method. The purpose is to find the most rational way to make a passive house under the constraints and building conditions of the Arctic.

Cost, indoor environment, environmental impact and energy consumption would be just a few of the typical objective functions.

The *objectives* in this thesis are divided into *measurable*, single and multi-criteria respectively, and *qualitative objectives*.

1. Measurable objectives, i.e. what is possible to achieve by investigating energy performance measures of energy efficient buildings: heating demand, minimizing heat loss and maximizing solar gains through the corresponding building elements within the practical limits of the constructions, air heating, and ventilation efficiency.
2. *Qualitative objectives*, i.e. which are more subjective, but they can be still measured: lifestyle preferences, thermal indoor comfort, temperature stability, and sustainable value of the insulation, socio-economic conditions along with culture gap and energy supply.

The *constraints* are certain limits, for instance, limits to heat loss and energy consumption which are needed in order to achieve the performance measures for a passive house which allow it to be certified as a passive house. These parameters are related to the so-called treated floor area (A_{TFA}) and they are the upper limits of a heating demand of 15 kWh/(m²·a), a peak heating power of 10 W/m² and total primary energy of 120 kWh/(m²·a) required for heating, cooling, domestic hot water, auxiliary and household electricity. There are also other constraints, for instance, related to indoor environment criteria and several other factors.

The identified *constraints* on the decision variables represented as the criteria regarding building limitations and design solutions are listed as the following:

- Building - limitations on insulation thickness; a window area to make the most of solar gains and to minimize heat loss through windows along whilst achieving daylight indoors.
- Design - denser living area, higher need for ventilation and increased interior temperature.
- Ventilation system - the ability to use air heating and the energy needed for after heating.
- Qualitative solutions - reasonable, feasible and not too complicated.

Decision variables or performance decisive-parameters respectively, refer to the set of variables which have a very significant relevance for the building design and energy performance of buildings. In this study, the decision variables are:

1. The insulation used in the building envelope: insulation thickness and thermal conductivity.
2. The windows: area, type, orientation, thermal transmittance and solar transmittance.
3. Air tightness of the building envelope: methods of conversion to neutral pressure, importance.
4. Heating system: efficiency, electricity, supply air temperature without heating.
5. Ventilation system: efficiency of heat exchanger, electricity.

Boundary conditions are parameters used as input values which represent necessary conditions used in analyses. These parameters will have constant values and are listed as the following:

- Location of a building: latitude, longitude, altitude.
- Weather data including mainly temperatures and solar radiation amount and availability.
- Design days with extreme temperatures and no solar gain in order to achieve a heating load of 10 W/m².
- Building design techniques - lightweight insulated structures, elevated foundations.
- Calculation methods: an internal heat gain of 2.1 W/m² or 5 W/m² and an air change rate 0.3 h⁻¹ or 0.5 h⁻¹.

In this thesis, the model “Kranichstein” is used for comparison along with several reference cases represented by actual buildings in Greenland. These buildings are: old standard wooden houses “Typehouse 18D” [10], dormitory “Apisseq” [26] and the “Low-energy house” in Sisimiut [11].

In this study, the main focus is on the building optimisation of construction elements which have a known and rather small uncertainty; for instance, the uncertainties of the thermal performance of the insulation materials are very small. In this study, the parameters which may create large uncertainties in the Arctic are not considered. For instance, it could be a fact that the economic costs of building elements could vary extensively in the Arctic due to monopoly. Other possible factors could be a hesitance to using new building methods, extra costs for transportation and limited availability of building materials, among others. Furthermore, a higher quality and accurate design weather data in the Arctic locations would be needed to achieve the most representative detailed model of an energy efficient house based on the passive house idea. Overheating and types of shading are not considered as they are rather unimportant problems in the Arctic, yet, the building must function and provide a certain level of comfort. The probability of failure using a reliability analyses is not calculated, but the potential problems regarding principles and

requirements of a passive house in an extreme climate are discussed in relation to the cold temperature, building knowledge, and user expectations, among many others.

3.3 Conclusion on optimisation

In this thesis, the analyses are mainly focused on constraints represented by the energy performance and heat load of a passive house. The mathematical optimisation was disregarded as there are too many specific and overwhelming uncertainties, boundary conditions and constraints regarding regions with an extremely cold climate. The focus was on combined investigations of measurable and qualitative parameters which play a major role in energy design. Firstly, single measurable parameters were investigated in order to see the influence on important constraints; furthermore, these parameters were limited to a reasonable and possible solution based on physical limits, other constraints and boundary conditions. In the next step, a multi-criteria method was applied through a combination of measurable objectives and it has led to several solutions. The measurable objectives were further limited by qualitative objectives. These qualitative parameters represent the objectives and challenges for a passive house located in the Arctic regarding sustainability, thermal comfort, temperature stability and socio-economic conditions along with energy supply.

Using this combined method of measurable and qualitative objectives, in which the decision variables, constraints and boundary conditions were implemented, has led to the finding of an optimum solution area. This area offers a space of solutions where all constraints are combined to give practical and reasonable solutions. Using a classic mathematical approach may have suggested another set of solutions; yet, by using such a set of solutions, the qualitative objectives would still need to be implemented. The optimal solution is based on an opinion which has been rationally argued and it considers how it can be done in reasonable and practical ways in an ideal world. In this thesis, the adaptation and optimisation of a passive house offers an energy efficient solution within the constraints in the Arctic regions taking into account all parameters regarding energy, excessive improvements of building elements, the extremity of climate, and the feasibility and practicality of optimisation.

4 The Arctic

4.1 Definition, climate and population

The Arctic and Antarctic have many different definitions starting with a *geographical* location, a *climatological* definition and a *climate* definition [27], among others. Geographically, the Arctic and Antarctic are defined by the Polar Circles at 66°33'38 Northern and Southern latitude. The land above the Polar Circle amounts to 5.6% of Earth's surface area. The Arctic is represented by the countries of Greenland, the northern parts of Scandinavia (Finland, Sweden, and Norway), Russia, Canada and Alaska. Climatologically, the Arctic is defined by treeless zones of tundra, unthawed permafrost of 2 meters depth and an isotherm of 10°C in July (Fig. 8). Climate-wise, the Arctic is represented by polar climate, alpine climate, and continental subarctic and taiga.



Fig. 8. Definition of Arctic based on discontinuous permafrost, Arctic Circle, 10° July isotherm, tree line

Approximately 0.06% of the world's population, or 4,000,000 people, live in the Arctic, and only 1,000 to 5,000 inhabitants live in the Antarctica and these are mostly scientific researches. Out of the 4 million, 90% people live between latitude 66° and 70°. The remaining 10% of the population live in latitudes 70° to 75°. The largest population number is found in the city of Murmansk which has a population of 325,100 at latitude 67.5°. There are also many small settlements scattered mainly along the costs of the Arctic regions with populations ranging in the thousands. Considering the Arctic climate, the inland areas between 60° and 66° with approximately 15 million people are regions which could potentially be characterised as Arctic. Also the regions at high altitudes with alpine climate are of interest such as mountain locations, like the Alps, and those locations with extreme climates such as Harbin in China. Yet, locations at high altitudes have solar gains compared to the locations above 66° latitude.

In Table 1, the statistics refer to the population of the Arctic countries as a whole for those countries that are completely within the Arctic. For the other countries, the statistics refer to the geographic areas included in the circumpolar region of the world.

Table 1. Population of Arctic regions and countries accounted for in year 2003 [28]

Arctic country / Regions	Area [km ²]	Population	Population density (per 100 km ²)
Alaska, USA	1,516,000	648,200	43
Arctic regions of Canada	4,191,000	130,300	3
Greenland	2,176,000	56,700	3
Iceland	103,000	288,500	280
Faroe Islands	1,000	47,700	3,410
Arctic regions of Norway	107,000	462,700	431
Arctic regions of Sweden	99,000	253,600	257
Arctic regions of Finland	93,000	187,800	202
Arctic regions of Russia	4,289,000	1,982,500	46

The climate is defined by the climatic elements: air temperature, relative humidity, solar radiation, cloud cover, windiness, and other factors. The climate of the Arctic is characterized by long, cold winters and short, cool summers. The ambient temperature averages from -40°C to 0°C which drops to -50°C as the hourly maximum in winters and an average temperature in summer which varies from -10°C to +10°C exceeding in some areas to 30°C as the hourly maximum (Table 2). Inland areas have more extreme temperatures compared to the coastal locations. The outdoor relative humidity is high, but the moisture content in the air is low.

Table 2. Climate characteristics in the selected locations between 66° - 75° in Arctic and Antarctic regions compared to selected locations between 40° - 55° latitudes, listed by latitudes

Location	Coordinates [°]	HDH [kKh/a] ⁽¹⁾	PHPP [kKh/a] ⁽²⁾	Temperatures [°C] ⁽³⁾		
				Mean annual	Minimum monthly	Mean daily
Würzburg, GE	49.5°N, 9.6°E	95	80	9.6	0.9	-10.6
Harbin, CH	45.5°N, 126.4°E	149	140	2.8	-20.3	-32.3
Copenhagen, DK	55.4°N, 12.3°E	105	83	7.7	-1.0	-21.1
Fairbanks, USA	64.5°N, 147.4°W	199	170	-2.9	-23.4	-43.8
Oulu, FI	65.1°N, 25.3°E	156	124	2.1	-11.0	-29.8
Sisimiut, GL	66.6°N, 53.4°E	209	146	-3.9	-18.5	-32.0
Sodankylä, SE	67.3°N, 26.3°E	183	143	-1.0	-15.1	-37.6
Kiruna, SE	67.8°N, 20.3°E	185	138	-1.1	-13.9	-33.2
Inuvik, CA	68.2°N, 133.3°W	256	206	-9.3	-28.5	-47.5
Murmansk, RU	68.6°N, 33.0°E	177	132	-0.3	-11.6	-31.7
Tromsø, NO	69.4°N, 18.6°E	126	99	5.5	-3.7	-16.8
Barrow, USA	71.2°N, 156.5°W	233	163	-12.5	-27.7	-44.1
Uummannaq, GL	70.4°N, 52.1°E	211	145	-4.1	-16.2	-33.5
Resolute, CA	74.4°N, 94.5°W	319	233	-16.5	-33.0	-45.3

⁽¹⁾ HDH = heating degree hours ($T_{base} = 20^{\circ}\text{C}$) and $HDH = 0.024 \times HDD$; ⁽²⁾ PHPP method (16°C and 10°C);

⁽³⁾ From representative collection of data (DRY, or else) or PHPP, DRY, METEONORM; grey color is inland

In some months, solar radiation is available for 24 hours/day, or it is not present. During the Polar day, solar radiation can reach extreme levels, but it can easily be decreased by a cloud cover in some locations in the Arctic. The sun elevation is low in the Arctic which is shown by the rather low global solar radiation with high amounts of solar radiation on vertical surfaces (Table 3). Most of the Arctic is covered by snow or ice in the winter and this reflects the radiation. The summer has continually low temperatures with a slow snow melt affect [29].

Table 3. Solar radiation in the Selected locations between 66° - 75° in Arctic and Antarctic regions compared to selected locations between 40° - 55° latitudes, listed by latitudes

Location	Coordinates [°]	Global radiation horizontal [kWh/(m ² ·a)] ⁽³⁾	Solar radiation on vertical surface [kWh/(m ² ·a)] ⁽¹⁾			
			South	West	North	East
Würzburg, GE	49.5°N, 9.6°E	1,087	914	695	371	692
Harbin, CH	45.5°N, 126.4°E	992	1,534	980	494	992
Copenhagen, DK	55.4°N, 12.3°E	909	909	654	671	338
Fairbanks, USA	64.5°N; 147.4°W	1,040	1,336	885	409	877
Oulu, FI	65.1°N, 25.3°E	841	927	667	354	673
Sisimiut, GL	66.6°N, 53.4°E	945	1,019	839	442	815
Sodankylä, SE	67.3°N, 26.3°E	816	883	648	310	644
Kiruna, SE	67.8°N, 20.3°E	748	616	438	295	411
Inuvik, CA	68.2°N, 133.3°W	923	1,193	866	464	870
Murmansk, RU	68.6°N, 33.0°E	724	824	618	348	610
Tromsø, NO	69.4°N, 18.6°E	646	705	552	334	531
Barrow, USA	71.2°N; 156.5°W	725	397	700	447	695
Uummannaq, GL	70.4°N, 52.1°E	779	726	623	379	641
Resolute, CA	74.4°N, 94.5°W	921	1,314	1,023	670	1,017

⁽¹⁾ From representative collection of data (DRY, or else) or PHPP, DRY, METEONORM; grey colour is inland

4.2 Residential buildings in the Arctic

In cold climate zones, closed compact building forms are preferably used due to the low ambient temperature in winter which overrules the available solar gain. Simply and tightly massed shapes such as igloos and earth-houses were the norm in the cold climates, until the major exploitation of cheap non-renewable energy from natural resources. In the past, the snow igloo was a sophisticated and compact bundle of building principles fitting into the landscape made of snow blocks and enhanced with each snow blizzard [30]. An igloo accommodates the needs of a family; it is quick to build and has a low surface-to-volume ratio. An igloo is a watertight and waterproof structure with good thermal and vapour resistance and it can easily be heated with the low heat source. The igloo can be considered as one of the first energy efficient houses successfully used in the Arctic. The earth houses, or earth sheltered house respectively, are also very well known and applied building structures in the cold regions which work with nature using landscape as protection and good insulation properties to avoid moisture problems. Another type of native dwelling is a tipi (wigwam) made of wood and animal skin. The tipi is durable, provides warmth and comfort in winter, shelter during heavy rains and a cool place to be in summer. The tipi can be disassembled so it could be moved and packed away quickly.

To investigate energy efficient houses representing several design solutions for the Arctic, several houses were chosen as *reference cases* to use in modelling, analyses and comparison:

- Passive house Kranichstein, Darmstadt, Germany, built in 1991, first example of a passive house, detached family house, $A_{TFA} = 156 \text{ m}^2$ as “carpeted” treated living area by PHI [14]
- Low-energy house in Sisimiut, Greenland, built in 2005, detached family house, $A_{TFA} = 195 \text{ m}^2$ [31]
- Typical standard family typehouse 18D, Greenland, built in 1960s, semi-detached family house, $A_{TFA} = 57 \text{ m}^2$ [10]
- Dormitory Apisseq, Sisimiut, Greenland, built in 2010, energy efficient building, multi-storey dormitory, $A_{TFA} = 1,136 \text{ m}^2$ [32]



Fig. 9. Standard wooden family house, typehouse 18D in Sisimiut, Greenland

The buildings of today are built of lightweight materials with a timber frame loading structure with mineral wool insulation in stud spaces and with a ventilated façade on the outside. A single stud system is used in family houses from 1960s (Fig. 9) [9]. In these, the wood stud is a thermal bridge because of the fact that it has a 3 times larger heat flow than the insulation. These wooden standard family houses are often problematic due to the insufficient amount of insulation and poor air tightness leading to very high energy consumption [10]. The houses also have problems with draft and uncomfortably low temperatures indoors. Nowadays, the double stud system is used to provide more thermal qualities limiting thermal bridges. Today, the houses built with this system are less leaky and have better insulation qualities, but, nevertheless, this type of building is quick to heat up but also quick to cool down. The double stud system and standoff wall systems have a load bearing structure consisting of a timber frame and insulation along with an additional non bearing wall on the exterior (Fig. 11).



Fig. 10. Low-energy house in Sisimiut, Greenland

An example of this is the Low-energy house in Sisimiut in Fig. 10, Greenland, and many houses in Canada. The applied insulation is mineral wool made of fibre glass batts. The sheathing is made from boards of plywood or OSB (oriented strand board) or gypsum boards. The system has a ventilated facade with a wind tight barrier on the outer façade. The vapour airtight barrier is located on the interior or inset no more than $\frac{1}{3}$ inside the total thermal resistance of insulation to secure that the condensation point stays within the vapour airtight layer. The prefabricated systems are the following: a structured insulated panel manufactured (SIP) with polystyrene, polyurethane or glass fibre insulation in the core sandwiched between wood panels or gypsum boards [9].



Fig. 11. Foundation wall / floor / wall junction of a double stud walls and standoff wall systems [9]

The multi-storey buildings (Fig. 11) are usually built with concrete load bearing structures which provide the formwork such as walls, floor, and roof, and additional lightweight wall structures made from timber frames and mineral wool insulation [32]. There are also other types of building structures such as prefabricated concrete building apartments which lack the proper level of insulation and are not airtight. Furthermore, the combined building structures of concrete, steel and timber framework with insulation have been used in the cold climate regions. Often, prefabricated elements are also used and these include rigid expanded polyurethane insulation in foam blocks in pre-determined shapes or laminated with various facings. Due to transport issues, the selection of compact, compressible and lightweight materials with low volume are preferable to reduce the shipping cost. Some experimental buildings have been built in the cold climate to test the performance of various promising building materials and technologies, e.g. paper insulation, sheep wool insulation, snow insulation, among many others.



Fig. 12. Multi-storey dormitory Apisseq in Sisimiut, Greenland

The method for calculating the floor area in the buildings in a cold climate usually refers to the floor area which is defined by the external dimensions of a building. The floor area is defined by the heated floor area (A_{gross}) which is, for example, defined for Greenland as a heated area of at

least 18°C and calculated with the external dimensions of a building [33]. The calculation procedures may vary slightly from one country to another. Using the heated floor area, the energy demand can be distributed over the whole heated floor area including the thickness of the building elements. However, one negative aspect is that the taxation system makes it more expensive to include the wall thickness into a heated floor area.

The energy design of the buildings is done in accordance with a calculation of the demand for energy needed to heat a building using heating degree day (HDD, in Kd/a) or heating degree hours (HDH, in kKh/a) respectively, and with conversion stated in (1). In general, the heating degree method helps to predict the oil consumption and it has been used for several decades to assess the average demand of a household consumption and necessary oil supplies from fuel distributors. The heating degree hours measure the energy needed for heating of which the heating degree days are related to the base temperature, i.e. outside temperature above which the building needs no heating. The heating degree hours (kKh/a) are calculated in (2) using the base interior temperature with the interior design temperature T_{base} (°C) and $T_{amb,j}$ is the average monthly temperature (°C) and D_j is the number of days in a month.

$$HDD = 0.024 \times HDH \quad (1)$$

$$\sum_{i=1}^1 (T_{base} - T_{amb,j}) \times D_j \times 0.024 \quad (2)$$

The heating requirements for a given building at a specific location are considered to be directly proportional to the number of HDD at the location. The energy needed for heating a building (kWh/a) is calculated using the specific heat loss rate through building components (3) using A_i as the surface area of different building elements (m²) and U_i as the U-value of building elements (W/(m²·K)). The oil consumption can be calculated using a conversion value in which 10 kWh of energy equals to 1 liter of oil. Note that the conversion value can differ slightly based on the oil-furnace efficiency.

$$\sum_{i=1}^1 (A_i \times U_i \times HDH) \quad (3)$$

Energy calculations using heating degree method have several problems, i.e. that the heat requirement is not linear with temperature and that heavily insulated buildings have a lower balancing point. This method does not take into account the following: how well insulated a building is, the amount of solar radiation reflecting into the interior of a building and the production of internal heat gain from sources in the interior of a building [34]. Other factors not accounted for are: amount and speed of wind on the outside, thermal comfort expected by an individual, cloud cover, snow and precipitation. Other problems arise because different base temperatures T_{base} are used in standards which are used to compare the climates internationally, for instance, for Greenland, $T_{base} = 19^\circ\text{C}$ is used. For historical reasons, heating degree days / hours are often made available with base temperatures of 18°C and 15.5°C.

4.3 Building techniques and technologies

The needs, objectives and realities of local conditions and user needs should be the basis for the energy design. System concepts and designs from the temperate climate should not just be mechanically adopted; rather, these should be set as standards for cold climates. The design concepts for a cold climate are: to minimize energy and source usage, to avoid disruption/damage of materials and possible freezing, simplicity and reliability of designed solutions, to maximize self support of users and community, and to maximize the use of local sources such as materials and labour. In the cold regions, failure of building systems and components are often expected, and, for this reason, a safety design would be preferred, but that is neither economical nor realistic. Often, back-up measures are considered and installed, such as standby power supply, duplicate and durable components in the building envelope, alternative components and systems. The following chapter lists some of the building barriers and logistic problems in the Arctic as they exist today [35].

Building barriers and limitations:

- Building Regulations reflect current (and even past) rather than the future design practises, construction methods and materials.
- Building Regulations are often adopted from temperate climates and implemented without a focus on the extreme climatic conditions.
- Building Regulations should manage the development in a more stringent way which focuses on energy savings.
- Political decisions influence future policy with a potential effect on energy savings in buildings.
- Energy prices for non-renewable resources are currently very low, mainly due to the lack of taxation in Greenland; however, an increase in the price is expected due to limited resources which will influence the currently low heating costs.
- Limited material selection and prices are influenced by logistics and availability of material.
- Transport must be planned using the traditional transportation routes; types of transportation are by road, air and water.
- Logistics is a problem with long distances involved making multiple sourcing disadvantageous; instead, the delivery points with the smallest possible distance are preferred.
- A traditional labour pool is available without the necessary skilled craftsmen.
- Absence of price competition leads to monopoly and higher prices.
- New methods of construction lead to a delay in the building process and are costly.
- The use of renewable and local resources is based on limited availability and on the utilisation of renewable energies, i.e. hydropower, wind and solar power slowly becomes available to a wider selection of users.

General considerations for the elements of the building envelope include super-insulated, airtight and breathable assemblies. Additional considerations are the availability of materials and construction equipment, and the need for a skilled labour force which are qualified and trained in the applied construction methods. The building walls need to be designed based on the local

climate, required level of thermal performance, and on an availability of material and skilled labour. In general, the elements of a building structure needs to be durable, structurally sound, and resistant to heat, air and moisture flows.

Several building systems are used in the Arctic including lightweight and heavy systems, or a combination of these [9]. In the Arctic, three general types of building construction may be used. These are concrete, metal and wood [36]. All these construction types need to be combined with insulation. All building systems need to contain the following components or secure characteristics delivered by a component: external skin or cladding, wind weather barrier, structural component for load bearing, insulation, vapour airtight barrier and interior skin or finish [9]. Evaluation criteria for each building process include transport, methods and cost, necessary labour needed for construction, material availability, the length of the construction season, stability, durability and fire resistance, among many others.

A concrete structure has a high thermal conductivity; even when it is coupled with insulation materials and it needs to be frost- and weatherproof and thermal bridge free. Heavy structures can be used for a load bearing structure located in the interior of the building shell and can serve as thermal heat storage. Combined metal structures have high conduction of heat with possible condensation, but, for example, the insulated metal panels which consist of metal exterior finish, insulation, vapour barrier and interior finish are fast to install. Wood frame construction is commonly used in residential housing and offers good thermal properties, but low thermal stability.

Thermal insulation is used in a building to combine the thermal, acoustic and fire properties. There are many types of insulation which are widely used with various formats and applications (batts and rolls, rigid or loose or blown-in, and sprayed). A number of insulation materials are listed in Table 4 with thermal conductivity and physical properties. Several experimental materials are listed in Table 5. In the Arctic, the insulation must be protected from getting wet from the interior through the control of moisture. The installation of an interior vapour barrier is combined with an airtight barrier and a mechanical ventilation system for controlling the indoor air quality. The mechanical ventilation system with heat recovery is not very commonly used in the Arctic at present. In the cold climate, a house must be able to withstand and respond to changing temperatures and moisture conditions. The cold climate creates a problem with build-up of ice dams which involve cold temperatures, air leakage and moisture. During the winter heating season, the humidity creates a problem as it is driven from the interior to the exterior through the walls, roof and floor. The water may condensate and in summer, the condensation needs to dry out from the structures. This moisture and air leaking are controlled by installing a vapour and airtight barrier on the interior side. The rule of 1/3 applies to situations when the vapour air barrier is located 1/3 of the total thermal resistance of insulation from the interior, and in order to prevent condensation forming within the construction, another 2/3 insulation thickness is installed toward the exterior [9]. The application of a vapour airtight barrier needs to be done in a qualified way without penetration, and it needs to be tightly sealed with particular attention towards details related to the caulking [37].

Windows are the part of the building envelope which provides the passage of daylight. The need for windows should be weighed carefully and the heat loss should be compared to the possible solar gain. Several factors influence the thermal performance of a window such as the type of glazing, the number of layers of glazing, the size of the air space between glass layers and type of filling,

the thermal resistance of the frame and spacers, and the tightness of the installation. To utilise and maximize the solar gains, the predominant number of windows should be installed on the south side. In a cold climate, it is important to use low-e coating glasses to reduce heat loss through the window ($U\text{-value} \leq 0.5 \text{ W/(m}^2\cdot\text{K)}$). Windows in the cold climate can have physical shadings to protect from blizzards and cold night temperatures (shutters, insulated glass panes, insulation between the panes, etc). Installation of a window in the building envelope has an influence on the performance, and the tightness of the installation needs to be done correctly. The windows must also be designed to avoid condensation and frost problems.

Table 4. List of traditional insulation materials with thermal conductivity properties [38]

Material	Thermal conductivity [W/(m·K)]	Physical qualities and installation method
Glass wool (fiber glass)	0.031 - 0.040	High embodied energy, Good tear strength, non-combustible up to 230°C, water repellent, rot proof Various formats: lightweight quilt rolls, loose fiber, batts or slabs Applied in wall (masonry or timber frame), floor and ceiling (timber frame structure or hand filling, blown in loft)
Mineral wool insulation	0.032 - 0.039	Compressive strength, non-combustive up to 850°C Various formats loose fiber, quilt rolls, batts, semi-rigid slabs, rigid slab Applied in walls, floor and ceiling
Extruded/expanded polystyrene (XPS, EPS)	0.030 - 0.038	High resistance to water absorption, compressive strength Low susceptibility to rot, combustible to flame, non-biodegradable Applied to concrete slabs and foundation
Polyurethane (PUR), polyisocyanurate (PIR)	0.019 - 0.023 0.023 - 0.038	Compression and shear strength Water resistance, material resistance to fungus and mould grow Non-combustive up to 75°C, non-biodegradable Good workability, transport problem

Table 5. List of non-traditional insulation materials with thermal conductivity properties [38]

Material	Thermal conductivity [W/(m·K)]	Physical qualities and installation method
Aerogel	0.018	Produced from silica (silicon dioxide), Transparent, lightweight, superb insulation qualities Used in glazing units, but frail
Vacuum insulated panels (VIP)	0.003 - 0.041	Gas-tight enclosure with rigid core without air Non-biodegradable, difficult to install
Sheep wool (lambs wool)	0.039	Sustainable material with low embodied energy, life expectancy 50 years Absorbs humidity and release without compromising the thermal efficiency High resistance to fire, melts on fire but should extinguish itself, treated to improve fire resistance, potentially susceptible to rodents
Cellulose	0.038 - 0.040	Sustainable material from recycled paper shredded and treated with borax or other for flammability and smoulder resistance Various formats: dry cellulose (loose fill, blown in, settlement 20%), spray applied cellulose (wet spray, with adhesive), stabilized cellulose insulation (in rafter and loft, with adhesive), low-dust cellulose Resistance to insects, fungus Needs to be blown in to vertical and sloping cavities to prevent air circulation Low embodied energy, may be used again or disposed off safely Applied in wall, ceiling
Hemp	0.040	Sustainable material, growing crops absorbs CO ₂ Produced as binding with synthetic fibres, durable long-lasting renewable material Absorbs and distributes moisture allowing the wall to breathe and thereby reducing humidity and condensation indoors

List of current building practises and techniques in the Arctic [39] based on the information obtained from Greenland, Canada and the Northern regions of Scandinavia.

- The building design is based on design heat loss calculated as transmission and ventilation heat loss; the building standards use an energy frame to establish the heating requirement.
- Combined use of thermal, air, vapour, wind and rain barrier and insulation to decrease the heat loss are not common in old houses but has become a practise for newly built buildings.
- A use of an airtight barrier to prevent the exfiltration through the available leakage paths is more commonly used, but the application is problematic due to the lack of skilled labour.
- The vapour airtight barrier on the warm side of the insulation is based on the old design practise (1/3 rule of thumb).
- An air barrier to prevent wind must be used and must be vapour permeable to avoid trapping water vapour between the two barriers.
- Cold air entering the building through the infiltration or stack effect is at high relative humidity, but at a low humidity ratio and the large amounts of air can be propelled by stack effect or wind forces in locations with extreme winds.
- Avoid a thermal bridge as it can have an impact through cold surface temperature on the interior and create condensation and further mould growth.
- Elevated foundation due to the wind and snow drifting and thawing of permafrost.

4.4 Energy systems in buildings

The traditional use of energy in traditional buildings in a cold climate is different from the use of energy in passive or low energy buildings, due to the longer heating period, different lifestyles depending on long cooking time of the natural food and the storage of frozen goods, a longer period of drying clothes mostly indoors, etc. There are several types of heating systems which are used in the cold climate and, often, the heating system covers the hot water demand too. The boiler is an appliance which distributes the heat through a hydronic heating system such as radiators or / and floor heating, and it can run on propane, natural gas, oil, electricity or other sources. It is one of the most common solutions used in the Arctic regions. Boiler efficiency can vary from 90% to 95% nowadays. The boiler provides the space heating and hot water consumption. The stove distributes heat mostly by convection where the heated air moves around the house. The stove can be based on wood, pellets or coal sources. Wood stoves are widely used in some Arctic regions with an abundance of wood (not in Greenland) and commonly used as a supplement to a boiler. The stove could be connected to a hydronic heating system to cover the heating demand. In some of the newly built buildings, the indoor air quality and energy savings are provided by mechanical ventilation with heat recovery. More advanced, combined systems are used nowadays such as the heat pump, combi solar system for hot water and space heating, low-temperature heating system with floor heating and thermal district heating system. The electricity is supplied by diesel engines in small and remote settlements, whereas larger cities may use hydropower or possibly wind power.

The space heating demand for a house located in the cold climate varies from 12,000 to 20,000 kWh/a, i.e. respectively 50 - 90 kWh/(m²·a) for the low energy houses in Canada [40] or

Greenland and up to 381 kWh/(m²·a) for the traditional standard houses in Greenland [10]. The space heating is usually provided by an oil-boiler (condensation, $\eta = 0.9$) in Canada and Greenland with an energy carrier factor 1.1 or electricity in Norway with energy carrier factors 2.7. The electricity appliances use from 3,000 kWh/a for one family in the Low-energy house, Greenland, up to 4,000 kWh/a in a typical house in Canada. The same amount of energy goes to the domestic hot water consumption, i.e. approximately 4,000 kWh/a at 90% efficiency supplied by an oil-boiler. The total primary energy for the typical residential buildings in the cold climate adds up to from 160 kWh/(m²·a) for buildings located around the Polar Circle in Canada to 400 kWh/(m²·a) for Greenlandic houses from the 1960s.

In the Arctic, single family houses usually do not have a back-up heating system and their poor thermal quality would result in an immediate temperature drop. Therefore, it is necessary to have back-up heating system which is often provided for small settlements by installing of a larger number of diesel engines in the Municipality Centre providing the power supply, instead of the exact number of diesel engines that would otherwise sufficiently cover the energy demand. Currently, the evacuation of the entire population in the settlement needs to be done as soon as possible if the power shortage occurs in the harshest winter months.

The design of heating and ventilation systems in the extreme regions needs to cover the extreme temperature at design conditions for periods in which solar gains are not present [9]. The combination of a heating system and a mechanical ventilation system with heat recovery is a preferred solution which must be modified for northern conditions to accommodate larger temperature differences, defrosting problems with ice build-up from humidity, reduction of flow and speed, switching, recirculation and after heating of the inlet air, among others. There are several types of heat exchangers based on recuperative or regenerative systems, on air-to-air or earth-to-air or air-to-water transport. By using seasonal bypassing, the heat recovery ventilation can be used for heating or cooling, although in the Arctic only heating is desirable and considered. The heat exchanger types used in the ventilation systems of the buildings are:

- A cross flow plate with temperature efficiency 50 - 70%
- A counter flow plate with temperature efficiency 70 - 80%
- A counter flow duct heat exchanger 85 - 99%
- A rotary heat exchanger 60 - 90%

Energy systems which are currently utilised in the Arctic are similar to the systems used in temperate climates and have to overcome the issues connected with large distances, isolated settlements and greater temperature drops in houses. Alternative methods of providing power can reduce the currently high oil consumption, and at the same time provide the economical, environmental, and security benefits and independency being off the power grid. Currently, there is a need for a hybrid system connected to the building systems which can incorporate different components and provide the production, storage and system control to supply the power to an insulated building. This system needs to incorporate renewable technology and an engine generator, battery storage, and a power converter. Renewable technology can be supplied from solar, wind or hydro sources.

5 Performance of a fundamental passive house in the Arctic

The performance of a passive house is expressed in the energy used for heating and/or cooling, ventilation, hot water demand, lighting and household appliances. The passive house concept is based on performance measures which are influenced by variables such as the shape and orientation of a building, thermal properties and areas of non transparent building elements, thermal characteristics and areas of transparent building elements including the orientation and use of daylight, use of passive gains, design and operation of systems such as heating and ventilation. The passive house performance is mainly evaluated based on the calculation of the relevant European Standards EN 13790 [41] and EN 12831 [42] using annual and monthly methods in the PHPP software. There are also other standards for the energy evaluation of a passive house which are used to evaluate the performance of building construction elements, air tightness, and efficiency of heat exchanger, among others.

The energy performance of a passive house varies according to the location which is characterized mainly by the weather profile, i.e. ambient temperature (°C) and solar radiation (kWh/m² or W/m²). For a passive house located in the Arctic, the control strategies in the winter include minimizing heat losses through the conductive heat flow and infiltration through the air flow in and out of the house. In addition, the solar gains through the windows are promoted to obtain radiant heat from the exterior. The control strategies in the summer concentrate on minimizing heat losses and infiltration along with maximizing solar gain whilst preventing overheating. At the same time, the ventilation system is controlled in order to supply fresh air of good indoor air quality along with a removal of air pollution and minimizing the ventilation heat losses through the heat recovery. The cooling system in a passive house located in the Arctic is assumed to be unnecessary since main emphasis is on keeping the heat in the house, even if there is overheating in the summer period which could be dealt with by installing vertical or horizontal shades to block the low angle sun.

5.1 Space heating demand

The space heating demand is calculated using annual and monthly methods. The monthly method, in accordance with EN 13790 [41], is a semi-dynamic method and represents the energy balance for each month of the year, but it does not fully consider the effects of thermal storage. The annual heat demand is calculated for the heating period. Both methods represent the energy balance consisting of the heating demand with total heat gains and total heat losses (kWh/a) with reference to the treated floor area (A_{TFA}). The specific space heating demand (respectively heating demand, in kWh/(m²·a)) is calculated in accordance with (4) where Q_T is the sum of transmission losses (5), Q_V is the sum of ventilation and infiltration heat losses (6 and 7), η is the utilization factor (8), Q_I is the sum of internal heat gains (9), and Q_S is the sum of solar gains (10).

$$Q_H = [Q_T + Q_V - \eta \times (Q_S + Q_I)] / A_{TFA} \quad (4)$$

The transmission heat losses (5) are calculated as the sum of all building elements which exchange the heat with the exterior climate. Where A_i is the area of the building element (m^2), U_i is the overall thermal transmittance (respectively U-value in $W/m^2 \cdot K$), f_T is the temperature factor, l_i is the length of outer thermal bridges (m), ψ_i is the heat transfer coefficient for the thermal bridge where the suitable connection for a passive house is considered to be $\psi \leq 0.01$ $W/m \cdot K$, and HDH is the heating degree hours (kWh/a) with base temperature T_{base} . The ventilation heat losses are calculated in (6) and (7) where $n_{V,system}$ is the average air change rate as standard maximum value for residences from 0.3 to 0.5 h^{-1} , η_{HR} is the efficiency of heat exchanger system, $n_{infiltration}$ is the infiltration air change rate which has a maximum value of 0.042 h^{-1} , n_V is the effective air change rate, V_{RAX} is the reference volume of the ventilation system (m^3) calculated as A_{TFA} multiplied with average internal room height. The formulas can be found in EN 13790 [41].

$$Q_T = \sum_{i=1}^j [A_i \times U_i \times f_T + l_i \times \psi_i \times f_T] \times HDH \quad (5)$$

$$Q_V = n_V \times V_{RAX} \times c \times HDH \quad (6)$$

$$n_V = n_{V,system} \times (1 - \eta_{HR}) + n_{infiltration} \quad (7)$$

$$\eta = \frac{1 - [(Q_I + Q_S)/(Q_T + Q_V)]^5}{1 - [(Q_I + Q_S)/(Q_T + Q_V)]^6} \quad (8)$$

The internal heat gains are calculated in (9) where the l is the duration of the heating period (d/a), q_i is the internal heat load where the fundamental value for a passive house is 2.1 W/m^2 for residential buildings. The solar gains are calculated in (10) where r represents the reduction factors (shading and dirt, non perpendicular and glazing fraction), g is the g-value (-), A_w is the window area (m^2) and G is the solar radiation on vertical surfaces for different orientations ($kWh/(m^2 \cdot a)$). The symbols i and j represent number of windows.

$$Q_I = 0.024 \times l \times q_i \times A_{TFA} \quad (9)$$

$$Q_S = \sum_{i=1}^j r \times g \times A_w \times G \quad (10)$$

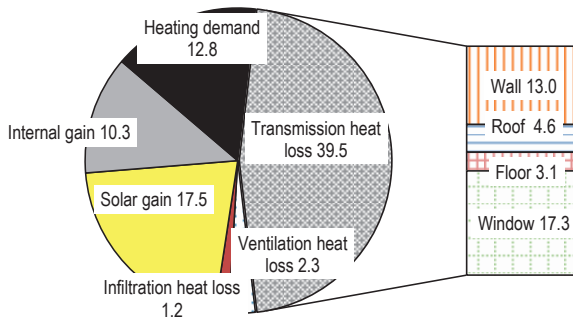


Fig. 13. Calculated energy balance in $kWh/(m^2 \cdot a)$ from PHPP software with distribution of gains and losses of a passive house using model "Kranichstein" located in Darmstadt, Germany [43]

The passive house located in the temperate climate in the latitude of 50° with an average annual temperature between 7 - 9°C has the annual heating demand $\leq 15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ where the total heat losses account for 40 - 41 $\text{kWh}/(\text{m}^2 \cdot \text{a})$, the sum of solar gains is approximately 16 - 17 $\text{kWh}/(\text{m}^2 \cdot \text{a})$ and internal gains equals approximately 10 $\text{kWh}/(\text{m}^2 \cdot \text{a})$ utilizing the gains 90 - 95% [43]. The energy balance of a typical passive house is shown in Fig. 13 where the passive house Kranichstein has the space heating demand 12.8 $\text{kWh}/(\text{m}^2 \cdot \text{a})$ which is even below 15 $\text{kWh}/(\text{m}^2 \cdot \text{a})$. These calculated results have been confirmed by actual measurements [14].

Table 6. Locations of the coastal and inland cities with main characteristics

	Location	Latitude [°]	Average annual temperature [°C]	Global radiation horizontal [$\text{kWh}/(\text{m}^2 \cdot \text{a})$]	Solar radiation on a vertical surface [$\text{kWh}/(\text{m}^2 \cdot \text{a})$]			
					South	West	North	East
Coastal	50° - 54° Plymouth (1)	50.4	11.1	1,051	850	677	355	645
	London (1)	51.5	11.4	946	781	586	332	591
	Hanover (1)	52.5	10.0	934	755	607	392	618
	Hamburg (1)	53.6	9.7	934	755	607	392	618
	Kiel (1)	54.3	9.4	934	755	618	392	618
	55° - 59° Copenhagen (1)	55.7	8.8	987	940	651	284	647
	Oslo (1)	59.9	6.6	985	1,043	686	276	668
	60° - 64° Helsinki (1)	60.2	6.0	965	941	668	281	667
	Reykjavik (1)	64.1	5.5	784	826	603	313	588
	65° - 69° Sisimiut (2)	66.6	-3.9	945	1,019	839	442	815
	Murmansk (3)	68.8	-0.3	724	824	618	348	610
	70° - 74° Uummannaq (2)	70.7	-4.1	779	726	623	379	641
	Barrow (3)	71.2	-12.5	725	397	700	447	695
	75° - 79° Longyearbyen (3)	78.3	-6.7	664	789	659	500	657
Inland	50° - 54° Brussels (1)	50.8	10.8	948	795	594	281	566
	Dresden (1)	51.0	10.1	998	796	632	415	629
	Poznan (1)	52.4	9.6	1,016	890	640	291	633
	Edmonton (1)	53.6	5.5	1,314	1,461	911	305	912
	Vilnius (1)	54.7	7.7	994	911	687	360	678
	55° - 59° Moscow (1)	55.8	6.8	962	896	669	362	661
	Yekaterinburg (1)	56.9	4.8	1,081	1,190	751	288	739
	60° - 64° Tampere (1)	61.5	5.1	929	962	708	360	712
	Yellowknife (1)	62.5	-2.4	1,070	1,327	811	291	802
	65° - 69° Kiruna (2)	67.8	-1.1	748	616	438	295	411
	70° - 74° Resolute (3)	74.4	-16.5	921	1,314	1,023	670	1,017
	75° - 79° Byrd Station (3)	80.0	-28.1	945	908	1,192	1,482	1,206

Data obtained from the PHPP ⁽¹⁾, DRY ⁽²⁾ and METEONORM ⁽³⁾, grey color is inland

The investigation of a passive house using model "Kranichstein" in the various weather climates at the different latitudes above 55° (Fig. 14) shows that there is a difference in energy performance between coastal and inland locations, i.e. a milder climate at the coastal location (Fig. 14). Towards the north, the greater temperature differences result in higher transmission losses through the building elements. In higher latitudes, there is also a smaller amount of potential solar gain through the windows and the solar gain is largely present in the summer months, but rarely present in the winter. Thus, there is a need for windows which are designed for a different solar pattern affected by low angle sun which can cause overheating in the summer months. The internal gain has a potential for investigation as the extreme temperature will keep the inhabitants indoors. Furthermore, research is needed on the different social patterns of the population such as denser living areas with higher indoor temperatures and higher heat gains from cooking, etc.

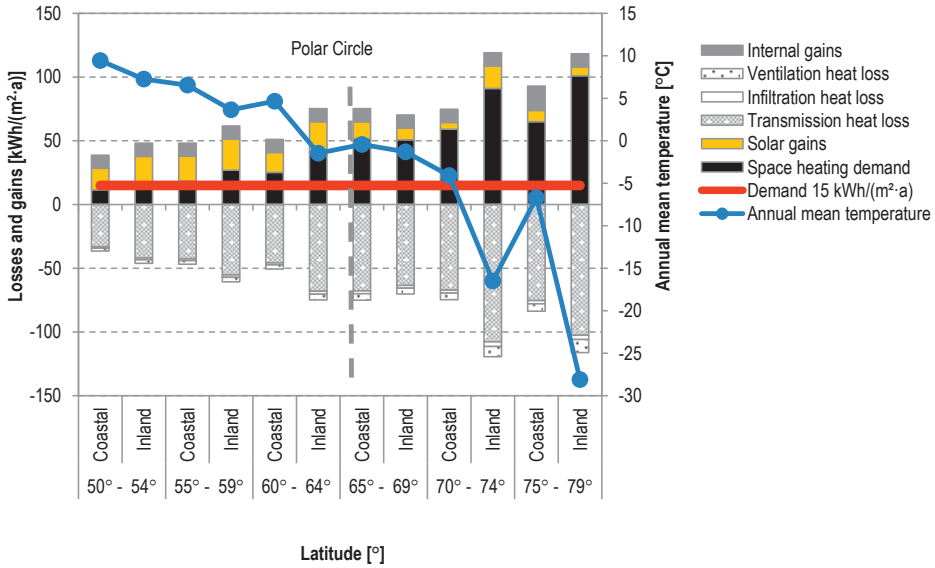


Fig. 14. Energy balance and space heating demand of a passive house in model "Kranichstein" relocated from Germany without change and placed in different latitudes

5.2 Heating load

The maximum heating load of 10 W/m² is determined from the heat and ventilation losses in accordance with EN 12831 [42] with subtraction of adequate heat gains including the solar and internal gains which are applied in the energy calculation of a passive house. The heating load is calculated as the maximum heating load for two design periods (11) where A_i is the area of each building element (m²), U_i is the overall thermal transmittance, i.e. U-value, of each building element (W/m²·K), f_T is the temperature factor, V_v is the volume of air (m³), n_v is the effective air change (h⁻¹), c_{AIR} is the heat capacity of air (0.33 Wh/(m³·K)). The symbol r represents the reduction factors (shading and dirt, non perpendicular and glazing fraction), g is the g-value (-), A_w is the window area (m²). The climate scenarios are represented by $V_{1,2}$ which is the temperature difference for scenario 1 against scenario 2, and the symbol $G_{1,2}$ is the solar radiation difference for scenario 1 against scenario 2. Particular attention is applied to the internal load which has a value of 1.6 W/m² [43] and is used as the internal gain in the heating load calculation. This is necessary in order to heat the house in unusual conditions, such as the presence of one person and, therefore, the lack of internal heat gains. The effective air change for infiltration used in the design conditions is 2.5 times the average value of the heating season.

$$\sum [(A_i \times U_i \times f_T \times V_{1,2}) + V_v \times n_v \times c_{air} \times V_{1,2}] - \sum [(A_{w,i} \times g_i \times r_i \times G_{1,2}) + p_i \times A_{IFA}] \quad (11)$$

The heating load is based on the maximum value which can be covered by low temperature heating and is derived from 3 separate values. Firstly, continuous fresh air supply of 30 m³/h per person must be ensured in order to maintain good indoor air quality. Secondly, the specific heat

capacity of the air is $0.33 \text{ Wh}/(\text{m}^3 \cdot \text{K})$. Lastly, the temperature of the fresh air increases by 30 K without compromising the quality of the air. From these 3 factors- the continuous supply of 300 W of heat per person; by the fresh air being supplied with a heat recovery system; and the implementation of a living area of 30 m^2 per a person gives the maximum specific heat load of $10 \text{ W}/\text{m}^2$ [43].

In a passive house, the heating load is calculated for two weather scenarios: one period with a minimum ambient temperature with a clear sky because the ground radiates more heat into the sky and, thus, it becomes colder (scenario 1 - cold, clear day). During this period, a passive house can obtain relatively high solar gains to cover part of the heat loss. The second period with a moderate temperature and overcast sky is also used with minimal contribution of solar gains (scenario 2 - moderate, overcast sky). The weather conditions are expressed as average daily temperature ($^{\circ}\text{C}$) and sum of daily solar radiation (W/m^2) for the heating and/or cooling load.

Table 7. Outdoor design temperatures compared to the design characteristics for heating load calculation - daily average temperature and sum of daily solar radiation as the average and extreme values obtained from METEONORM

Location		Scenario 1: Cold, clear day				Scenario 2: Moderate, overcast sky		
		Outdoor design temp. [°C]	Mean temp. [°C]	Global radiation horizontal [W/m²]	Solar radiation on a vertical surface [W/m²] S, W, N, E	Mean temp. [°C]	Global radiation horizontal [W/m²]	Solar radiation on a vertical surface [W/m²] S, W, N, E
Average periods	Würzburg, GE	-12.0	-6.6	30	47; 18; 11; 20	-1.5	15	16; 9; 6; 8
	Harbin, CH	-26.0	-27.3	65	143; 49; 17; 42	-20.1	50	101; 36; 15; 32
	Copenhagen, DK	-12.0	-5.5	17	35; 11; 7; 14	-3.1	17	35; 11; 7; 14
	Fairbanks, CA	-43.0	-39.1	6	29; 4; 2; 4	-33.2	6	29; 4; 2; 4
	Oulu, FI	-32.0	-25.1	4	0; 0; 0; 0	-21.1	4	0; 0; 0; 0
	Sisimiut, GL	-30.0	-27.6	0	0; 0; 0; 0	-22.9	0	0; 0; 0; 0
	Sodankylä, SE	-38.0	-31.0	0	0; 0; 0; 0	-25.9	0	0; 0; 0; 0
	Kiruna, SE	-27.0	-25.2	0	0; 0; 0; 0	-20.7	0	0; 0; 0; 0
	Inuvik, CA	-46.0	-39.6	0	0; 0; 0; 0	-33.6	0	0; 0; 0; 0
	Murmansk, RU	-27.0	-26.7	0	0; 0; 0; 0	-22.1	0	0; 0; 0; 0
	Tromsø, NO	-17.5	-10.0	0	0; 0; 0; 0	-7.1	0	0; 0; 0; 0
	Barrow, USA	-35.0	-35.5	0	0; 0; 0; 0	-30.2	0	0; 0; 0; 0
	Uummannaq, GL	-30.0	-29.6	22	58; 23; 8; 22	-22.8	0	0; 0; 0; 0
	Resolute, CA	-44.0	-40.2	0	0; 0; 0; 0	-34.2	0	0; 0; 0; 0
Extreme periods	Würzburg, GE	-12.0	-10.0	23	31; 13; 9; 14	-7.0	19	16; 11; 8; 10
	Harbin, CH	-26.0	-33.0	50	88; 38; 16; 30	-24.5	28	35; 20; 11; 15
	Copenhagen, DK	-12.0	-7.9	8	8; 6; 4; 4	-4.4	8	8; 6; 4; 4
	Fairbanks, CA	-43.0	-44.1	3	13; 3; 1; 2	-37.7	3	13; 3; 1; 2
	Oulu, FI	-32.0	-33.7	2	10; 2; 1; 2	-28.4	2	10; 2; 1; 2
	Sisimiut, GL	-30.0	-32.2	0	0; 0; 0; 0	-26.9	0	0; 0; 0; 0
	Sodankylä, SE	-38.0	-40.2	0	0; 0; 0; 0	-34.2	0	0; 0; 0; 0
	Kiruna, SE	-27.0	-32.2	0	0; 0; 0; 0	-26.9	0	0; 0; 0; 0
	Inuvik, CA	-46.0	-44.4	0	0; 0; 0; 0	-37.9	0	0; 0; 0; 0
	Murmansk, RU	-27.0	-34.9	0	0; 0; 0; 0	-29.4	0	0; 0; 0; 0
	Tromsø, NO	-17.5	-13.8	0	0; 0; 0; 0	-10.6	0	0; 0; 0; 0
	Barrow, USA	-35.0	-39.3	3	20; 4; 1; 5	-33.2	0	0; 0; 0; 0
	Uummannaq, GL	-30.0	-33.2	19	39; 20; 8; 13	-26.2	0	0; 0; 0; 0
	Resolute, CA	-44.0	-44.3	0	0; 0; 0; 0	-36.5	0	0; 0; 0; 0

Note: grey color is inland, temp. = temperature

The two design days' characteristics are rarely calculated and certified by PHI for the Arctic locations due to the poor availability of weather data collection. In the Arctic, the outdoor design temperature is used for the energy design of the building in which the outdoor design temperature is the lowest two day average achieved at least 10 times in the last 20 years. The design days' characteristics for any locations can be obtained from software METEONORM 6.0 [44] as average and extreme values. Data from METEONORM 6.0 are produced as the average values obtained from a combination for climate zones because of the fact that there is a limited number of weather stations in the Arctic. The data does not take recent climate changes such as warm winters into account. The obtained design days show that there is no solar radiation at all for most of the Arctic locations. There is a similarity between the daily temperatures and solar radiation data obtained from PHI and METEONORM 6.0 respectively, and the outdoor design temperature. Table 6 shows the comparison of the design outdoor temperature and two design days which are represented by the average and extreme values obtained from METEONORM 6.0 for several European and Arctic locations. The average values are representing long term means for the monthly values and the design temperatures. The extreme values are representing worst case values for these characteristics [45].

In the calculation of the design heat loss for buildings in the Arctic, only the design heat loss through the building envelope is accounted for without the effect of the heat gains through solar and internal inputs. The graph in Fig. 15 shows the calculated maximum value for the heating load in model "Kranichstein" which is derived from two values based on the two design days defined as a cold, clear day and a moderate, overcast day. The investigation of the heating load in the different latitudes from 50° up to 80° (Fig. 15) above 65° latitude shows the difference between coastal and inland locations as the outdoor temperature is higher for inland locations compared to the costal. There are no solar gains at the design days. The design heating load is mainly influenced by the transmission, ventilation and infiltration (2.5 times the average value) heat losses and subtracted from the internal gain of 1.6 W/m².

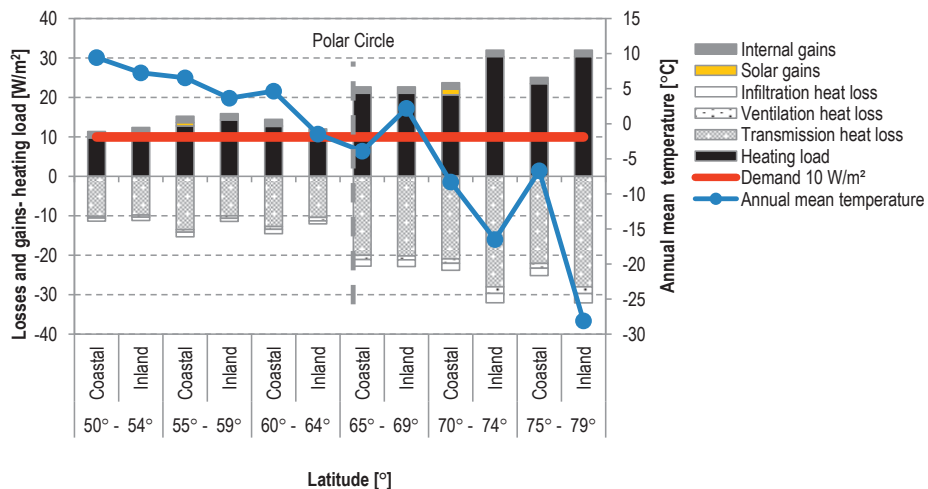


Fig. 15. Energy balance and heating load of a passive house in model "Kranichstein" relocated from Germany without change and placed in different latitudes

5.3 Primary energy

The passive house definition is based on the performance method in which the focus is primarily on using less energy, i.e. how much energy the house uses in a lifetime of 60 years compared to the amount of energy which is needed to build the house. The annual amount of energy used in a passive house is expressed as a primary energy demand which is the sum of all primary energy demands for heating, domestic hot water, auxiliary and household electricity. Referring to the treated floor area and the energy carrier for non-renewable primary energy, the primary energy demand describes the amount of non-renewable primary energy supplied to the end user of a building including the losses from distribution, conversion and delivery. The supply of energy for heating in a passive house comes from the district heating, bio fuels or electricity while fossil fuels are not considered as alternatives for sustainability.

The primary energy demand calculated for a passive house includes the energy needed for the distribution and supply of the heat for space heating and hot water, cooling energy, electricity demand for appliances, auxiliary and lighting. There are different values for energy factors depending on the country. In other words, the lower values are usually for a temperate climate countries and higher values are for high latitude regions. The heating can be supplied from non-renewable sources with energy carrier 1.1 (oil, gas, coal) or energy carrier 0.05 - 0.2 for an energy source obtained from wood or pellets or other biomass sources [46], [43]. The electricity requirement includes primarily all domestic appliances and lighting, and secondly, the electricity consumption for auxiliary electricity requirement specified for mechanical ventilation system fans and controls (energy factors between 2.5 - 3.0 for electricity grid sources, or 0.7 for photovoltaic panels).

The passive house uses approximately 15 kWh/(m²·a) for space heating with an additional low temperature heat source (wood or electrical panels, etc). The recommended maximum value for electricity is 18 kWh/(m²·a) secured by high efficient appliances with primary energy factor 2.7 and including the hot water demand of 25 litres/person at 60°C covered by 50% from solar panels. It also includes the electricity for non-domestic appliances and the heat pump or boiler. Implementing the energy carrier factor, the total primary energy in the passive house adds up to approximately 64 kWh/(m²·a).

The main problem related to reaching the primary energy demand for a passive house limit in the cold climate lies in the space heating demand. Compared to the current situation, the electricity demand can be decreased by using highly efficient domestic appliances operating and maintaining the house in the low energy manner. Many renewable energy sources of electricity such as wind, bio-fuel, photovoltaic or hydropower can reduce the energy consumption almost by 3 times. The hot water demand can be covered partly by solar thermal panels and if the solar storage tank could work as the thermal storage for colder months.

6 Evaluation of decision variables for optimising to be developed for passive houses in the Arctic

In the design of sustainable buildings, it is beneficial to identify the most important design parameters in order to more efficiently develop alternative design solutions or reach optimized design solutions. The passive house is an application of building physics in which the energy performance is dependent on the design factors and climate parameters, the characteristics of the building envelope, building systems and internal gains. The single objective method uses one measurable objective which is represented by different parameters of a building. These analyses make it possible to identify the most important parameters in relation to building performance and to help optimize an energy efficient building using just these parameters. The analyses reveal the parameters which have the largest influence on the energy consumption. The main focus in this thesis is on the overall energy performance rather than on a detailed analysis and the design parameters leading to the energy efficient houses. The first main subject of the studies is the building insulation and minimizing the transmission heat loss. The second important subject is the windows with positive net energy gains, afterwards the infiltration through the building envelope, the building systems and finally the parameters for energy calculations. The study of the analyses is focused on achieving the target of a passive house using the building materials characteristics which have advanced performance. And these already exist on the market or will be in few years. The combinations of single objective and multi-criteria methods along with qualitative parameters lead to the optimisation of a passive house in the Arctic climate.

6.1 Fundamental and national values

In this thesis, some boundary conditions have a great influence on the design of a passive house in accordance with a fundamental definition. In a passive house design, the fundamental values are used as boundary conditions for energy calculation of a passive house in the temperate climate. These conditions are different for Greenland based on the national values, for instance, internal gain of 5 W/m^2 for residential buildings and increased air change rate for ventilation of 0.5 h^{-1} [47], limitation of window/floor areas $\leq 22\%$ and a building design with lightweight timber structure with mineral wool insulation and elevated foundation. Yet, these conditions prove to be input values in passive house design for the Arctic climates as they have great impact on energy performance and at the same time they are interconnected with consequences regarding the Arctic. Through changing these boundary conditions, the passive house design in the Arctic climate would be achievable and more realistic.

Using a fundamental method with fundamental values derived from the European conditions, the heating load of 10 W/m^2 is difficult to achieve for a passive house located in the locations above 66° latitudes. This is mainly due to the fact that no solar radiation is available at the design days in winter months. In a passive house in the temperate climate, the solar gains account for up to 3 W/m^2 and internal gains are 1.6 W/m^2 together with a heating load of 10 W/m^2 , the transmission

and ventilation heat losses can add up to 14.6 W/m². In the passive house in the Arctic locations, the heat losses must add up to maximum 11.6 W/m² to be able to use the heating load of 10 W/m², i.e. the transmission and ventilation heat losses must almost be equal to the heating load. Fig.16 shows the proportion of heat loss and gains when calculating the heating load and expressing the contribution of different parameters at the design days are shown. These are the following days: day 1 with cold temperatures with clear sky and day 2 with moderate temperatures with overcast sky. The scenarios show the fundamental values of a passive house applied in the different Arctic locations, i.e. the internal gain 1.6 W/m² when the house is inhabited, ventilation air change 0.3 h⁻¹, infiltration value is 2.5 times larger compared to heating load calculation that is used in energy calculations, and even the area of the window in relation to floor area had to be restricted to lower the transmission heat losses (Table 8).

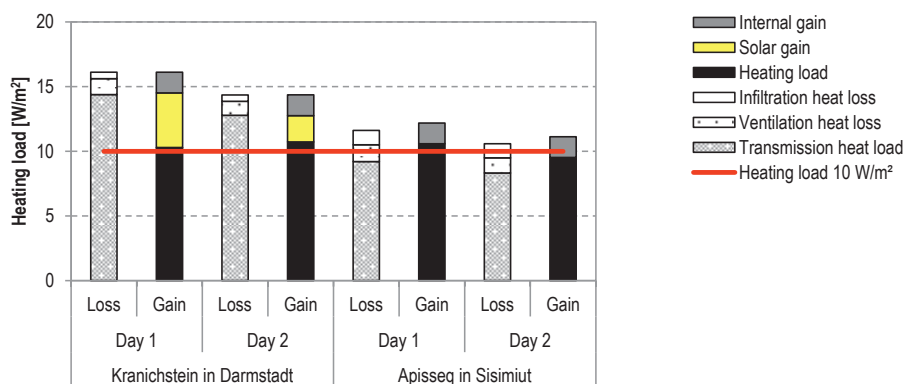


Fig. 16. Example of distribution of losses and gains for calculation of peak heating loads for the passive houses located in Darmstadt compared to the location of Sisimiut (model "Kranichstein" and "Apisseq")

Table 8. The passive house in the Arctic locations according the passive houses' fundamental values and techniques (model "Kranichstein")

Location	Sisimiut Latitude 66.4° T _{amb} = -3.9°C	Barrow Latitude 71.2° T _{amb} = -12.5°C	Resolute Latitude 74.4° T _{amb} = -16.5°C
U _{wall,floor,roof} [W/(m ² ·K)]	0.055; 0.050; 0.050	0.035; 0.030; 0.030	0.033; 0.030; 0.030
U _{glazing} , g-value [W/(m ² ·K)], [-]	0.33; g=0.60	0.25; g=0.60	0.23; g=0.60
Infiltration air change [h ⁻¹]	0.019	0.014	0.010
Heat exchanger η [%]	92	95	95
Window / floor area [%]	22	18	18
Annual space heating demand [kWh/(m ² ·a)]	15.4	15.4	15.2
Monthly space heating demand [kWh/(m ² ·a)]	16.6	15.8	17.4
Heating load [W/m ²]	9.6	9.3	10.1

When designing a passive house for an extremely cold climate, some important circumstances need to be considered such as internal gains in which different conditions might justify a different value for the internal heat gains. Different sources already claim different numbers for the internal heat load, varying from 2.0 to 8.0 W/m². [13], [47], [48], [49]. The dwelling area per person is significantly smaller in the cold climate regions compared to the temperate regions [8], [50], [51],

and, thus, the internal heat load is distributed on a smaller area. There is also a different pattern of use resulting from the fact that people in the Arctic stay indoors for longer periods of time because of the extreme temperatures and the greater length of the heating period. The sun will be above the horizon for 24 hours in a day in the summer, but for some periods in winter there will be almost no hours with natural daylight. Some daylight and heat gain will be blocked by a cloud cover which varies significantly for each location, but the amount of daylight will be increased due to reflectance from the snow covered ground. The smaller living area will need less energy to be artificially lighted, but the need for artificial lighting may differ based on the different habitant requirements. The smaller dwelling area also means that the ventilation per area ideally is higher, and the contribution due to a larger amount of time spent on cooking will contribute to internal gains, but it will also require more ventilation in the form of energy needed for direct kitchen exhaust (Fig. 17) [52].

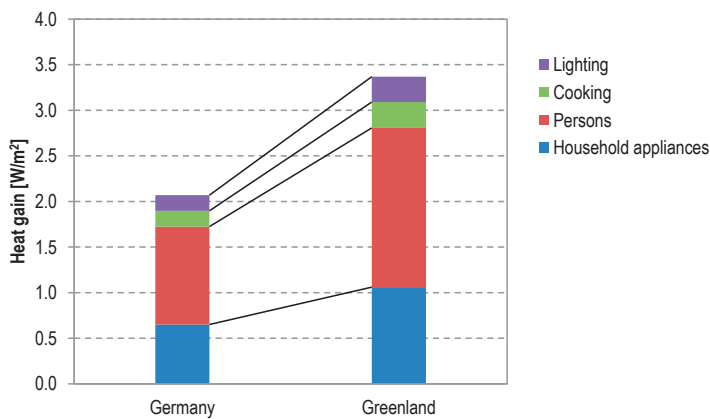


Fig. 17. Example of internal heat gain for Germany and Greenland including the effect of people, cooking, lighting and household appliances

Increased air change from 0.3 h^{-1} to 0.5 h^{-1} will enlarge the heating load by 50 W/a in the Sisimiut, Greenland location, which is equal to the model "Kranichstein" in total energy calculation of a heating load by 0.3 W/m^2 . With increased air change rate, the heating load transportable by air could be increased and cover the calculated heating load and at the same time, it could change the air change rate in the rooms in the cold regions. Conversely, the increase of the ventilation air change rate from 0.3 h^{-1} to 0.5 h^{-1} will cost energy every day because of excessive ventilation while the peak heating load is only needed in the worst design days (Table 12). If the air change is too high, this may lead to dry indoor air during the heating season, i.e. a higher ventilation rate which will increase fan energy. One way is to increase the ventilation air change to 0.5 h^{-1} only when it is necessary. This implies having a two mode switch in the ventilation system, thus saving the everyday costs of high ventilation rate over a full year. A survey will be required if the ventilation rates of 0.3 h^{-1} and the costs of investment, running and maintenance with ease of use, and the inhabitant's demands and flexibility have to be considered [53].

Applying a passive house building standard in Greenland requires adaptation of the national values, i.e. an internal gain of 5 W/m^2 , window/floor area $\leq 22\%$, increased air change rate 0.5 h^{-1}

and changing the building structure from medium to lightweight timber structure with mineral wool insulation and elevated foundation. These values are used as input values in the model. The prospect of achieving a passive house in the Arctic lies in minimizing the heat loss with a sufficient amount of insulation, e.g. mineral wool insulation as a traditional building material in Greenland, in which the thickness of the wall insulation need to be 670 mm with $\lambda = 0.037 \text{ W}/(\text{m}^2 \cdot \text{K})$ for coastal locations around the Polar Circle in Sisimiut and up to 1,100 mm at 70° latitudes. The thickness of the insulation would have to be even larger in the roof and floor. Using more efficient insulation such as PUR would decrease the thickness to 650 mm with $\lambda = 0.022 \text{ W}/(\text{m}^2 \cdot \text{K})$. The air tightness of the house would have to be increased four times the standard value of 0.042 h^{-1} , and the heat exchanger efficiency would have to be 95% (Table 9). The investigation shows that the results for space heating demand calculated using annual and monthly methods in accordance with EN 13790 [41] varies significantly; in the monthly method, the absence of solar gains in the winter months is revealed and can be compensated only by internal gains. There is a significant amount of the solar gain in summer months which can lead to the possible overheating even in the cold regions (Fig. 18, Fig. 19 and Fig. 20).

Table 9. Passive house in the Arctic with Danish / Greenlandic national values and techniques in model "Kranichstein"

Location	Sisimiut Latitude 66.4° $T_{\text{amb}} = -3.9^\circ\text{C}$	Barrow Latitude 71.2° $T_{\text{amb}} = -12.5^\circ\text{C}$	Resolute Latitude 74.4° $T_{\text{amb}} = -16.5^\circ\text{C}$
U-value $[\text{W}/(\text{m}^2 \cdot \text{K})]$ ¹	0.070; 0.065; 0.065	0.044; 0.040; 0.040	0.040; 0.035; 0.035
U _{glazing} $[\text{W}/(\text{m}^2 \cdot \text{K})]$, g-value [-]	0.55; g=0.60	0.33; g=0.60	0.32; g=0.60
Infiltration air change $[\text{h}^{-1}]$	0.020	0.015	0.010
Heat exchanger η [%]	85	87	88
Window / floor area [%]	22	18	18
Annual space heating demand $[\text{kWh}/(\text{m}^2 \cdot \text{a})]$	14.9	15.4	15.0
Monthly space heating demand $[\text{kWh}/(\text{m}^2 \cdot \text{a})]$	14.7	14.5	15.5
Heating load $[\text{W}/\text{m}^2]$	12.8	12.3	12.7

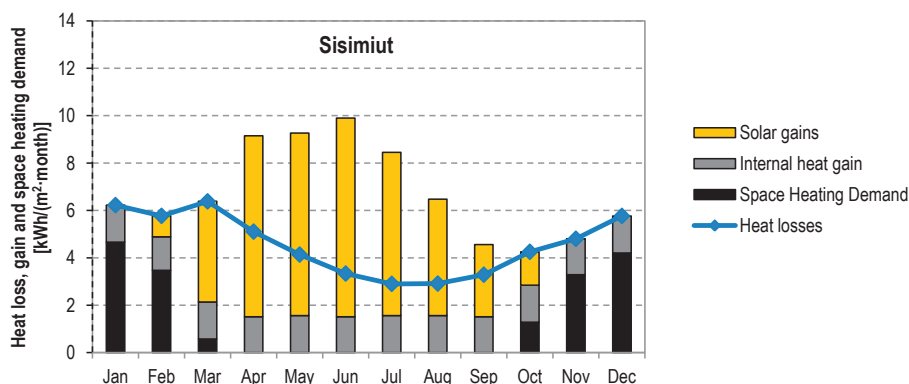


Fig. 18. Heat and gain distribution with space heating demand in a passive house in model "Kranichstein" in Sisimiut

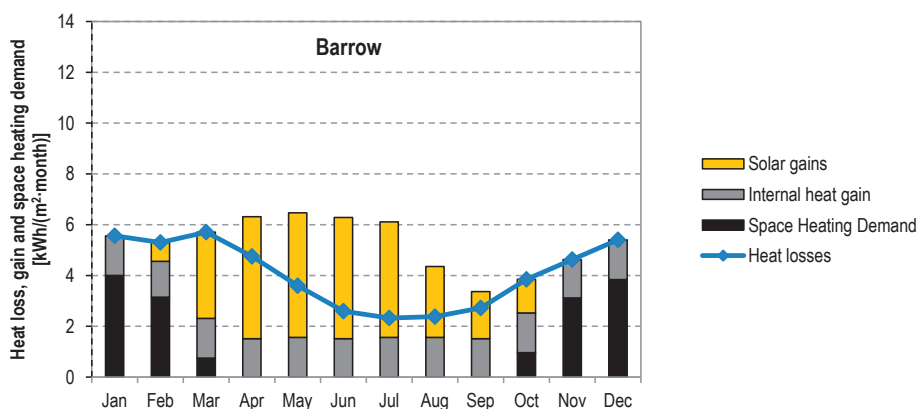


Fig. 19. Heat and gain distribution with space heating demand in a passive house in model “Kranichstein” in Barrow

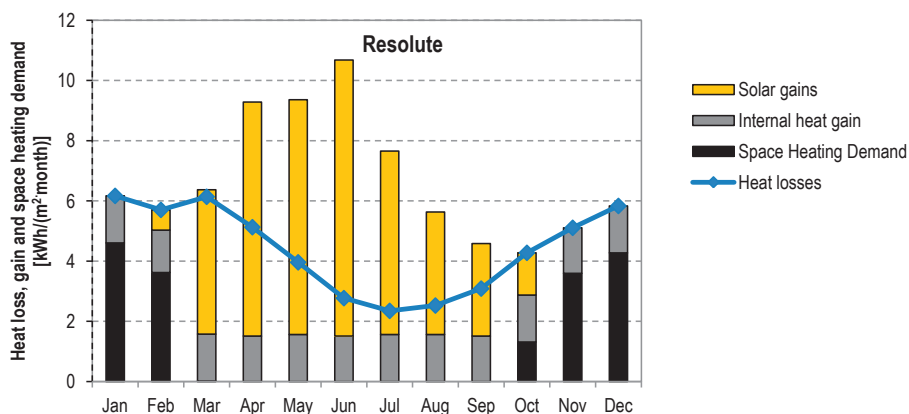


Fig. 20. Heat and gain distribution with space heating demand in a passive house in model “Kranichstein” in Resolute

6.2 The insulation of the building

The insulation is one of the main design characteristics in a building. The insulation is characterized with the thermal conductivity (λ), insulation thickness and thermal bridge free both strongly influence the space heating demand of the building. The thermal conductivity calculation assumes that the heat transfer of the material is linearly related to its thickness, but the reduction of U-value by increasing of insulation thickness is non linear with insulation width. The optimum insulation thickness is evaluated using the heat flow (Fig. 21) through the building wall in which the potential improvement of a building element is proportional with increase of heating degree hours, but the energy savings for additional insulation will decrease with increased insulation thickness.

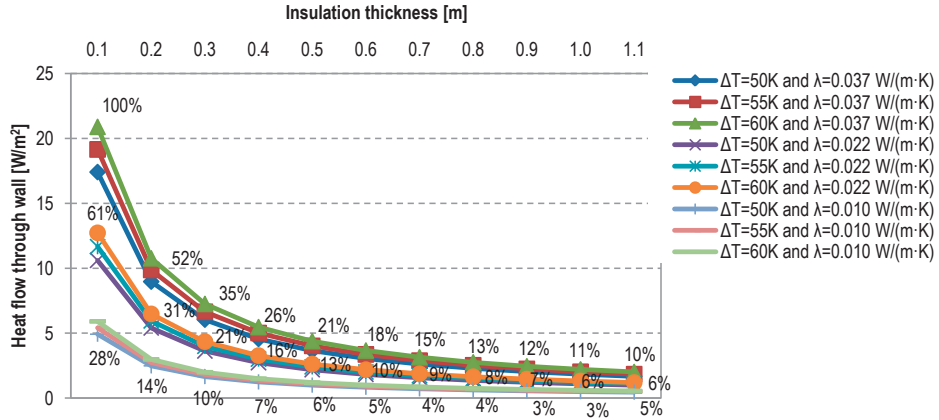


Fig. 21. Heat flow through 1 m² with increasing insulation thickness for different temperature differences and thermal conductivities

The equivalent value describes that the wall transmission heat loss should reach the standards of a passive house, i.e. the transmission heat loss through the insulated building wall should be equal to 13.0 kWh/(m²·a) as shown for a passive house located in Darmstadt (temperate climate). To obtain the same wall transmission heat loss for a location in Sisimiut (Arctic climate) the U_{wall} would need to be as low as 0.075 W/(m²·K), see example in Fig. 22 compared to the wall transmission heat loss for dormitory Apisseq where the U_{wall} would have to be 0.067 W/(m²·K) to reach the same transmission heat loss through the wall [26]. The minimizing of transmission heat loss through the largest building element, such as the wall, has the biggest potential to save energy and, therefore, the improvement of the wall's thermal characteristics is the most beneficial compared to the improvements in other parts and systems of the building (Table 10).

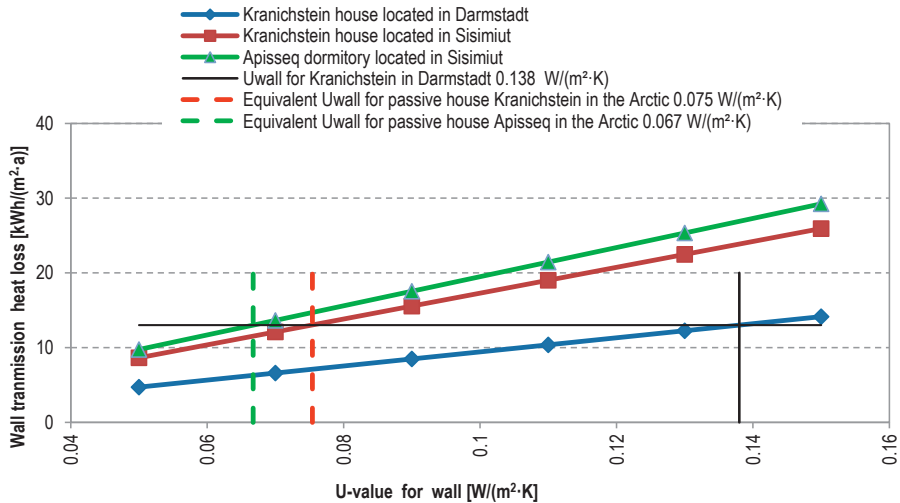


Fig. 22. Example of level of insulation for model “Apisseq” compared to level of insulation for model “Kranichstein”, and equivalent effects with values for locations in Darmstadt and Sisimiut

Table 10. Example of equivalents for improvement to a passive house standard and energy improvements for Apisseq from current state to passive house standards (model "Kranichstein" and "Apisseq")

State and Location	Current state		Passive house		Energy improvements for Apisseq [kWh/(m ² ·a)]
	Kranichstein Darmstadt	Apisseq Sisimiut	Kranichstein Sisimiut	Apisseq Sisimiut	
U _{wall} [W/(m ² ·K)]	0.138	0.150	0.075	0.068	12.8
U _{floor} [W/(m ² ·K)]	0.131	0.130	0.041	0.038	6.1
U _{roof} [W/(m ² ·K)]	0.108	0.130	0.069	0.059	4.8
Ψ _{window/foundation} [W/(m·K)]	0.010	0.03/0.25	0.010	0.010	4.5
Infiltration air change [h ⁻¹]	0.022	0.135	0.022	0.012	3.0
Heat exchanger [%]	80	75	90	90	4.1

The passive house significantly decreases the heat losses to a negligible level through the thermal bridge bridges in the building envelope. The unsolved thermal bridges decrease the interior surface temperature which can result in mould growth and, significantly, they increase the heat losses through the transmission and infiltration. If the thermal bridge coefficient is $\psi \leq 0.01$ W/(m·K), the construction can be considered "thermal bridge free". In the most commonly used building structure in the Arctic, a lightweight timber frame structure, the thermal bridges of wooden studs can be solved by the double stud walls or standoff walls systems which break the thermal bridge with the separate layers of wooden studs and girders supplemented with large insulation thickness. With all thermal bridge free details solved, the thick super insulated walls provide a significantly smaller range of internal temperatures ($> 16^{\circ}\text{C}$) on the surfaces with consistent temperature over all of the walls. Furthermore, the consistent temperatures in the corners are better for the health, thermal comfort and lifetime durability, and it also prevents cold surfaces and possible condensation and/or mould growth.

6.3 Windows

The characteristics of the windows strongly influence the overall heat transfer coefficient, the total solar heat gain coefficient, ψ -value for installation and orientation. The glazing in a passive house should have a low-e coating limiting the heat loss through the radiation, triple glazing filled with argon or krypton which reduces conductive heat transfer and a window frame which is made from composite materials, fibreglass or PVC materials, with warm edge spaces to reduce thermal bridging [43]. The window in a German passive house must have an U-value below 0.8 W/(m²·K) to ensure that the surface temperature on the interior would not drop below approximately 17°C . The windows are designed to bring a net energy gain which is calculated in (12) where the S_i is the solar radiation on vertical surface kWh/m² towards different site orientation, f is a reduction factor influenced by shading, window area and glass ($f = 0.8$).

$$S_i \times f \times g - HDD \times U \quad (12)$$

The results from simple variation analyses [12] show the potential of mainly orientating the windows towards the south, which gives the greatest solar benefits, and, also, that the orientation towards the east and the west is beneficial, but the orientation towards the north should be limited as much as possible. Due to the low solar angle, there is a risk of overheating in the summer for windows facing south.

In Table 11, different characteristics of windows are listed for different locations orientated towards the south, east and west, and these are compared to the windows orientated towards the north which need to have the best thermal insulation properties with low g-value, e.g. aerogel window [54]. Table 11 shows the net energy gain for different windows in different locations based on available solar radiation where Barrow located at 71.2° latitude has slightly larger solar radiation than the location in Resolute at latitude 74.4°.

Table 11. Net energy gain (kWh/m²) for different windows in different locations and orientated towards different orientation

Window's characteristics	Orientation	Sisimiut Latitude 66.4° T _{amb} = -3.9°C	Barrow Latitude 71.2° T _{amb} = -12.5°C	Resolute Latitude 74.4° T _{amb} = -16.5°C
U _{window} / g-value 0.8 / 0.6	South	17	-20	10
	East	-36	-97	-83
	West	-36	-96	-84
	North	-76	-147	-146
U _{window} / g-value 0.5 / 0.6	South	61	42	80
	East	8	-35	-13
	West	8	-33	-14
	North	-32	-85	-76
U _{window} / g-value 0.3 / 0.6	South	90	83	127
	East	37	6	34
	West	37	8	32
	North	-3	-43	-29

The percentage of window area in relation to floor area is another design parameter for houses in the Arctic and, usually, the recommended percentage for window to heated floor area is below 22% which helps to achieve a lower heat loss in the Arctic [47]. Fig. 23 shows the fraction of glazed area towards the treated floor area and a window facing the south for different types of glazing compared to the annual space heating requirement. The same window characteristics are used in a passive house located in the cold climate of Sisimiut as shown in Fig. 24 which deals with the large influence of the glazing on the space heating demand [53].

To achieve a passive house in the cold climate of Sisimiut, the windows would have to have very good thermal characteristics and limits on the window area would have to be made. For example, in the model "Kranichstein" located in the cold climate of Sisimiut, the window characteristics would have to be U_{glazing} = 0.3 W/(m²·K) and the overall heat transfer coefficient through the window U_{window} 0.5 W/(m²·K) with g-value 0.6, yet the total window area would have to be approximately around 20% depending on the window orientation, e.g. 18% of windows facing west, 75% of windows facing south and 7% facing east/west. If the passive house design in the Arctic demanded a larger percentage of window/glazing, the heat loss through the openings would have to be compensated with more insulation in the walls. Windows with such characteristics are not yet available on the market.

The best windows available on the market for passive houses in a temperate climate have the following characteristics: U-value reaching 0.5 W/(m²·K) for glass, 0.11 W/(m²·K) for frame. The g-value can vary between 0.3 to 0.6 dependent on the type of solar control. Usually, the low U-value means that the g-value is low as well. For the Arctic, the most beneficial window characteristics should be a low U-value and a high g-value.

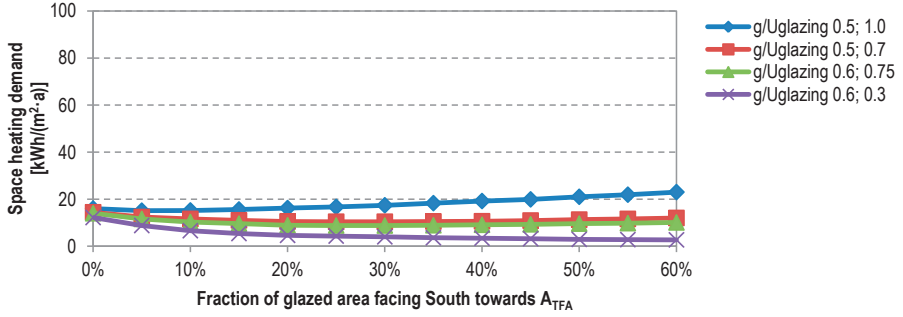


Fig. 23. Example of fraction of glazed area facing south calculated towards A_{TFA} for different types of windows and the impact on the space heating demand performed on passive house using model "Kranichstein" located in the temperate climate

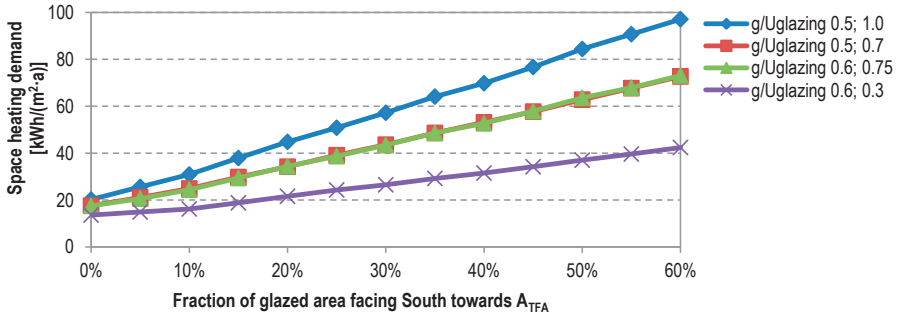


Fig. 24. Example of fraction of glazed area facing south calculated towards A_{TFA} for different types of windows and the impact on the space heating demand performed on passive house using model "Kranichstein" located in the cold climate

The passive house in the form of an octagonal shape in the temperate climate often exploits the solar gains by designing the windows towards all the world's orientations, e.g. MB-Haus [55] and the passive house Harresø [56] that have been constructed in the temperate climate of Austria or Denmark, respectively. The advantage of solar distribution towards all site orientations shows good solar benefits in the temperate climate compared to the transmission heat loss through the windows.

This design approach has been adopted in the new dormitory Apisseq in Sisimiut [26], Greenland, and combined with embedded balconies for protection against harsh windstorms. The design included windows facing all orientations (with each orientation set at 22° to the adjacent ones) and evenly distributed over the whole façade of the circular building. The structure included windows with exterior placement and embedded windows/doors. Investigations show that the solar gains obtained are equal to 7,600 kWh/a and the total transmission heat loss is 32,800 kWh/a with $U_{\text{window}} = 1.1 \text{ W/(m}^2\cdot\text{K)}$ and g-value of 0.56 with shading factor F_s of 0.56. The combination of the embedded balconies protecting the windows from wind and providing shading is the Arctic design approach. The circular building with windows distributed evenly over the various orientations on the façade is the European design which has proven to be energy deficient when used under an Arctic climate [26].

Due to the extreme climate in the Arctic, full compensation of the transmission heat loss through the windows with solar gains can be done only in European locations with current technologies, e.g. the transmission heat loss through a window with $U_{\text{window}} = 0.78 \text{ W}/(\text{m}^2 \cdot \text{K})$ in Darmstadt can be covered by using a glass with g-value 0.45-0.65 for south oriented windows. To fully cover the transmission heat loss [26] in Sisimiut, i.e. to have a positive net energy gain, a super window with $U_{\text{window}} \leq 0.44 \text{ W}/(\text{m}^2 \cdot \text{K})$ with g-value ≥ 0.57 would have to be used windows facing the south. And for ones facing west and east, the g-value should be ≥ 0.95 and higher (Fig. 25). The embedded balconies in Apisseq shade the solar gain with the resulting shading factor 0.56 while the windows on the outer façade have a shading factor F_s of 0.9.

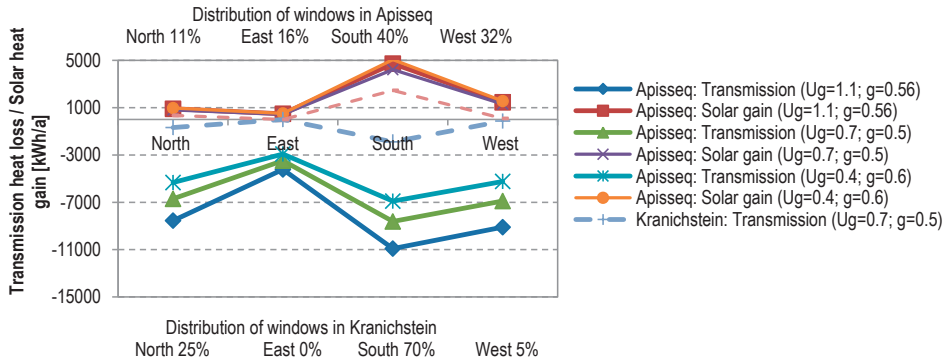


Fig. 25. Example comparison of solar heat gains and transmission losses of the passive house in model “Kranichstein” in Darmstadt with similar values for the windows of the model of “Apisseq” dormitory in Sisimiut analyzing different scenarios for U_{glazing} and g-value

There are several window types working effectively in the Arctic. Currently, a window with an outward opening with “tilt-and-turn” is mainly used, and a shutting mechanism with multiple locking points provides secure tight sealing. Sliding windows to the side are more difficult to make and could be problematic in the extreme climate because of difficulties with a positive airtight sealing. Skylight windows in the extreme climate pose a challenge with snow pressure, problems with sealing and weather characteristics. Regarding window installation, the best position is the current practice for a temperate climate in which the window is centrally placed in the middle of the wall and the window frame overlaps the insulation from the outside. Exterior placement of windows is more favourable in the Arctic to prevent possible snow accumulation and other climate related problems but it does cause a deep window sill on the inside. This deep window sill could be problematic in a passive house as it restricts airflow of heated air and its access to the window corners where possible condensation could occur. The windows must have a method of regulating shading in Arctic locations to prevent overheating. Due to the low angle sun, the roof overhang does not work in the Arctic, and therefore, other types of shading are preferable such as vertical blinds, curtains or shutters which also ensure privacy and provide additional insulation. Often the windows can be supplemented with another layer of glass to enhance the thermal or solar properties.

6.4 Air tightness

Air tightness is secured by using an airtight barrier installed in the building envelope to prevent heat loss through the infiltration and exfiltration. In a cold climate, local thermal comfort is influenced by draughts caused by air leakages through the building envelope and these causes extreme discomfort for the users. For air tightness evaluation of a passive house, the most common method is the blower-door test performed to measure the air change rate n_{50} at 50 Pa pressure differences through the building envelope under steady state conditions. The air tightness is a crucial performance measure in a passive house where the air change at a pressurized state of 50 Pa must be below 0.6 h^{-1} measured by the blower-door test. Another alternative method for measuring the infiltration air change is the tracer gas method which uses the Concentration-decay method.

The investigations of air tightness using the blower-door test in residential buildings in Greenland show a diversity of the results which is strongly influenced by the building age and the application of an airtight layer. The air change rates at 50 Pa obtained from the blower-door test vary between $n_{50} = 11.3 - 18.5 \text{ h}^{-1} @ 50\text{Pa}$ in the standard family houses built in 1960s in Greenland depending on the state and maintenance of the building's structure [10]. While for the newer buildings, the air change rate @ 50 Pa is reduced to 4.9 h^{-1} for the neighbouring house to the Low-energy house in Sisimiut (built in 2006) compared to results from the blower-door test of $3.1 \text{ h}^{-1} @ 50 \text{ Pa}$ for the Low-energy house itself (built in 2005) and the 2.9 h^{-1} for the dormitory Apisseq (built in 2010), in Sisimiut, Greenland.

From the results of the blower-door test, the infiltration air change $n_{\text{infiltration}}$ can use different methods to translate the results from pressurized state to the neutral pressure state. A passive house uses the translation method in accordance with EN 13829 [17]. Depending on the protection of the building from wind, the limiting air tightness value of $n_{50} = 0.6 \text{ h}^{-1}$ at 50 Pa can be converted to 0.074 h^{-1} at the normal state pressure with complete exposure and screening from the wind, or respectively 0.007 h^{-1} with high screening and small exposure to the wind. The other methods for conversion of pressured air change rate to the normal state are the Princeton method using factor "20" derived from several experiments performed in North America, but neglecting many factors affecting the infiltration, the Sherman method [57] including climate correction factor, height factor, shielding factor and leakiness factor, and the SBi method [58] developed by the Danish Building Research Institute. The Princeton and Sherman methods have been developed and usually apply for U.S. conditions; the EN and SBi methods apply for the European conditions. The results of the conversion to the neutral pressure state from different methods are shown (Fig. 26) proving that if the air change rate n_{50} is below 0.6 h^{-1} at 50 Pa, i.e. for super airtight buildings, the conversion using different methods to the normal state differs insignificantly.

Based on the results from the blower-door test, the infiltration heat loss due to the building envelope air tightness can be estimated from $20 - 40 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ for old and not airtight buildings in a temperate climate of Germany. Due to the special attention of the application of an airtight layer in a passive house, the calculated infiltration heat loss can be $1.3 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ with infiltration air change rate of 0.019 h^{-1} ($n_{50} = 0.22 \text{ h}^{-1}$) in the temperate climate of Würzburg. In the cold climates, the infiltration heat loss in a passive house can be increased to $2.3 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ at 66.6° latitude, $3.2 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ in latitude 71.2° and $3.7 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ in latitude 74.4° .

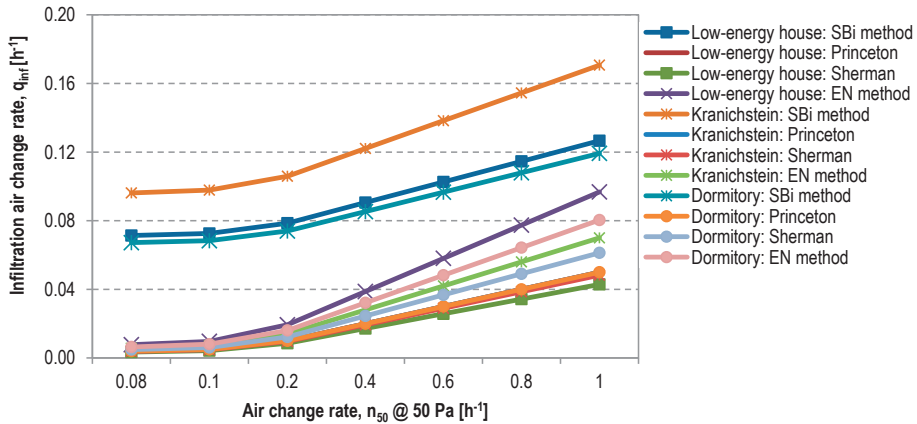


Fig. 26. Conversion of infiltration air change rate from 50 Pa to a neutral pressure state using different method for various models: “Low-energy house”, “Kranichstein” and “Apisseq”

The conversion of a single blower-door test results in an infiltration air change rate which has to take into account the effects of various climate-dependent factors, and the quality of the building construction [59]. The climate-dependent factors depend on the local conditions such as wind, high temperature differences and stack effect where the height of the building can have great influence on the results for non-airtight buildings. The calculated infiltration is under steady conditions, which means that the effect of the wind, stack effect and temperature with other weather effects are not considered. The investigation of the actual houses in the cold climate [59] shows that air tightness problems are identified with window flashing and penetration for electric and other kind of tubing. The major problem is the low level of attention paid to the application of an airtight layer by unskilled and uneducated labour. In other words, the significant importance of an airtight layer is not stressed enough. Therefore, the results of the design infiltration heat loss can vary significantly from the calculated ones. The expected results in an actual house in the cold climate can be even more enhanced by a combination of larger temperature differences, non-steady conditions throughout the year influenced by wind and stack effect, and conversion methods.

6.5 Heating and ventilation systems

The optimization of a passive house for the Arctic climate is dependent on climate characteristics and building data including the type and characteristics of the building, and on the heat produced and consumed in a building, i.e. solar and internal gains, space heating demand and other energies. The key parameter in a passive house is the very low heating load without the need for a traditional hydronic heating system. This needs to be reviewed for the Arctic, and supplementary low-temperature heating will need to be considered. According to the fundamental values used in the passive house in a temperate climate, the possibility of fresh heating by air with a heating load of 10 W/m² based on typical sizes of the houses in which the default occupancy is 35 m² of treated floor area per person and this area need to be supplied by 30 m³/h of fresh air per person with temperature difference of 32°C. The temperature difference is between supply air at 52°C required

by PHI and interior temperature 20°C and along with heat capacity of the air 0.33 Wh/(m³·K). In (13), the result shows the calculated heating load for a passive house in the temperate climate.

$$30[m^3/h] \times 0.33[Wh/(m^3 \cdot K)] \times 32[K] \approx \frac{317[W/person]}{35[m^2/person]} \approx 9.1[W/m^2] \quad (13)$$

In the Arctic, the floor area per person is reduced and the interior temperature is increased, e.g. occupancy 25 m² per living area per person [8], and increased interior temperature on average of 23°C [11]. Assuming a lower ceiling height of 2.5 meter and an increased required air change of 0.5 h⁻¹, the supplied fresh air is increased to 31 m³/h. The calculation procedure is expressed in (14) where the heating load based on the Arctic conditions is calculated to be 11.9 W/m². Theoretically, the heating load can be increased and, therefore, the passive house demand can be met with a classic passive house heating system, because of the smaller living areas of smaller houses. But the houses with larger living areas, high ventilation rates and less occupancy would require stronger heating sources.

$$31[m^3/h] \times 0.33[Wh/(m^3 \cdot K)] \times 29[K] \approx \frac{297[W/person]}{25[m^2/person]} \approx 11.9[W/m^2] \quad (14)$$

The main problem with having a passive house without a traditional hydronic heating system in the Arctic is related to the heating load which can be transported without supplying air with a required air change of 0.3 h⁻¹. The maximum power calculated in (15) is used in the ventilation air heating where the ventilation rate is 0.3 h⁻¹ for a passive house assuming that the maximum supply air temperature is T_{supply,air} = 52°C for interior design temperature T_i = 20°C, heat capacity of the air c_{air} = 0.33 Wh/(m²·K), T_{outdoor,design} as design outdoor temperature and η is the heat recovery efficiency and T_{outdoor,design} is the temperature from design days. The calculated specific heating load has to be lower than the heating load transportable by maximum supply air temperature including the effect of achievable supply air temperature without heating (16) and (Table 14).

$$V \times c_p \times q \times [T_{sup ply, air} - T_{sup ply, min}] \quad (15)$$

$$T_{outdoor, design} + \eta \times (T_i - T_{outdoor, design}) \quad (16)$$

Table 12. Heating load delivered through the ventilation system calculated based on outdoor design temperature in model "Kranichstein"

	Sisimiut Latitude 66.4° T _{amb} = -3.9°C	Barrow Latitude 71.2° T _{amb} = -12.5°C	Resolute Latitude 74.4° T _{amb} = -16.5°C
Heating load [W/m²]	9.6 W/m²	9.3 W/m²	10.1 W/m²
Heat exchanger efficiency η [%]	92%	95%	95%
Temperature on design days [°C], extreme and average values ⁽¹⁾	-27.6; -22.9	-35.5; -30.2	-40.2; -34.2
Supply air temperature without heating [°C]	16.7	17.2	17.0
Heating load transportable with supply air [W/m²] with air change rate 0.3 h⁻¹ and supply temperature of 52°C	8.7	8.6	8.7

⁽¹⁾ obtained from METEONORM 6.0

A properly designed mechanical ventilation system with a heat recovery unit provides good indoor air quality and secures the interior temperature between 18 - 21°C with range of humidity from

30 - 50% while removing pollutants from the air. Those values are considered to be achievable and healthful in the Arctic [60]. Yet, the research has showed that the preferred interior temperature is approximately 21 - 23°C, for instance, for Greenland [10], [11]. The heat recovery unit recovers more energy than it needs for running fans and other electricity energy, and, therefore, it saves a large amount of energy compared to a leaky house with natural ventilation. In the temperate climate, the ventilation heat loss through natural air change in a very airtight and insulated building will be 20 - 30 kWh/(m²·a) without heat recovery and with heat recovery with an efficiency between 85 - 95% the ventilation heat loss decreases to 2 - 3 kWh/(m²·a). In a cold climate, the ventilation heat loss in airtight and insulated building adds up to 60 - 90 kWh/(m²·a) through natural air change. With a heat recovery unit it can be reduced to 7 - 12 kWh/(m²·a). Fig. 27 shows the effect of the efficiency of the heat exchanger on space heating demand in a passive house located in different climates.

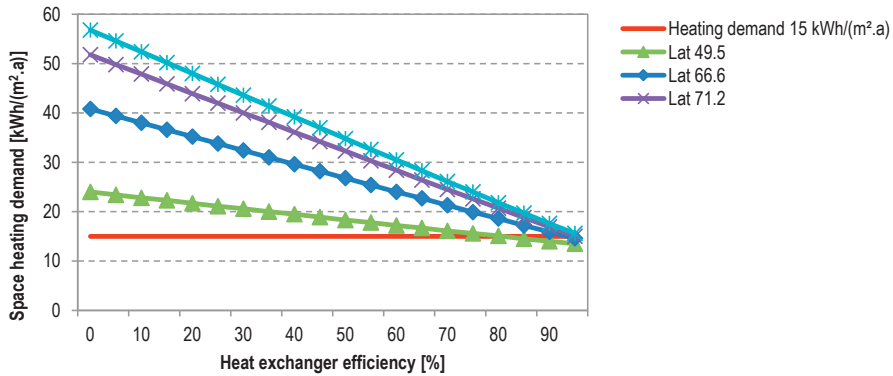


Fig. 27. Heat exchanger efficiency and space heating demand in the passive house in model “Kranichstein” in different climates

Air change and supply of the air are strongly dependent on the efficiency of the heat exchangers and that is a crucial problem in the cold regions. The efficiency can be calculated in many ways, but the one most widely used is the method related to the supply side in accordance with EN 831. According to this method, the efficiency of heat recovery η_t is determined where T_{supply} is the temperature of the supply air after the heat exchanger (°C), $T_{ambient}$ is outdoor temperature (°C) and $T_{extract}$ is the extract air temperature (°C) as following (17), otherwise the PHPP subtracts 12% to make sure that the efficiency of an uncertified heat recovery unit can be reached.

$$\eta = \frac{T_{supply} - T_{ambient}}{T_{extract} - T_{ambient}} \quad (17)$$

To reach an efficiency of 80% is difficult in the cold climate due to the problems with freezing and moisture in the heat exchanger unit which will cost additional energy needed for after heating of the inlet air. Additional energy for after heating of the inlet air is needed in a passive house located in different climates of the cold regions where the defrosting is necessary if $T_{amb} < -3.5^\circ\text{C}$. The $T_{amb} = -3.5^\circ\text{C}$ is chosen as a reference value recommended by producers of heat exchangers; for instance, the plate heat exchanger need defrosting when $T_a < -7.0^\circ\text{C}$ and estimated value compromising efficiency of the heat exchanger [61], [62], [63]. The energy needed for after heating

of inlet air in the passive house with $A_{TFA} = 156 \text{ m}^2$, efficiency of heat exchanger of 90% and air change rate is 0.3 h^{-1} is equal to 1,200 kWh/a for location in Sisimiut ($T_{avg,a} = -3.9^\circ\text{C}$) equalling to $7.7 \text{ kWh}/(\text{m}^2\cdot\text{a})$, 3,700 kWh/a for Barrow ($T_{avg,a} = -12.5^\circ\text{C}$) equalling to $23.4 \text{ kWh}/(\text{m}^2\cdot\text{a})$ and 4,800 kWh/a for Resolute ($T_{avg,a} = -16.5^\circ\text{C}$) equalling to $30.9 \text{ kWh}/(\text{m}^2\cdot\text{a})$ (Fig. 28).

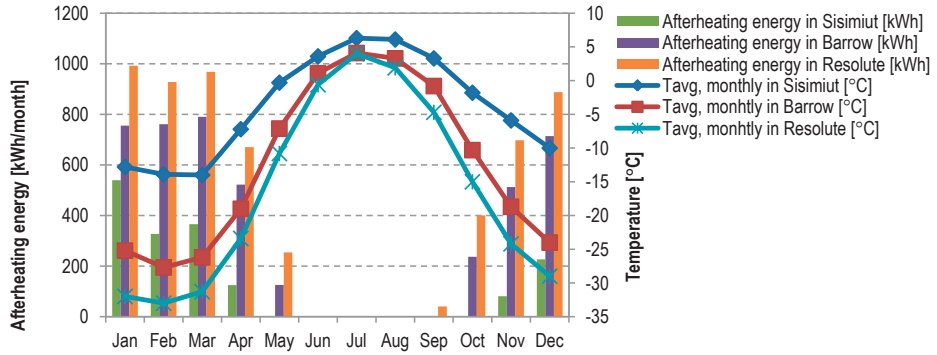


Fig. 28. The energy needed for after heating in a passive house in model “Kranichstein” located in different cold climates

The investigation in the Low-energy house in Sisimiut, Greenland, shows that there are problems with the efficiency and that there is a need for after heating of the inlet air if the temperature drops below zero, although there is an experimental heat exchanger installed consisting of two aluminium counter flow heat exchangers coupled in a serial connection to avoid freezing problems during cold periods [61]. Using the damper, the switch of the air flow can be redirected to the colder exchanger with frost formation and it can be defrosted intermittently by warmer air passing through with a theoretical efficiency of 80%. There is a need for after heating of the inlet air of approximately 2,100 kWh/a (Fig. 29) and the heat exchanger, due to the switching, varies from 60 - 80% with an average efficiency of 70% in the year 2010. The results from the monitoring system point out some interesting things about heat exchangers used in the cold climate, e.g. the heat exchanger unit and air ducts must be placed in an insulated envelope, and that the theoretical efficiency can be achieved at the peaks before switching, but the average efficiency is approximately 70%.

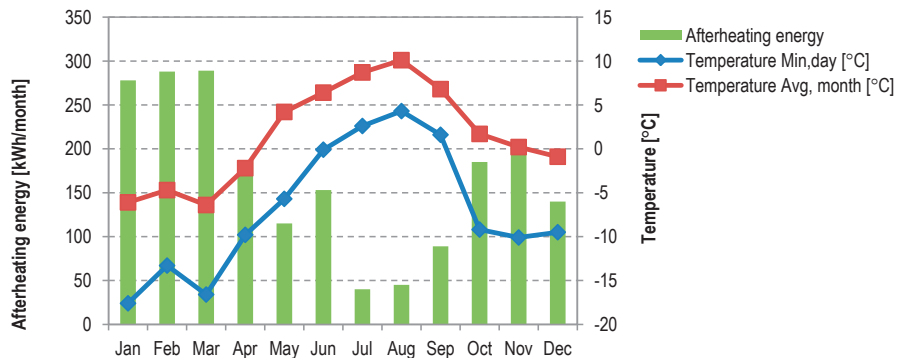


Fig. 29. The energy for after heating of the inlet air in the Low-energy house in Sisimiut measured for year 2010

The prime criteria for the design are the overall heat transfer coefficient and the transfer area, size of heat exchanger, airflow, efficiency, maintenance and durability. The systems must be reliable and easily maintained because of the fact that transportation is expensive and sometimes not available due to the bad weather. The intake openings must be able to cope with high air velocities and they have to be protected from snow and rain entering. Exhaust openings should have higher velocities to propel moist air away from the opening to prevent frost from build-up. The air duct supplies fresh air to bedrooms and living rooms while it is exhausting used and humid air from the bathrooms, kitchens and laundry rooms. The effectiveness above 0.9 can be very expensive and problematic to reach. All systems need to solve the issue with the transmission heat loss through the pipes.

The function of a ventilation system in dwellings is to keep concentration of pollutants and humidity at required levels, supplying fresh air along with extracting polluted air in most efficient and hygienic way. The basic rules for design are to keep the pressure low, keep the ducts as short as possible, round ducts are preferred, careful selection of inlets / outlets, design of sound absorbers. The heating and ventilation systems have to be placed within the insulated heated building envelope; heating and ventilation ducts should not be run in the external walls or through unheated or spaces which lack insulation. Preventing condensation and frost is necessary as it decreases the efficiency of the heat exchanger unit. The ventilation system with heat exchanger for northern conditions needs to accommodate larger temperature differences, defrosting problems with ice build-up from humidity, reduction of flow and speed, switching, recirculation and after heating of the inlet air, among others.

7 Qualitative objectives and challenges in the Arctic climate

Challenges in building a passive house in the Arctic are significantly increased by different climate conditions and limitations on technical and material (re)sources along with the building knowledge. However, there are other qualitative objectives and challenges in the implementation of a passive house in the Arctic. These include the qualitative objectives related to the passive house in the climatically different regions such as economical value with very long payback time and sustainable value expressed in CO₂ emissions. The other influencing factors are the sociological and cultural differences together with a focus on temperature stability of buildings in the extreme climate. The Northern Arctic regions are mostly undeveloped, lack technically skilled labour and have rich non-renewable resources without the ability to exploit them due to the high production cost and transport costs. Not only do the Arctic regions have a different and challenging weather climate; they also have different non-technical aspects such as political, environmental, and economical and culture sustainability differences. Some of these aspects are based on the culture gap [9] between different societies existing in the Arctic [30] and the implementation processes for new technologies and, thus, a decrease in the energy consumption in the Arctic while offering an alternative lifestyle.

7.1 Thermal comfort

The house must secure a good level of indoor environment including the interior temperature securing daylight, preventing overheating and ensuring good indoor air quality. The design temperatures for thermal comfort are considered in accordance with European Standards, for instance, interior temperature of 20°C - 25°C, among many others [64]. The thermal comfort is determined by health, psychology, sociology and situational factors as clothing and activity. In general, the thermal comfort is influenced by air temperature, relative humidity and uneven variations in operative temperature. Locally, the thermal comfort is influenced by draughts, vertical air temperature differences, asymmetric thermal radiation, and whether the floor is warm or cold. The indoor air quality is controlled by interior temperature and humidity which are controlled through the ventilation strategies in energy efficient buildings. The variation of the interior temperature depends on the occupants' behaviour and is one of the key parameters influencing the performance of a building [53].

In the Arctic, the indoor air temperature tends to increase (24 - 26°C) which leads to more energy used than planned. Thus the energy which was planned to be saved is consumed by the higher standards demanded by the inhabitants (Table 13). Depending on the building structure, the additional energy used for higher interior temperatures in the Low-energy house is estimated to be approximately 10 kWh/(m²·a) and for the standard family houses it is calculated to be 30 kWh/(m²·a). When comparing the traditional and low energy buildings, the passive house has an interior design temperature of 20°C in the temperate climate and the increase of interior

temperature in a passive house from design interior temperature of 20°C to a realistically measured temperature of 23°C, can lead to an additional energy increase of 5 kWh/(m²·a).

Table 13. Measured average values of temperature and relative humidity in investigated houses in Sisimiut, Greenland [11], [10], [65]

Type of building	Prime orientation of windows	Temperature [°C]		Relative humidity [%]	
		Summer	Winter	Summer	Winter
Standard wooden family houses ⁽¹⁾	South-orientated house	~17-23	~20-22	~34-42	~32-36
	North-orientated house	~18-24	~24-25	~39-44	~27-30
Low-energy house ⁽²⁾	South-west orientated apartment	~25-27	~23-25	~25-36	~28-36
	North-east orientated apartment	~22-24	~21-23	~23-36	~27-37

⁽¹⁾ Measured in period of 3 weeks in August 2009 and March 2010 in different type houses with different orientations. ⁽²⁾ Measured all year round, for south-west (occupied) and north-east orientated (unoccupied) apartments. Interior design temperature is 21.0°C in Greenland.

The thermal comfort uses two different models: static and adaptive thermal comfort. The static model states that the indoor temperature should not change as the seasons do. Rather, it should be one set temperature all year-around. The adaptive thermal comfort has a variable interior temperature dependent on the outdoor air temperature, taking into account that humans can adapt and tolerate different temperatures during different times of the year. The comfort in the cold regions is different as the temperature difference is very high with high wind velocities and the perception of warmth is different for different people. The adaptive thermal comfort tends to be favourable to use in the Arctic as the definition of the static model for human comfort seems to be too narrow as it has been derived from the investigations and experiences with people living in the temperate climates of Europe and the United States.

The potential of using a passive house in the Arctic is in the living comforts offered compared to the current buildings which are draughty, badly insulated, have low wall surface temperatures, cold temperature radiating from the window's glazing and large temperature stratification in the rooms. In the Arctic, the passive house with its super insulated, air tight and thermal bridge free building envelope would be able to offer comfortable surface temperatures for the walls and windows, which with super thermal characteristics could maintain the surface temperature of the glazing at a maximum of 3.5°C below the interior temperature. The low humidity which causes dry air, static electricity and several sorts of irritation to the human body would have to be solved either through a ventilation system or another type of humidifier. The question is whether the steady interior design temperature of 20°C offered by a passive house throughout the year would satisfy the inhabitant's perception of warmth against a cold outdoor temperature in winter whilst, in summer, the increased hours of overheating would have to be accepted.

7.2 Sustainable value

The payback time on a passive house built in a temperate climate could be different from one built in a region with extreme climate when using the traditional method. Currently, the traditional method of payback is calculated as the costs of building a traditional house with a household with average consumption compared to the additional costs of building a passive house (5 - 15%) [13]. The additional costs of a passive house include the extra building materials, but the costs of a traditional hydronic heating system are subtracted due to the efficiency of the house. The passive house consumes 10 times less heating than an average household in a temperate climate. In the

traditional method, this would mean that the additional costs of a passive house would pay back in less than 5 - 10 years represented in saved energy for heating from a normal to a passive house. The investment in building a passive house is financed by a mortgage with annual interest. In the temperate climate of Europe and USA mainly, the building of a passive house is also encouraged by grants or other loans with fixed low interest from the government which is interested in enhancing sustainable and energy efficient housing. In the temperate climate of Europe and USA mainly, the economical value of saved energy on heating compared to the economical and sustainable (CO₂) costs of the building is fully recognized and practiced.

The economical value of an energy efficient building is yet to be fully recognized in the Arctic. In general, there is an understanding about the current situation with high oil consumption for heating and unhealthy indoor environments in poor insulated houses in the Arctic. Slowing down climate changing is a strong point in the discussion; and so is slowing down the depletion of natural resources. The task is to either lower the use of non-renewable resources, or completely switch from non-renewable to renewable resources. Yet the simple availability of the non-renewable resources and the current building practices applied in the Arctic regions makes it harder to implement the idea and use of an energy efficient house. Although, the benefits from building an energy efficient house would enhance environmental protection, health improvement, comfort living along with creating job opportunities, further education and development of communities. The economy of the energy efficient building is difficult to calculate in the Arctic regions where the payback time is calculated using a traditional method which would lead to an unacceptably long payback period. This is caused by the currently very low prices of non-renewable resources, existing monopoly between building companies and very high prices of the technically complicated buildings.

Therefore, the sustainability value represents the impact of materials on the environment in the Arctic and one of the comparable values is the CO₂ factor, i.e. carbon footprint. The impact on environment is expressed in two ways in which the first one describes the savings on heating consumption if the current heating consumption is decreased to the passive house demand of 15 kWh/(m²-a) and the impact on environment caused by materials used to turn the houses into passive houses, i.e. mainly with focus on the building insulation and transport. The current buildings in selected Arctic locations (Table 14) have very high heating consumption supplied by oil. Table 14 shows the savings achieved for turning them into passive houses through the CO₂ emission for oil of 0.245 kg/kWh [46] and total energy use per average floor area [53].

Table 14. Examples of average energy use and savings for heating and CO₂ emission for current stock buildings in different countries compared to passive house

Country	Average floor area [m ²]	Number of dwellings	Average heating consumption [kWh/(m ² -a)]	Energy use [GWh/year]	Current CO ₂ emission [tons CO ₂ /year]	Passive house CO ₂ emission [tons CO ₂ /year]
Greenland	65.5	11,600	416	317	77,700	2,800
Norway	119.0	2,200,000	181	47,400	11,613,000	962,100
Canada	134.0	12,437,500	231	385,000	94,325,000	6,124,800

Note: Average heating consumption, number of dwellings and average floor area refer to the statistical averages considered for the whole country, i.e. Norway and Canada are considered as the whole country, but they are not all part of the Arctic

Table 14 shows the energy savings and emission production for the building stocks in selected cold regions where the current energy use is calculated based on the average floor area, number of dwellings and average heating consumption obtained from the relevant national Statistics [8], [6], [7]. The current building stock in the selected Arctic countries emits ~ 10.6 megatons of CO₂/year through oil-based heating using the conversion factor of 0.245 kg CO₂/kWh [46]. If all building stock could be upgraded to a passive house using 15 kWh/(m²·a) for heating, the potential savings in consumed energy and thus emissions would be approximately 90%. Building a passive house requires a significant amount of insulation; therefore, the CO₂ emission of traditional building insulation is calculated. The insulation material for construction of a passive house in the Arctic with an average mineral wool thickness of 700 mm would equal 31.1 tons CO₂ emissions per house and 455.5 megatons of CO₂ emissions for the total number of houses in the selected cold regions when using the conversion factor of 1.2 kg CO₂ for manufacturing 1 kg of mineral wool insulation (Rockwool) [66]. The comparison of the insulation material against the heating savings is expressed in emission factors. These results are shown for selected cold regions, and they would be able to be paid back in ~ 40 - 45 years. Other building materials depending on the type of building structure, super windows and building systems could even more significantly increase the years of CO₂ return time.

7.3 Temperature stability

Surviving in an extreme climate depends on keeping warm and on the availability of nourishment, but you can only survive for a limited period of time. The survival refers to outliving extreme temperatures, but in the building design, the focus is on the temperature stability of a building. When energy supply is limited or stops abruptly, suddenly, the temperature stability of a building becomes the determining factor for outlasting the extreme climate. The survivability is strongly dependent on the temperature ability of the structure, i.e. freezing temperatures, strong winds and driving rains, etc. Current lightweight building constructions with an insufficient amount of insulation and a non-airtight building envelope are not able to withstand extreme temperatures for a sufficient amount of time. The current method for solving the problem of temperature stability is based on using the back-up system, i.e. a second source of heating in a building, or oversized diesel engines to supply the community house with energy.

There is a need to build a house in the Arctic in a way that will maintain the temperature for longer time periods without it cooling down if the power supply or heating resources/systems are disrupted. The advantage of a passive house lies in the ability to provide passive survivability [67], i.e. the ability of a building to maintain life-support conditions in the event of an extended loss of power, heating fuel or water, or in the event of extreme climate conditions. The temperature stability is based on the temperature drop and stabilization of internal temperature in a building. For instance, in a passive house located in the climate of Würzburg, Germany, as the location of Kranichstein; the temperature drop is approximately 1°C in 24 hours and the interior temperature slowly stabilizes to 15°C. These values are true for the climate of Würzburg with an average ambient temperature approximately of 3.8°C with an average temperature in the coldest month of 9.6°C and a daily minimum temperature of -9.1°C.

The temperature stability is shown in Table 15 where the standard wooden family house in Greenland (typehouse 18D, [10]) is simulated using BSim and hourly dynamic simulation. The stability is represented by an interior temperature drop and period of time for stabilization in a normal house with lightweight structure in which the heating is switched off during a period of the coldest day and week, obtained from the design reference year for the selected areas (Table 15).

Table 15. Indoor temperature drop and stabilization in a normal house represented as lightweight buildings in different climates (model "Typehouse 18D")

Location and temperature characteristics	Temperature drop and stabilization
	Normal house (lightweight structure)
Sisimiut, Greenland, latitude 66.6° $T_{amb, monthly} = -3.6^{\circ}\text{C}$, $T_{amb, daily, min} = -27.6^{\circ}\text{C}$	15.0°C in first 24h, in a week follows profile of T_{amb} with +4.0°C difference
Barrow, USA, latitude 71.2° $T_{amb, monthly} = -12.5^{\circ}\text{C}$, $T_{amb, daily, min} = -40.3^{\circ}\text{C}$	17.0°C in first 24h, in a week follows profile of T_{amb} with +2.0°C difference
Resolute, Canada, latitude 74.4° $T_{amb, monthly} = -16.5^{\circ}\text{C}$, $T_{amb, daily, min} = -45.3^{\circ}\text{C}$	16.0°C in first 24h, in a week follows profile of T_{amb} completely

The temperature stability of a passive house is based on an example of a Greenlandic standard family house which is turned into a passive house in two forms: a lightweight wooden insulated structure and a thermally massed building represented by an exterior lightweight structure with internal walls and floors made of concrete (Table 16). The lightweight structure made from a wood load bearing structure has a largely insulated building envelope which has a great ability to thermally insulate, but it reacts more rapidly to the temperature changes. Furthermore, the thermally massed buildings can store the temperature in internal walls and floors made of concrete. The internal massed walls and floors present a small risk of condensation because of the fact that they are indirectly connected to the exterior climate and, thus, it poses a small risk of problems related to condensation. Note: In case of black-out there is no ventilation.

Table 16. Indoor temperature drop and stabilization in the passive house represented as lightweight and medium weight buildings in different climates using model "Typehouse 18D" which is renovated into passive house standard

Location and temperature characteristics	Temperature drop and stabilization	
	Passive house (lightweight structure)	Passive house (medium weight structure)
Sisimiut, Greenland, latitude 66.6° $T_{amb, monthly} = -3.6^{\circ}\text{C}$, $T_{amb, daily, min} = -27.6^{\circ}\text{C}$	1.8°C in first 24h, drop of 2.0°C every next 24h, in week slowly stabilizes to $T_i = 8.0^{\circ}\text{C}$ with $T_{amb, daily, min} = -23.0^{\circ}\text{C}$	1.3°C in first 24h, drop of 1.5°C every next 24h, in week slowly stabilizes to $T_i = 11.0^{\circ}\text{C}$ with $T_{amb, daily, min} = -23.0^{\circ}\text{C}$
Barrow, USA, latitude 71.2° $T_{amb, monthly} = -12.5^{\circ}\text{C}$, $T_{amb, daily, min} = -40.3^{\circ}\text{C}$	2.1°C in first 24h, drop of 2.4°C every next 24h, in week slowly stabilizes to $T_i = 5.0^{\circ}\text{C}$ with $T_{amb, daily, min} = -28.0^{\circ}\text{C}$	0.9°C in first 24h, drop of 1.8°C every next 24h, in week slowly stabilizes to $T_i = 10.0^{\circ}\text{C}$ with $T_{amb, daily, min} = -28.0^{\circ}\text{C}$
Resolute, Canada, latitude 74.4° $T_{amb, monthly} = -16.5^{\circ}\text{C}$, $T_{amb, daily, min} = -45.3^{\circ}\text{C}$	2.5°C in first 24h, drop of 2.8°C every next 24h, in week slowly stabilizes to $T_i = 0.0^{\circ}\text{C}$ with $T_{amb, daily, min} = -34.0^{\circ}\text{C}$	1.6°C in first 24h, drop of 2.1°C every next 24h, in week slowly stabilizes to $T_i = 8.0^{\circ}\text{C}$ with $T_{amb, daily, min} = -34.0^{\circ}\text{C}$

7.4 Socio-economic conditions and culture gap

The socio-economic analyses are focused on social impacts of economic changes in the society and they consider the behavioural interactions of individuals or groups. There are different impacts closely connected to the climate through the eco-system, people and housing related to the lifestyle and culture. The socio-economic conditions related to climate change play an important role in the Arctic affecting the permanent dwellings, many of them being located on the coast with access to the marine resources. The fish catchers, e.g. the Inuit, are affected by the depletion of living marine resources and this damage can disrupt the eco-system and that change may cause major socio-economic impacts on the local communities [68]. Additionally, many Arctic marine species depend upon the presence of sea ice. Climate change can also destroy Arctic tourism and, furthermore, oil and gas extraction can reduce the ability of the Arctic to adapt to the climate change. In other words, any oil spills have an impact on local ecology and damage the sea ice. Coastal locations of settlements are vulnerable to flooding by storm surges and coastal erosion. These catastrophes cause problems in the low lying coastal communities which have problems with harbours, water supplies, and fuel storage and sewage disposal systems [69]. Furthermore, the Arctic depends on air and marine transport; especially the freight to remote locations, transport of marine harvesting and emergency operation. This reliance on air and marine transport will increase in the winter with the increased periods of ice-free conditions or the strength of the ice pack, etc.

Other sociological circumstances [70] regarding the people, housing and culture are listed as factors which influence the decision connected to choosing adequate, sustainable and affordable housing in the Arctic. These circumstances need to be considered when encouraging local support for building a passive house in the cold climate. Sociological circumstances are health, level of interest in improvements and the community leadership, willingness and ability to pay, created employment opportunities, labour force ability and further education on constructing, operating and maintenance.

The cultural differences between different societies coexisting in the Arctic, presented as the culture gap [71], are other non-technical aspects. These aspects need to be considered as they play a significant role in the building development in the Arctic and will influence the marketing and use of a passive house. The general population living in the Arctic have further aspects to consider such as a dependency on the knowledge coming from the temperate climate countries, a lack of focus on the different lifestyle of locals which is based on survival, food consumption based on availability, waste management and the use of non-renewable resources at reduced rates, which gives nature more time to regenerate. The design of a passive house in the Arctic needs to consider some design strategies that influence the living requirements, e.g. open floor plans without long central corridors where the small bedrooms should open directly to the central living space with an integrated kitchen [71]. The kitchen should have ventilation exhaust to remove the high moisture levels created by cooking. A single floor plan, i.e. one-storey building, reflects a greater visual interaction and reduces overheating on the upper floor in the summer months when compared to the multi-storey building. Large enclosed porches for storage and equipment are needed, and the houses should have a cold entrance to prevent cold air from entering [9].

Using more energy and advanced materials offer higher standards and more comfortable living; yet, it will increase the rate of consumption. Problems with waste treatment can occur. These problems will result in changes of the traditional lifestyles, e.g. buildings with elevated floors raised above ground epitomizes the cultural divorce from the land, sleeping and collective living will be changed from a single space to different rooms acting as individual selves instead of community, freedom of choice of a house and free movement will no longer exist. All those culture gaps will change the knowledge which the local society possesses, recognizes and understands, and, therefore, it will change the preferred way of living into a more structured way of living. In addition to the culture gap and the socio-economic relations, the successful implementation of a passive house would require educating the people on the aspects related to energy efficient buildings and using energy, and, thus, the education will increase the energy savings and lower the environmental impact through a lowering of the carbon footprint.

7.5 Energy supply

Energy supply is important in the Arctic and, today, it is mostly dependent on imported oil. It is dependent on the fluctuation of oil prices, means of transport and unpredictable weather along with the possible problems connected to means of transport. The energy supply in the Arctic mainly involves relatively small and isolated systems with different sizes, e.g. small cities/towns connected to the electricity grid or collective energy systems, small settlements/villages dependent on supplies by ship (Greenland), ice road (Canada), railway (Russia) or plane (Canada). The single houses and tourist huts in remote locations are totally independent and they are not connected to any energy supply. The energy supply depends on the distribution systems (district, local, independent), managements and security of the supply. Energy production in the Arctic can be supplied from hydropower, incineration plants, wind turbines, solar panels or photovoltaic for heat or hot water and electricity, heat pumps and district heating system.

The passive house in the Arctic must be able to preserve the energy through passive features together with alternate sources for heating, and, at the same time, passive houses must be able to keep going using other means, e.g. using a battery as a back-up from the solar panels, a second hot water tank or batteries. The space heating demand of $15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ can be supplied by a low temperature heating source with a power of 3 - 5 kW which can also supply the hot water for domestic use. Some common methods to heat the air in the passive house include the use of a small heat pump, electrical panel or small combustion unit for biomass. All those heat sources in a passive house in a temperate climate are not to be supplied from non-renewable resources, but in some cases, the energy sources may be a problem for a passive house in the Arctic, mainly due to the remote locations and time-limited availability of renewable resources. The passive house in the Arctic can be supplied by renewable energy resources integrated in the building, but also from other sources optimally combined together with another system, e.g. a hybrid power system.

In normal situations on days with solar radiation, the passive house itself can be independent of heating sources and, thus, work most of the time based on the conservation of energy and the energy supplied from the renewable resources, e.g. heating, hot water and electricity coming from solar and photovoltaic panels. In extreme situations in periods in winter with extreme temperatures and no solar gains, the traditional method of using a small oil-furnace or a diesel

engine will serve as the heating source and cover the hot water consumption and / or contribute to the electricity needed for the ventilation system. Those systems will also easily serve in remote locations without a direct connection to the energy supply. In extreme situations, even without the diesel engine in case of a power shortage from the common electricity grid, the passive house itself will be a backup system which can withstand the wrath of nature and the small amount of electricity energy needed for the heat exchanger can be supplied from batteries and the hot water can come from the second hot water storage.

8 Adaptation and optimisation requirements for the use of a passive house in the Arctic

The adaptation of a passive house is based on the performed analyses of a passive house considering the technical performance of building elements, weather characterizations, resource availability and other special conditions in the Arctic. The adaptation of a passive house in the Arctic is an offspring of the fundamental definition of a passive house with the values and materials available on the European market. The performance of each element of a building is evaluated using a combination of optimisation methods to reach the optimal energy efficiency considering the application of each element and this is combined to give practical and reasonable solutions. The implementation of a passive house in the Arctic also includes the different boundary conditions expressed in an increased value for internal gain, increased air change rate for ventilation and different building structures using suitable techniques. Energy supply is inevitable requirement for an energy efficient building in the Arctic; thus, the energy sources and the usage of energy are very important factors. The optimal solution is based on an opinion which has been supported by a combination of analyses and constraints. This solution offers practical and reasonable solutions taking into account all constraints regarding the Arctic climate. The recommendations for energy efficient buildings in the Arctic are listed based on a study of relevant literature [72], own investigations and an implementation of thoughts about a passive house concept in the Arctic.

8.1 An optimal energy efficient house based on a passive house idea

The implementation of the fundamental idea of a passive house with a heating load below 10 W/m^2 in the Arctic with only low temperature heating sources is a key challenge. The solution is difficult to realize since the design days for calculation of the heating load have no available solar radiation and the internal gains are limited to 1.6 W/m^2 . To reach such a low heating load, the envelope of the building would have to be over dimensioned; especially regarding building insulation thickness and the properties of super efficient windows. The adaptation of a passive house is first and foremost dependent on the optimization of the building materials and systems which are perfected to reach their best performance based on analyses and an equivalent value for a passive house. The further adaptation of a passive house requires an optimization of some input values in order to be able to use the current building materials with reasonable obtained results. The passive house in the Arctic needs to accommodate the needs for different lifestyles, and thus, one of the optimizations is based on the increased values of internal gains with higher needs for ventilation.

The optimization of a passive house and its usage in the Arctic is based on the presented investigations which show that the heating load can be increased in the Arctic regions based on a denser living area together with different social and cultural habits. Those conditions also vindicate the use of increased internal gains 5 W/m^2 coming from the national value (e.g. Greenland) and an average air change rate of 0.5 h^{-1} used for ventilation. With a heat exchanger recovery efficiency of 85% and an infiltration air change rate of 0.020 h^{-1} , the passive house can be

built in a Sisimiut location with reasonable values $U_{\text{walls}} = 0.055 \text{ W/(m}^2\cdot\text{K)}$ and $U_{\text{floor,ceiling}} = 0.050 \text{ W/(m}^2\cdot\text{K)}$ and with efficient windows $U_{\text{glazing}} = 0.7 \text{ W/(m}^2\cdot\text{K)}$ with g-value 0.6 with window area towards floor area below 22%. Applying these values can lead to space heating demand $15 \text{ kWh/(m}^2\cdot\text{a)}$, but the heating load would be 13.1 W/m^2 resulting in a need of a low temperature heating system of approximately 3 - 5 kW which could work in the cold periods without solar radiation (Fig. 30).

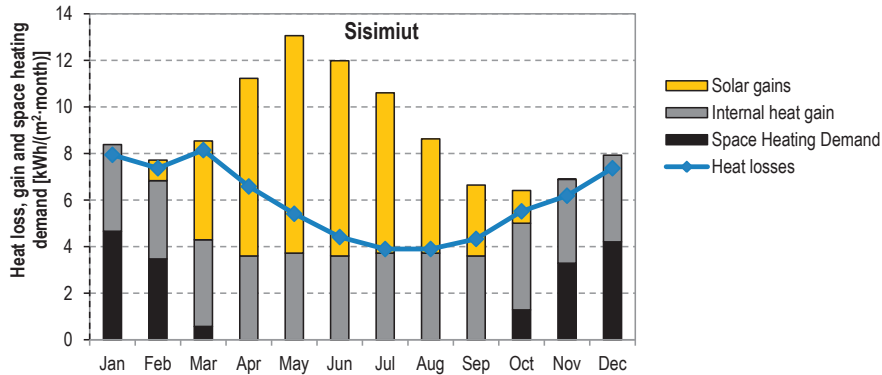


Fig. 30. Monthly energy balance of optimized energy efficient building for the Arctic (model "Kranichstein")

The values for an optimal energy efficient building in Sisimiut are technically and economically reasonable values which can be achieved by using passive house details, modern technologies and efficient materials. Regions which are further north, i.e. Barrow and Resolute, would require technical solutions that are beyond the reasonable use of building materials when using current technologies. The solution may be to keep the current set up of an energy efficient building in Sisimiut and just relocate it to Barrow and Resolute without depict the need for improvements of the houses taking into account the different climate boundaries. Thus, another small solution is proposed in which the improvement of the insulation by $+0.01 \text{ W/(m}^2\cdot\text{K)}$ and decrease of the window to floor area by -2% for each $+5^\circ$ of latitude towards the North Pole lead to the following results for the energy efficient building in Barrow with space heating demand of $26.6 \text{ kWh/(m}^2\cdot\text{a)}$ with heating load of 15.9 W/m^2 , and in Resolute with space heating demand of $23.9 \text{ kWh/(m}^2\cdot\text{a)}$ with heating load of 15.0 W/m^2 . Besides the technical improvements for building elements, the findings show that the reasonable energy efficient house based on the passive house idea is very difficult to achieve. Using the national values it would be possible to make use of a passive house concept in latitude 66° , yet, above this latitude, the implementation of a passive house is very difficult when using current technologies [53].

The primary energy demand may offer another small means of optimization with the combined energy usage of the fundamental design values of a passive house, i.e. specific primary energy $120 \text{ kWh/(m}^2\cdot\text{a)}$, heating load 10 W/m^2 and space heating demand $120 \text{ kWh/(m}^2\cdot\text{a)}$. The heating demand and half of the hot water consumption will be covered by an oil-boiler, and the hot water consumption, auxiliary and household electricity add up to approximately $60 \text{ kWh/(m}^2\cdot\text{a)}$, being 50% of $120 \text{ kWh/(m}^2\cdot\text{a)}$ for specific primary energy. Instead of limiting space heating, one could use another $40 - 45 \text{ kWh/(m}^2\cdot\text{a)}$ for heating a building, i.e. primary energy $120 \text{ kWh/(m}^2\cdot\text{a)}$ deducting

60 kWh/(m²·a) of energy for DHW, auxiliary and electricity, and subtracting 15 kWh/(m²·a). Using only 50% of 40 - 45 kWh/(m²·a), i.e. in case of other energy needed for ventilation or household appliances, would mean that there is approximately 20 kWh/(m²·a) which can be used in the heating system and, thus, the space heating can be increased by this value.

8.2 Design approach for energy efficient buildings in the Arctic

The design approaches for housing in the Arctic are based on the investigation, study of relevant literature and thoughts on a passive house. These recommendations are focused on design advice at the building site level, overall building techniques suitable for the Arctic and building elements considered for improvement of energy performance. To achieve an energy efficient building which performs in accordance with the energy design specifications in the Arctic, the measuring and monitoring methods for follow-up on building construction and energy performance are crucial for a successful implementation of an energy efficient building in the cold regions [9], [73].

Design

- shape and orientation of the building shell to minimize heat loss and maximize exposure to sun combined with shading from low angle sun rays to prevent overheating
- intermediate zone - buildings surrounded by other buildings to reduce the effect of the strong winds on infiltration and reduction of the heat loss
- use attic, side crawl and basement spaces as buffer zones between the interior and outdoor climate; these spaces need to be considered in connection with the air and vapour tight barrier
- exterior “wind shield” entry points serve to protect the interior thermal space within the thermally insulated envelope, and cold entrance is also used as storage
- outdoor rooms such as a protected courtyard, glazed atrium and sun rooms for summer and winter heating benefits should be thermally separated from the building as they only have a limited solar potential
- earth sheltering and foundation slab on the ground are difficult to use in the Arctic regions due to the permafrost and enhanced level of insulation from the ground
- pile foundations with ventilation openings below the building to prevent snow accumulation under the buildings and to prevent the entry of wind-driven snow
- a reflective surface in front of the building increases the solar heat gain and it can bring uncomfortable glare from snow cover
- embedded and hereby weather protected windows / balconies contribute a very small amount of heat gain due to the commonly used properties of windows
- in the Arctic, seasonal heat storage may be difficult to control, such as insulated space around the foundation, due to the permafrost and ice formation around the house
- renewable systems must be connected to the building system, but the building must be able to operate independently of the energy supply and, thus, have a heating system, preferably a low temperature heating system
- effective storage of excess energy needs to be implemented, e.g. a second hot water tank, batteries

Building

- the temperature in the Arctic can be described as “twice as cold”; for this reason, the normal practise requirement should be that houses have the overall heat transfer coefficient “twice as good” which is equivalent to a minimum value of $0.05 - 0.07 \text{ W}/(\text{m}^2\cdot\text{K})$, i.e. half the passive house value applicable in Europe
- the air tightness of the building envelope is crucial in the Arctic and the infiltration air change has to be below 0.020 h^{-1} at a normalized pressure state
- building penetration should be kept at a minimum because of the high wind, snow drifting and stack effect; special attention must be paid to the plumbing and other penetrations
- a high number of inefficient building details is less preferable and can only be avoided using a smaller number of efficient building details
- use of double roof and wall constructions for ventilation within the building shelf
- the potential for net energy gain through the vertical windows is mainly for a southerly orientation; orientation towards east and west can bring zero energy gain;
- window characteristics: U-value below $0.5 \text{ W}/(\text{m}^2\cdot\text{K})$ and g-value above 0.6, and include necessary shadings
- the heat loss through the windows facing north will always be larger than the solar gains and it will be the weakest point of a building
- consider thermal shutters for windows operated by sensors based on the temperature and daylight
- skylight windows have problems with fixing, snow, and heat and ventilation heat losses, and they are not fit for use in the Arctic
- thermal mass in the form of concrete walls may be beneficial but difficult to implement for interior walls without connection to the exterior, but, after 3 - 4 months in the winter without sun, they will pose a risk as a “cooling part”

Systems

- all services must be kept in the inside of the thermal membrane, i.e. wiring, plumbing, communications and HVAC, to ensure effectiveness
- the heating system must have a power of 3 - 5 kW and should be run independently in relation to the outdoor situation, i.e. it must be supplied from a climate or weather independent source
- the ability to adjust temperature at room level. i.e. adjustable thermostat, needs to be considered for the winter season, and in summer, it has to be possible to manually influence the thermal conditions, e.g. by opening the windows
- HVAC must be easily maintained, reliable and designed for continuous operation
- the average efficiency of a heat recovery unit must be above 80%, preferably 90%, which has to be documented in-situ, e.g. air to air heat exchanger and run-around-loop have been recommended as high-performing systems in the Arctic regions of Alaska
- the ventilation system must be able to deal with a possibly large amount of condensation
- ventilation intake and exhaust must be protected from air and snow entry, and ventilation intakes and exhaust must be carefully designed

- the defrosting must activate when the ambient temperature goes below -3°C , top up heating of supply air reduces the recovered heat benefits, defrosting can be provided by recirculation of the exhaust air back through the supply to the heat exchanger, i.e. air with recirculation
- using earth for a ground temperature heat exchanger may be difficult due to the permafrost and/or rocks foundations
- ecological treatment of sewage and water

To certify a passive house in a temperate climate requires delivery of an energy calculation and performance of a blower-door test. To get these results for a passive house in the cold regions requires greater effort due to the fact that a small error can result in twice as much energy loss. To ensure that the designed passive house performs in accordance with the PHPP calculations, the building commissioning process needs to be implemented as a follow-up to both the construction and operation of a building. For at least the first year of operation, the energy monitoring should be a standard procedure and part of the certification process of a passive house in the Arctic. This will lead to a successful implementation of a passive house in the Arctic.

9 Thesis summary

The main conclusions from the work carried out during this Ph.D. study are summarized in the following chapter as the main conclusions from the thesis and the appended papers. At the end of the chapter, suggestions for further work are given.

9.1 Conclusions

This thesis intends to add valuable knowledge to the present information on the fundamental passive house in terms of the implementation and use of a passive house in the extremely cold areas of the Arctic. The limits for the design and performance of a passive house are examined in regions with ambient temperatures twice as cold as in temperate climates and with different solar distribution and quantity. The importance of the design parameters in designing such an energy restricted building in an extreme climate is described, and the investigations show how close one can come to the limit of a passive house design in extreme climatic conditions. The analyses presented in this thesis offer a theoretical possibility of building a fundamental passive house in the Arctic, an improvement of the technical solutions in a full sense of the original definition, a discussion of the new definition based on the optimization of building construction products and adaptation of a passive house in the Arctic based on the best combination of building design aspects, climate characteristics, material availability and energy resources combined with ecological impacts.

In this thesis, the application of a passive house in the Arctic regions is based on achieving the required performance such as the space heating demand of $15 \text{ kWh}/(\text{m}^2\cdot\text{a})$ with the heating load of $10 \text{ W}/\text{m}^2$ for the design days and a primary energy demand of $120 \text{ kWh}/(\text{m}^2\cdot\text{a})$ when using the fundamental values of a passive house. The equivalent parameter based on the reversion of a passive house design and simple building physics show how far one has to go to reach the passive house in any climate. Yet, the simple adaptation of a passive house in extreme climate proves to be too technically demanding in relation to the unfeasible thickness of building insulation in a highly airtight building envelope, windows with unrealistic properties which are not designed for shallow sunrays and the requirement for a highly efficient heat recovery unit. Without the alternation of passive house design values, the heating load of $10 \text{ W}/\text{m}^2$ can be achieved with an unrealistically over dimensioned building.

The adaptation of a passive house in the Arctic can be achieved using the following optimisation methods: a single, a multi and a qualitative method. These methods are combined to give the most optimal solutions using practical and reasonable means. The optimised energy efficient building is derived from the fundamental concept of a passive house. This is based on the interactions between energy demand, indoor climate, building technologies and the impact on the environment. Firstly, the design of a passive house in the Arctic needs to focus on minimizing the heat loss through the insulated and opaque elements of the building envelope, and on minimizing the impacts from snow and wind exposure using neighbouring land forms and structures for winter protection. This can be achieved by thermally insulated, simple shaped building design resulting in a simple building form without details that are structured in a way which is too complicated.

This results in a reduced number of thermal bridges and a limited window size with orientation mainly towards the south, east or west. The temperature in the Arctic is 'twice as cold' compared to European conditions, and thus, the values connected to the building envelope of a passive house need to be doubly energy improved, i.e. overall transmission heat transfer for insulation below $0.05 \text{ W}/(\text{m}^2\cdot\text{K})$ and excellent window characteristics with U-value below $0.5 - 0.7 \text{ W}/(\text{m}^2\cdot\text{K})$. Secondly, the solar exploitation needed to obtain maximum solar heat gains from low angle sunrays along with minimizing the transmission heat loss through the opaque elements, i.e. the energy efficient windows with solar energy transmittance of at least 0.6. However, there will still be several winter months without sun.

The different perception of warmth due to the extreme climate and the different culturally influenced lifestyles result in denser living areas and would allow a usage of higher internal gains, but smaller dwelling areas would also mean that the ventilation per area is ideally higher. At some point, a supplementary local exhaust fan would need to be used to remove excess humidity. Moreover, the recovered heat through an efficient ventilation system must be secured to reach a level above average, i.e. efficiency should fluctuate between 80 - 90% at design days. Because of the scarce renewable resources and the transportation of all of these resources for most of the Arctic regions, the non-renewable resources will have to be available throughout the entire year. Thus, supplementary heating will have to be provided from non-renewable resources. The energy efficient house designed for the Arctic climate needs to be equipped with renewable systems which will be able to work independently and cover at least half of the various consumptions based on the solar and/or wind sources.

The passive house built in the Arctic in accordance with a fundamental definition, or with an alteration of this, has positive characteristics which can benefit the inhabitants. The passive house in cold climate regions can be a very comfortable house and maintain a high level of indoor comfort and temperature stability in case of heating or power abruption. The passive house is quite complicated to build, but it offers a good solution in relation to the annual costs compared to the ordinary systems / buildings used so far. The simplicity and affordability of a passive house in the Arctic is the main question. In the near future when high technology and building knowledge are fully available in the Arctic region, the passive house will be more attractive and comparable to the conventional technology currently used. The key contribution of an adaptation of the standard passive house for use in a cold climate is the market stimulation for the innovative products needed for an energy efficient building in the cold climate, i.e. low U-value of window and super insulated airtight window / door, very efficient heat recovery units with after heating along with a combination of another small heating supplementary system. The main point is that the heating system with heat recovery, which can be massed produced, would be cheaper than conventional hydronic systems.

Due to its low energy consumption, the passive house optimizes its relationship with the local ecology and minimizes the environmental impact originating from heating consumption. On the other hand, the environmental impact is very high when calculating the embodied energies in the building process and the fact that there is a limited choice of building materials and, long distance transport is necessary. For an energy efficient building, it is essential that project planning of the building construction is done with careful attention to detail. This is a crucial aspect in the cold climate regions. The transfer of an altered concept of a passive house would be easier to adopt in Canada, Alaska and in Scandinavian countries which already use a very well insulated and

airtight building with ventilation heat recovery system. In countries such as Greenland and Russia, where the use of energy efficient buildings is less developed and where there are greater transport distances, the adoption of a passive house would be more demanding; even if the technical solution would be provided, the affordability of a passive house in its full definition would still be a big challenge in these Arctic regions.

The design and performance of a passive house through improved building envelopes and energy performance need to relate to the cultural and ecological context. The passive house needs to connect to the local characteristics and culture such as regional building traditions, site specific context, local society, behaviour, needs and tradition, transport, local ecology and land use.

The implementation of a passive house concept based on sensible solutions of material use and practical level of construction methods leads to the conclusion that it is theoretically possible to build a passive house with some alterations of internal gain use, the limitation of window areas and very efficient building systems in the Arctic regions, especially above 66° latitudes. But further north, the technical parameters of the building components go beyond the reasonable values; even with the alterations and the heating load increased to a level where an additional local heating source is unavoidable. The smart design of a passive house is the most pragmatic solution which offers a very comfortable way of living for any climate and it can be adapted to any climate regardless of the final amount of energy required for heating consumption of such a house.

9.2 Suggestions for further work

Acceptance and marketing of a passive house with low heating consumption in the Arctic will be very difficult because economic issues, such as the payback time, are often underestimated. Currently, a full life cycle analysis of the passive house in the Arctic shows a rather big impact on the environment due to the use of existing technologies.

It is a clear assumption that reaching exactly 15 kWh/(m²·a) or 10 W/m² will be difficult in buildings in the Arctic because of the large temperature differences and different lifestyles. A passive house and its use in the cold regions can offer a comfortable lifestyle, but the inhabitants may need to adapt their lifestyles to keep the interior temperature of 20°C.

The passive house techniques will require a deeper understanding of the importance for each feature in the building and from every party involved in building process. There will be a need for a strong dissemination of knowledge about every aspect of a passive house to architects and engineers. Technically skilled labour will be required to execute the very precise job of building a passive house. Yet, the acceptance of super insulation thickness is the major opposition in the extremely cold regions.

Adapting a passive house to the future climate changes in the Arctic regions, i.e. increasing the ambient temperature, different patterns of precipitation and perhaps changes in solar radiation, would also alter the heating sources and require a necessary implementation of renewable resources. The systems for renewable resources and their best usage in the Arctic regions would require systems with high efficiency, low maintenance and high reliability.

10 Summary of appended papers

Paper 1: ***Passive houses for the Arctic climates***

Petra Vladykova, Carsten Rode, Toke Rammer Nielsen, Søren Pedersen
Published in the 1st Norden Passivhus Conference, Trondheim, Norway, 2008

The article *Passive Houses for Arctic Climates* introduces a new PhD project at the Technical University of Denmark. This Ph.D. project deals with the German definition of a passive house for European climate conditions and, by means of analysis, it tries to find a new optimum suitable for Passive Houses in more severe regions where the sources are limited. Furthermore, the best building energy performance is sought. The focus is on how the passive houses will work and how its performance could be improved under more severe or even extreme cold climate conditions through examining the various technologies, energy sources and outdoor climate.

Paper 2: ***The potential and need for energy savings in standard family detached and semi-detached wooden houses in arctic Greenland***

Søren Peter Bjarløv, Petra Vladykova
Published in the Journal of Building and Environment, 2010

The article describes the present situation of energy efficiency related to the standard wooden houses (typehouse) in Greenland based on research carried out on real buildings in the Arctic and provides physical results which are important to verify the theoretical work. The significant potential for fuel and CO₂ savings are of great interest to others living in extreme climates. The improvement of the energy potential is represented by different types of improvements such as original state, existing GBR, future low energy, passive house.

Paper 3: ***Low-energy house in Arctic climate - 5 years of experience***

Petra Vladykova, Carsten Rode, Jesper Kragh, Martin Kotol
Accepted in the Journal of Cold Regions Engineering, 2011

The Low-energy house in Sisimiut, Greenland, is an example of a highly insulated and energy efficient building with low temperature heating and heat recovery ventilation system. The article presents the importance of insulation, air tightness and an efficient heat exchanger. The description of the experiences with building energy efficient houses is presented and the building techniques in the Arctic are described. The paper presents experiences with the actual house located in the Arctic based on the measurements from monitoring systems, investigation of ventilation systems and air tightness, and on a theoretical analysis of calculation models.

Paper 4: ***Passive houses in the Arctic. Measures and alternatives***

Petra Vladykova, Carsten Rode, Toke Rammer Nielsen, Søren Pedersen
Published in the 13th International Conference on Passive House, Frankfurt am Main, Germany, 2009

The paper describes the measures and alternatives of a passive house and its possible use in extreme climate. The functional definition of a passive house is investigated in Greenland and different circumstances are considered. The internal gain for Germany and Greenland are calculated including aspects of the living conditions and habits of the Inuit people. The local conditions and correct climate and weather data are highlighted. Alternative optimization of the fundamental passive house and its use in other locations above the Polar Circle are discussed.

Paper 5: ***The energy potential from the building design's differences between Europe and Arctic***

Petra Vladykova, Carsten Rode
Published in the 9th Nordic Symposium on Building Physics, Tampere, Finland, 2011

The new energy efficient dormitory Apisseq with its monitoring system is used as a key example for investigating main parameters needed to decrease the energy demand to a lower standard, even compared to a passive house. The work deals with boundary parameters for optimal energy design, solar radiation potential through the low angle sun in the Arctic, the necessity of retaining the heat during periods without sun, the importance of air tightness of a building envelope and heat recovery ventilation system to provide good indoor climate.

Paper 6: ***The study of an appropriate and reasonable building solution for the Arctic climates based on a passive house concept***

Petra Vladykova, Carsten Rode
Submitted to the Journal of Cold Regions Engineering, 2011

The Arctic / Antarctic regions and climates are cross investigated in order to select the most interesting areas based on population, location and weather data. These locations and climates in Arctic areas are evaluated as the best suited locations for a passive house. The performance of a passive house is investigated based on definition, boundary conditions, design parameters, and, furthermore, the perspective aspects of a building design suitable for the Arctic are investigated. The adaptation of a passive house is based on a modification of building technologies, available techniques and climate parameters in the Arctic. Therefore, the paper represents an optimal energy efficient house which is designed based on reasonable building solutions for the Arctic derived from a passive house concept.

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12 Appended Papers (I-VI)

Paper I: Passive houses for the Arctic climates

Petra Vladykova, Carsten Rode, Toke Rammer Nielsen, Søren Pedersen

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Passive Houses for the Arctic Climates

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Abstract

The article Passive Houses for Arctic Climates introduces the new PhD project at Technical University of Denmark, which deals with the German definition of Passive House for the European climate conditions and by means of analysis tries to find an new optimum suitable for Passive Houses in more severe regions where the sources are limited and the best building energy performance is sought. The article illustrates a few examples of the sensible sensitivity analysis made by a thermal building analysis tool – Bsim, where the focus is put on the insulation thickness of wall, roof and floor, and on the window's thermal characteristics. The analysis are made for the Low Energy house build in 2005 in Sisimiut, Greenland, where the weather is extreme and there are long periods with/without sun. Therefore the solar gains are also investigated. Furthermore the simulations are focused on Greenland (Sisimiut) and Denmark (Copenhagen) weather conditions. And the focus is put on how the Passive Houses will work and how their performance could be improved under more severe or even extreme cold climate conditions where the various technologies, energy sources and outdoor climate are very different.

Keywords

passive house, arctic climate, simulation analysis

1 Introduction to the project Passive Houses for Arctic Climates

To make a building a passive house as defined by Wolfgang Feist, Passivhaus Institut, its annual heat demand shall not exceed 15 kWh/m², its total primary energy demand shall not exceed 120 kWh/(m²·a), and the air change by 50 Pa pressurization shall not exceed 0.6 air changes per hour [1]. The reference area is net area and well-defined standard conditions apply. Thereby the heat can be supplied just by post-heating after a heat recovery unit the amount of fresh air that is needed to ensure satisfactory indoor air quality. The definition holds for all climates, but can in some climates be realized only by increasing the amount of thermal insulation, by using better windows, and by having a very air tight building envelope while using ventilation systems with highly efficient heat recovery units. Passive houses also take advantage of free gains such as solar heat, heat from occupants and their activities, and possibly from underground heat exchangers.

Supposedly, the passive house should be realizable in all climates [2]; however the arctic climates pose challenges. The insulation level would be very large, and solar gains are in some areas completely missing or much greater in the part of the year. The heat recovery systems are very often blocked by ice formation; therefore the new implementation/techniques will be needed.

The project "*Passive Houses for the Arctic Climates*" has the following **research questions**:

- Can the European definition of a passive house make use in the Arctic countries?
- How will a European passive house perform in Greenland?
- Could an Arctic passive house stimulate the development of low-energy building technology in other climates?

The new definition of the passive house for Arctic climate will be need it and the project should contribute to accomplish this goal where the building will be thermally conditioned to a satisfactory level for indoor and health environment by minimal provision of energy. Presumably the energy could be obtained from local and renewable (re)sources. The project is focused on current technologies used to achieve such a low energy building in the Europe and in the Arctic. The technologies will be adapted to the extreme climate conditions, where the low energy consumption is a main objective of the study as well as a good indoor climate in the Arctic regions.

The project uses the computational and analytical tools such as BSim, TRNSYS, and PHPP. The computations and analysis will be carried out to investigate the possible extent of reducing energy consumption for conditioning of buildings in Arctic climates, so called **the sensitivity analysis**. It will be sought to determine what it requires to meet the ambition of making building without traditional heating equipment.

Using the computational analysis the current existing low-energy and passive houses in Europe will be virtually moved to the extreme weather regions where the energy-performance analysis of the performance in such climate will be performed. The analysis will answer how the European passive house will behave under extreme climate and what it would take to turn such a building into the passive house according to the European passive house definition.

The project "*Passive Houses for Arctic Climates*" is the main topic of recently started Ph.D. project at Technical University of Denmark. Through the Centre for Arctic Technology the project will contribute to the development of optimal energy design for a new dormitory building in Sisimiut (funded equally by the Villum Kann Rasmussen foundation and the A.P. Møller og Hustru Chastine Mc-Kinney Møllers Foundation) that will be build in 2008 in Sisimiut, Greenland, in particular, and for advanced Arctic buildings in general. The project will as well contribute to defining goals for passive houses in various climate regions.

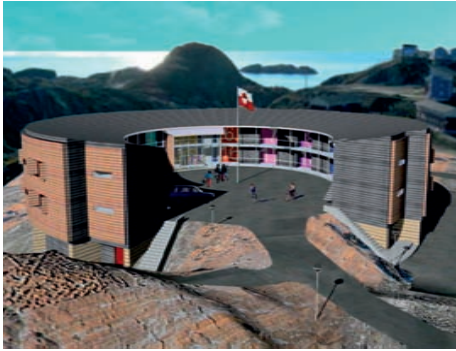


Fig. 1. Dormitory building in Sisimiut, Greenland

The project will end up with the well-documented summary of technologies to adopt extreme low-energy building technologies in Arctic climates and it will give the scientific input to the new products developments for the extreme climate as well as for the innovation parts for moderate climate. The task is to come up with the definition of a passive house in the extreme weather regions and such a definition of the well energy performing building could be in the future called **the Arctic passive house**.

2 Introduction to the Sensitivity analysis

The article deals with a **computer based parametric study** of the building design of Low-energy house in Sisimiut, Greenland, and checks the results for energy demands. The simulations are focused on modifying of the elements step-by-step:

1. building envelope = external walls, roofs, floor slabs and windows (thermal transmittance of materials)
2. long periods with/without sun and solar radiation (solar gains)

The purpose of the article is to present a few examples of the sensitivity analysis made in BSim where the simulations are focused on the extreme climate in Greenland (extreme weather) and the long periods with/without sun. Later on the completed analysis will lead to answering the following question: What it would take to make an existing Low-energy house in Sisimiut, Greenland, from the low-energy house into the passive house (German definition) in the Arctic climate?

Low-energy house in Sisimiut, Greenland [3] has been built in 2005 by the Technical University of Denmark and Sanaartormik Ilinniarfik (The Building and Construction School of Sisimiut) with funding from the Villum Kann Rasmussen. Sisimiut is located north of the Arctic Circle (latitude 66.96°, longitude 53.68°; heating season the whole year).

The house is approximately 200 m² and it is a double house with common entrance and technical room. The building envelope has increased insulation thickness and wood profiles with minimum

thermal bridge effects (see Table 1 for the envelope thermal characteristics). The building contains lots of measuring equipments for measuring the floor heating consumption, solar collector's production and oil burner consumption. Furthermore the house has a newly developed ventilation system with a new prototype of heat recovery unit.



Fig. 2. Low-energy house in Sisimiut, Greenland



Fig. 3. Windows in the Low-energy house in Sisimiut, Greenland

3 The used method and BSim

Method used for the examples of the computational analysis is focusing on the building envelope (wall, roof, and floor insulation thickness, and thermal characteristics of windows). As “LEH designed” is considered the calculated U-value and insulation thickness which were designed and used for building the Low Energy house. As “LEH +10%” is taken the variation of insulation level by 10% (e.g. adding extra 10% of insulation to “LEH designed”). And as LEH -10% is calculated with insulation thickness lowered by 10% (e.g. taken out 10% of insulation from “LEH designed”). Also the window thermal characteristic (heat transmission coefficient) has been varied the same way. For input data see Table 1 and Table 2. These simulations have been run under the “Sisimiut.dry” file with input date from reference year [4].

The simulation of LEH has been than run under the “danmark.dry” file to illustrate the energy behaviour of Greenlandic Low Energy house in Denmark (Fig. 6). Furthermore the illustration of the solar gains in LEH in Greenland is modelled in BSim software where the distributions of solar gains all over the year can be found in Fig. 7.

BSim software [5] is a computational design tool for analysis of the indoor climate, energy consumption, and daylight performance of building, developed by the Danish Building Research Institute. The system uses the common building data model with the design tools and typical building materials database (constructions, windows, and doors). The software can represent a multi-zone building with heat gains, solar radiation through windows (with shadings), internal loads, heating, cooling, photovoltaic, ventilation, and infiltration, but also transient moisture model for the whole building.

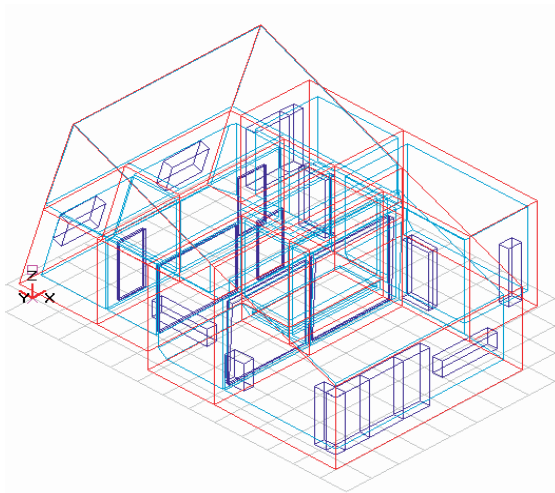


Fig. 4. BSim model of Low-energy house in Sisimiut

4 Results of the examples of the sensitivity analysis

4.1. Results regarding the building envelope (wall, roof, floor, window)

Table 1 Construction U-values (wall, roof, and floor) and variations

Construction	Thickness [mm]	Calculated U-value [W/m ² ·K]	Variation of insulation level +10% ⁽¹⁾ [mm]	Variation of insulation level - 10% ⁽¹⁾ [mm]	Future U-value demand ⁽²⁾ [W/m ² ·K]
External wall	300	0.150	330	270	0.200
External floor	350	0.142	385	315	0.150
External roof	350	0.133	385	315	0.150

⁽¹⁾ Designed insulation thickness 300mm plus 30 mm of extra insulation => total insulation thickness for walls is 330 mm for variation -10%.⁽²⁾ Greenlandic Building Regulations [6]

Table 2. Heat transmission coefficient

Type ⁽¹⁾	U_{glass} [W/m ² ·K]	U_w [W/m ² ·K]	Variation of U_w +10% ⁽¹⁾ [W/m ² ·K]	Variation of U_w -10% ⁽¹⁾ [W/m ² ·K]
1: 1+2	0.70	1.00	0.90	1.10
2: 2+ Vac.	0.70	1.10	1.00	1.20
3: 2+1	0.80	1.10	1.00	1.20

⁽¹⁾ Placement of windows (see Fig. 3). ⁽²⁾ Increasing of the window's thermal characteristic properties by 10%

NOTE: The following tables "Heat balance in kWh" do not include the heat balance for cooling system, people gains, and lighting energy.

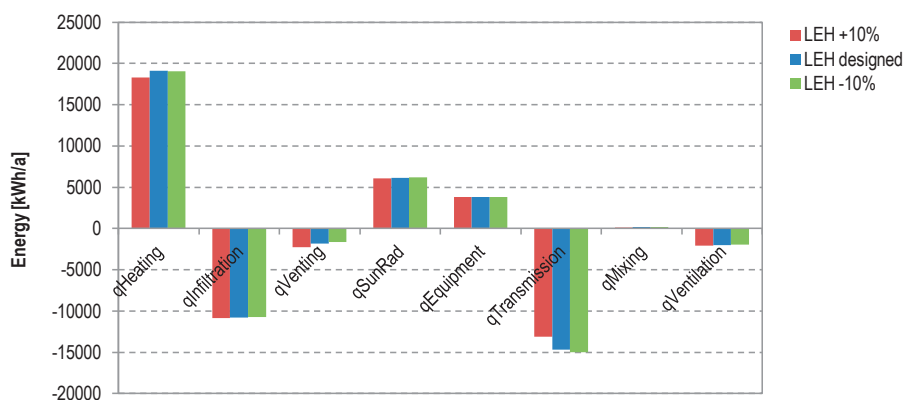


Fig. 5. Heat balance in kWh for the Low Energy house placed in Sisimiut (LEH +10%, LEH designed, LEH -10%)

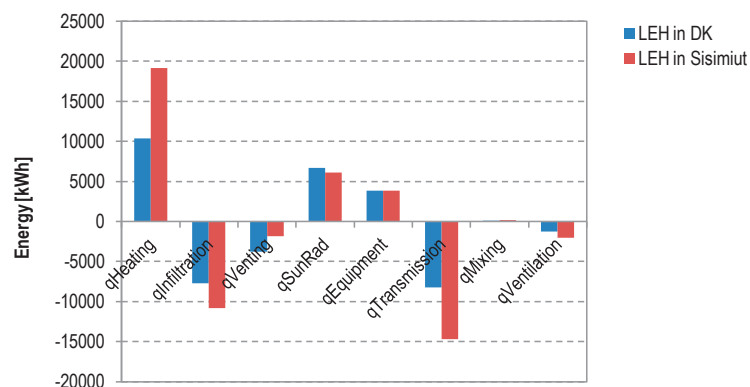


Fig. 6. Heat balance in kWh for the Low Energy house placed in Denmark and Sisimiut

4.2. Results regarding the solar gains

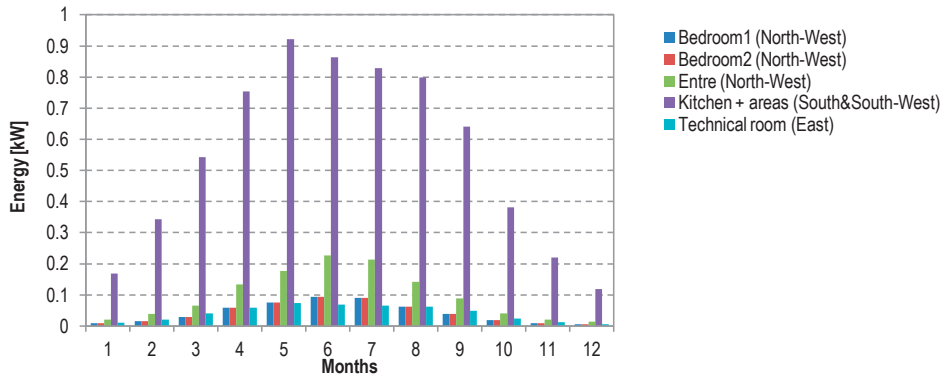


Fig. 7. qSunRad for LEH designed (Sisimiut) in kW for the year period for the window area: bedroom1 & 2 = 1.40 m²; entrance = 3.76 m²; kitchen+areas = 12.39 m²; technical room = 1.02 m²

5 Conclusion

This article has two main purposes: the first is to introduce the new PhD project called “Passive Houses for Arctic climates”, and the latter is to show the examples of so called sensible sensitivity analysis made by a detailed thermal building analysis tool – Bsim. The focus is put on insulation thickness and thermal properties of wall, floor, roof and window.

The examples of sensitivity analysis made for Low-energy house in Sisimiut, Greenland, indicate possible ways of investigating how big the influence is when specific building components are changed, for instance increasing the insulation thickness and thermal performance of windows. The heat balance proves saving energy when increasing the thermal properties by adding extra 10% of insulations and improving the window performance. But decreasing the thermal performance of building envelope and windows by -10% has smaller energy savings than the increasing one. The solar gains are significantly large for South side (kitchen+areas) where the window area is 12.39 m² in total, which proves the optimized design of building and the best possible use of solar gains.

Furthermore analyses will investigate the influence of increasing the air-tightness of the building envelope and the performance of ventilation systems with heat recovery units. Later focus should be put also on different habitant’s customs (vapour from the cooking, etc.) and on the low humidity in Greenland.

For evaluating more specific and large-scale analysis are needed. The theoretical parametric studies of Low-energy house in Sisimiut have no validation yet and therefore the future comparison with the analysis made in PHPP and TRNSYS will be performed.

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Paper II: The potential and need for energy savings in standard family detached and semi detached wooden houses in arctic Greenland

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The potential and need for energy saving in standard family detached and semi-detached wooden houses in arctic Greenland

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Abstract

The paper gives an account of the potential and need for energy saving in standard family detached and semi-detached wooden houses in Greenland. It is based on studies of house construction compared with Building Regulation requirements and the spread of buildings over time. In the climatic conditions of Greenland, there is considerable potential for energy saving in houses due to their construction, shape and condition. To estimate the total potential for energy saving and thus reducing CO₂ emissions, we carried out a detailed investigation of three typical standard semi-detached family houses (type 18D). Temperature, relative humidity and air tightness were measured, and thermal bridges were determined from drawings, visual inspection, and by using a thermal camera. The findings show a current energy consumption of up to 383 kWh/(m²·a) for heating, poor air tightness, a large number of thermal bridges, and high indoor temperatures. We demonstrate a potential for a reduction in CO₂ emission by a factor of 10. Finally, the paper describes a practical way of reducing thermal bridges significantly, increasing air tightness, upgrading insulation and adding mechanical ventilation to approximately half of the housing stock without changing the architectural expression or having to relocate the occupants during the renovation.

Keywords

potential for energy savings, standard wood-framed houses, thermal insulation, CO₂ emission, arctic climate

1 Introduction

This paper gives an estimation of the potential for energy savings, and thus reductions in CO₂ emissions, in detached and semi-detached family houses in Greenland based on calculations, measurements, and studies of the construction of the houses compared with Building Regulation requirements and the spread of buildings over time.

Studies of the literature show that very little has been published on energy savings in buildings in the arctic climate and the implication on the environment. A performed study by Tobiasson [1] describes the needs and research necessary for buildings and utilities in very cold regions.

The article by Norling [2] is based on studies of the project carried out in 2005 of a new Low-energy house in Greenland where the target was to build low-energy building fulfilling the requirement of Greenlandic Building Regulation 2006. The publication by Vladykova [3] deals with building renovation and briefly outlines the possibility of energy savings in a wooden house in Sarfannguit, Greenland. The national Statistic gives information's on the average energy consumption for heating in detached and semi-detached houses in cold climate countries. Greenland's Statistics [4] shows that an average household with an average floor area of 65.5 m² uses 416 kWh/(m²·a) for heating and Norway's Statistics [5] shows 181 kWh/(m²·a) with an average floor area of 119 m² and Canada's Statistics [6] has heating consumption of 231 kWh/(m²·a) with an average floor area of 134 m² for detached, semi-detached and row houses.

The contribution of this article lies in its outline of a systematic method of energy renovation and a remarkable reduction of CO₂ using standardized packages for the renovation of more than half of the housing stock in Greenland. The method is significant in the number of houses it applies to and in the way it adds the air tightness and the vapour barrier from the outside - a method which gives a better technical solution and interferes very little with the interior, making it unnecessary to relocate the occupants. The solution is expected to be broadly accepted since it preserves the architectural expression of the houses. The originality of the work is based on the combination of a study of the Building Regulations over time, the reuse of packages solutions based on the methods of house construction and implementation in Greenland, common knowledge and findings from the investigation of three standard wooden houses.

Energy savings and reductions in CO₂ emissions are important for the climate, and Greenland is actively working on a reduction of CO₂ emissions by 8% (from 1990 level) over the period 2008-2012 [7]. Although the price of oil is relatively low for the end-consumer at present, oil is a limited natural source. Greenland has to prepare for considerable future increases in oil prices. The major consumer of energy is the building sector, so a considerable reduction in the use of fossil fuels must take place in this sector.



Fig. 1. Standard houses 18D

From the point of view of construction and usability most detached and semi-detached family houses in Greenland are basically of good quality, mainly because most are well designed standard wooden houses. To make sure that all components were delivered to the building site and properly erected, every component was carefully described in detail in drawings and in writing. But most

of the houses are poorly insulated due to the lack of stringent requirements in earlier Greenland Building Regulation (GBR), and their air tightness is considered equally poor. To some extent, houses built before 1982 have been further insulated up to the requirements of GBR 1982, following recommendations from the Greenland Technical Organisation (GTO) [8]. Usually, this was done by adding 50 mm insulation from the outside and constructing new exterior cladding, but without improving air tightness. These houses are in general need of renovation, but thanks to the rather dry climate in Greenland the materials that make up the outer cladding of the building envelope are generally well preserved, even when the houses are more than fifty years old.

To help us estimate the total potential for energy saving, we carried out a detailed investigation and made calculations for three typical standard semi-detached family houses (type 18D). Outdoor and indoor temperatures and relative humidity were measured with HOBO data loggers, and the air tightness was measured by using the blower-door test. Thermal bridges were determined from drawings, visual inspection and by using a thermal camera. To determine the climate impact of the potential energy saving, an account is given of its effect on CO₂ emissions.

2 Residential houses in Greenland

2.1. Description and styles of housing

Compared to most other countries, Greenland is in a unique situation when it comes to natural building materials: there are none. There is no natural access to wood, no clay for bricks and tiles. There are no factories producing glass, insulation materials, cement, or other important building materials. Greenland is therefore completely dependent on imports. Transportation is by sea or air, since the population of 56,462 (1.1.2008) is scattered in small towns and settlements without road connections [4].

During the first half of the 1900s, various committees travelled around Greenland and collected information on the housing situation. Several different house types were developed. By the middle of the 1950s, there were more than 40 different house types of wooden construction that could be built with financial support. Until 1952, the Greenlanders were self-builders. The standard houses were introduced in 1945. In the beginning the standard houses were developed locally, later on it was centralised. The advantage of standard houses was that the building materials required could be collected and packed in Denmark, and shipped and assembled on-site anywhere in Greenland. At first the standard houses were erected by self-builders, but in the middle of 1950s the government decided that houses must be erected by skilled craftsmen to achieve healthy housing of good quality.

In 1955, the Minister for Greenland decided to reduce the number of types eligible for financial support to approximately ten. The Office for Housing Support, "Boligstøttekontoret", collected all the drawings and a working group sorted the types into size categories: less than 20 m², between 20 and 30 m², between 30 and 40 m², and so on. A technical panel then identified the eight best types. Detailed standard construction drawings were then produced for each category. More or less the same standard windows, doors and inventory were produced for all types. The standardized types were numbered 1, 2, 3, 5, 10, 16, 17, and 25. In 1957, these types were approved as eligible for financial support. House types 1 and 3 were only to be built in special situations. In 1960, a new

type 18 was added to the series. Type 18D was a semi-detached family house. The series was called the standard series, and was built from 1957 to the early 1970s. In the late 1960s a new series of four new types, 67/8, 67/12, 67/14, 67/16, was introduced. The latest series, called “Illoput”, dates from 1973 to 1998 (e.g. Illoput 43 and Illoput 82). In 1998, the Illoput 2000 was introduced and consists of types 1–4 ranging in size from 58 m² to 104 m². This development has resulted in practically all detached and semi-detached family houses in Greenland being wood-framed structures with wooden cladding and a pitched wooden roof covered with tarred paper [9].

2.2. Building Regulation requirements

The Building Regulation in Greenland (GBR) closely follows the Danish Building Regulation (DBR), but with modifications that take into account the different climate and living conditions. The U-value requirements have also closely followed the DBR, but with a few alterations. Before 1971, there was no specific Building Regulation for Greenland. Standard houses were developed under the Danish regulations, but the GTO increased the requirements for insulation, e.g. the standard series from the 1960s were insulated with 100 mm Rockwool in walls, roofs and floors even though the DBR at that time only required approx. 70 mm for the walls and floors. From 1971 to 1982, the U-value requirements were decided by the GTO (Greenland Technical Organisation) and followed the Danish requirements closely except in a few cases; e.g. the DBR from 1977 requires a U-value of 0.3 W/(m²·K) for the floor and the GTO requires 0.2 W/(m²·K) [8]. Since 1982, Greenland has had its own Building Regulation. The differences between the DBR and the GBR with regard to U-values are, as in the period before 1982, that the U-value for floors over ventilated crawl spaces is lower in Greenland. In the latest DBR from 2008 [10], the U-values for roofs and windows are lower than the GBR 2006 [11].

Table 1. Requirements for houses in Denmark (maximum values for U-value)

Danish Building Regulation Year of DBR U-value [W/(m ² ·K)]	Wall with a weight < 100 kg/m ²	Roof {directly towards sloping walls}	Floor over ventilated crawl spaces	Window / doors
1962, 1966, 1972	0.60	0.45	0.60	3.60
1977, 1982, 1985 Small Houses	0.30	0.20	0.30	2.90
1995, 1998 Small Houses	0.20	0.15 {0.20}	0.20	1.80
2008	0.20	0.15	0.15	1.50

NOTE: Before DBR 1966, there was no recommended U-value for windows, only a minimum 12 mm between 2 layers of glass. In DBR 1962 and 1966 kcal/m²·h·°C (k-value) was used as unit, but Table 1 lists U-values in units of W/(m²·K).

Table 1 and Table 2 show the decreasing U-values over the last 50 years. In 1977, the U-value was reduced markedly due to the two oil crises in the 1970s. In DBR 1998, the U-value again drops, especially for windows, where the U-value decreases from 2.90 to 1.80 W/(m²·K). Although the decrease in U-values did not formally apply to Greenland before the GBR 2006, one can see by looking at some standard houses (e.g. Illoput) that the thickness of the insulation was increased even though it was not mandatory in Greenland. The GBR 1982 is based on DBR 1977 except that the U-value for floors is lower. The GBR 2006 is mainly based on the DBR 1995 and the Standards supporting it, but altered and issued in Greenland taking into account the conditions in Greenland, e.g. lower U-value for floors.

Table 2. Requirements for houses in Greenland (maximum values for U-value)

Greenland Building Regulation Year of GBR U-value [W/(m ² ·K)]	Wall with weight < 100 kg/m ²	Roof { directly towards sloping walls}	Floors over ventilated crawl spaces	Window / doors
1982	0.30	0.20 {0.30}	0.20	2.00
2006	0.20	0.20	0.15	1.80 / 1.80

In DBR 2008, the air tightness requirement at 50 Pa pressure is a maximum 1.5 l/s per m² floor area, whereas in GBR a limit for air change has yet to be introduced, but is expected to be implemented in 2010/2011. In GBR 2006, the required maximum linear loss Ψ (W/(m·K)) is between 0.03 (outer wall/door/hatch and window) and 0.25 (foundation/base and floor without floor heating).

The use of energy frameworks as a tool for energy regulation was adopted from the Danish Building Regulation [12]. The energy frame value was introduced in GBR 2006 and is used as the maximum allowable annual requirement for heating and ventilation per m² floor area of heating space [11]. The energy frame value depends on the location of the building. Zone 1 is south of the Polar Circle and is calculated in accordance with (1), and Zone 2 is north of the Polar Circle and is calculated in accordance with (2) in (MJ/m²·y), where the e value is calculated as total floor area divided by floor area of the footprint of the building:

$$\text{Energy frame for Zone 1} = 420 + \frac{280}{e} \quad (1)$$

$$\text{Energy frame for Zone 2} = 510 + \frac{325}{e} \quad (2)$$

2.3. The spread of buildings in Greenland

In 2007, there were a total of 22,075 (1.1.2007) houses in Greenland [4], and of these 11,632 were detached and semi-detached family houses, constituting the most common house types. The calculation is based on list of houses recorded by the Municipalities and obtained from INI [13]. The 11,632 detached and semi-detached family houses can be divided into three periods. Period 1: the 6,479 detached and semi-detached family houses built before 1977 (i.e. the year the first DBR was implemented after the oil crises) are very interesting to look at with regard to energy renovation because usually they only have 100 mm insulation (150 mm if restored) in walls and 100 mm in floors and roofs. Period 2: the 4,973 detached and semi-detached family houses built in 1977–2006 also have an energy saving potential, but they have at least 150 mm insulation in the walls and 200 mm in the floors and roofs. Period 3: the houses built after 2006, which therefore meet the requirements of GBR 2006 with a minimum insulation in the walls of 185 mm, and in the floors and roofs of 250 mm ($\lambda = 0.037$ W/(m·K)). The average floor area of all detached and semi-detached family houses is approximately 65.5 m² [4]. It is the houses built before 2006, i.e. 11,452 houses, which are considered to have potential for renovation, out of which 6,845 are located in Zone 1 (south of Polar Circle) and 4,787 are located in Zone 2 (north of Polar Circle).

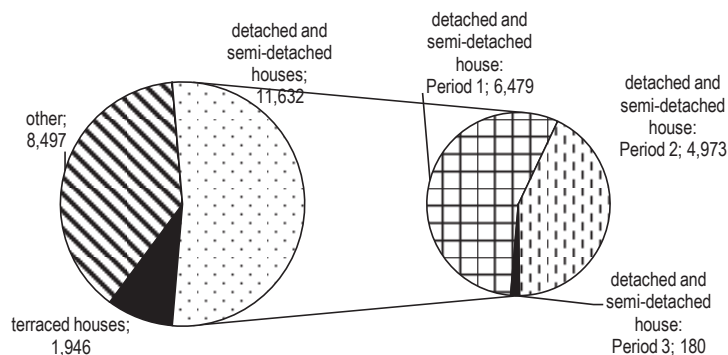


Fig. 2. Distribution of buildings in Greenland in 2007

3 Methods of investigation

The following methods were used to determine the existing conditions of the buildings and reveal principles for energy renovation which could lead to standard methods of improving the energy standard of the houses and make them energy efficient for the coming decades.

A **general review** was carried out based on studies of the description and drawings of house type 18D and on-site visual inspection was used to examine three of these houses. The visual examinations involved the surfaces, the construction and the condition, both in the attics and below the houses. Furthermore, the heating and ventilation systems, the window types and insulation levels were recorded and evaluated.

The **thermal bridges** were investigated using a thermographic camera (thermo camera SAT HotFind) [14]. The thermo images were taken during the blower-door test from inside and also as a stand-alone test of the outside façades of each house. The thermal camera was used to confirm the existence and position of the thermal bridges, whilst the drawings and the visual observations were used to determine the size and the number of the thermal bridges. The thermo camera was also used to locate air leakages during blower-door test.

The **humidity and temperature** were measured in the heated area as well as in the unheated attic. The method of measurements involved installing three HOBO data loggers (HOBO U12-001) in each house to register temperature and humidity in the living room, one bedroom and in an attic. One HOBO data logger recorded the outside conditions. In one house, referred to as Osvald's house, only the temperature was measured using three data loggers (HOBO U12-008). The data loggers were installed in August 2009 and the measurements were conducted for approximately 3 weeks. The data loggers were set to record the temperature and humidity every 15 minutes. The data were processed and evaluated using the program HOBOWare Pro [15].

The blower-door test was used to determine the **air tightness** of the building envelope for each building. A fan 2000AvgFull, DM-2 gauge and computer were used to provide airflow to

depressurize and pressurize up to 50 Pascal. Two measurements were carried out in each house: 1. with all ventilation openings closed but not sealed; 2. with all ventilation openings closed and sealed with tape. The test results were evaluated in accordance with the European Standard 13829 [16].

To determine the actual oil consumption for each house, bills for oil delivery for the years 2005-2008 and part of 2009 were collected from the local oil distributor in August 2009. This documentation was used to calculate the **actual consumption**. This made it possible to compare the calculated energy consumption with the oil actually delivered to the houses. The oil is only used for heating and hot water. The hot water consumption is not measured separately therefore the consumption is estimated based on standard consumption in Danish's homes as 250 l/m² per household per year with temperature difference of 45°C [17] equals on average to 3 kWh/(m²·a).

The **theoretical energy consumption** was calculated in accordance with Danish Standard DS 418 and SBI 184 [18,19] that is closely following the method in EN 13790 [20]. The heating demand calculation is the balance of energy when the heat loss via envelope and ventilation is summed as total heat loss and heat gains from people and the sun are deducted; the result represents the heating demand. The method reflects the steady state analysis with monthly input data, and the method is widely used in energy calculations to design and calculate the heating demands of buildings.

The heating demands for potential energy improvements were estimated for various models: Average 18D, GBR with and without heat recovery, future low-energy house requirements (LEH) and passive house requirements (PH). The model Average 18D is based on investigation results from Osvald's, Eva's and Ester's houses, in combination with climate data for zone 1 and 2 and weighted to reflect housing pro rata for zone 1 and 2. The model average 18D is based on the requirements of GBR 2006 with and without use of ventilation system with heat recovery. Since the GBR has followed the DBR with a few years of delay the definition of the future low-energy house is based on DBR 2010 [21], where the low-energy requirement for year 2015 is introduced as $30+1,000/A_{\text{gross}}$ for heating, ventilation, cooling and hot water. For 18D with heated area of 65 m² that equals to approximately 45 kWh/(m²·a). The passive house demand for renovation undependably on climate equals to 25 kWh/(m²·a) only for heating and without the use of "active heating system".

The **CO₂ emission** calculation of the current state of the house includes just the oil consumption. The calculation for the renovated houses includes both oil consumption and the production and transportation of extra insulation and materials. The transportation was calculated as cargo ship transport by container from Copenhagen to Sisimiut.

4 Results

4.1. The construction of the wooden standard house 18D

In order to estimate the total potential for energy saving, detailed investigations and calculations were conducted for three typical standard semi-detached family houses (type 18D) built in 1962 and situated in Sisimiut, north of the Polar Circle and latitude 66° N. One house had been left

unchanged (Osvald's house) from the day it was built, and the other houses (Eva's and Ester's houses) had been further insulated with 50 mm glass wool and the windows had been replaced with new ones with 4/12/4 Danaplus window glass filled with Argon.

The type 18D from 1960 is a wood-framed standard semi-detached house. It has total floor area of 65 m². On the ground floor, a house consists of a living room, a kitchen, a bathroom, a hall, a weather porch, a storage room, and a room for cold storage, which nowadays in most cases contains the oil-fired boiler. On the first floor is a corridor with staircase and two bedrooms [9].

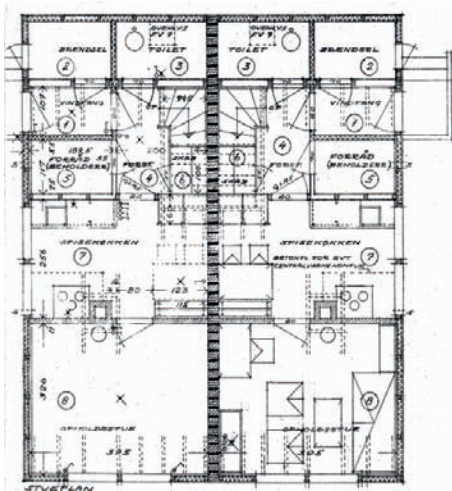


Fig. 3. Drawing of two semi-detached standard 18D houses – ground floor

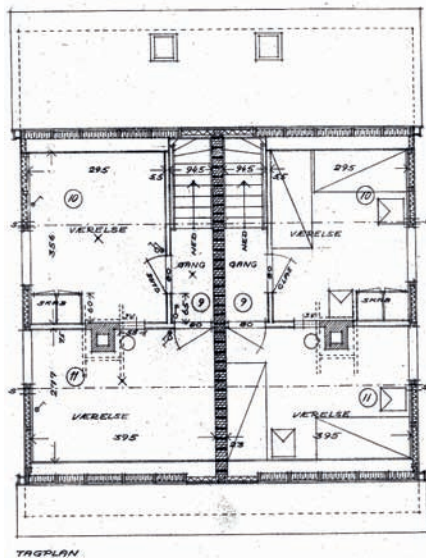


Fig. 4. Drawing of two semi-detached standard 18D houses – first floor

The construction of the external walls is based on a wooden frame with 100 x 100 mm posts and 50 x 100 mm crossbars inlaid in the posts. On the outside, the cladding consists of 25 x 125 mm boards with the joints covered by a 12 x 32 mm fillet. Between the crossbars and the cladding is a windshield of tarred paper. On the interior a formwork of 19 x 100 mm boards is covered with 13 mm plasterboard. Between the formwork and the plasterboard is a vapour barrier of aluminium-covered paper. Between the posts is 100 mm of Rockwool insulation (mineral wool insulation). The windows consist of a wooden casing with two outer and two inner side-hinged single pane windows. The outside windows both have a horizontal mullion.

The construction of the roof from the outside consists of 50 x 125 mm trusses with 25 x 100 mm boards connected with tongue and groove and covered with tarred paper, and on the inside is made up of a formwork of 19 x 100 mm boards covered with 13 mm plasterboard. Between the formwork and the plasterboard is a vapour barrier of aluminium-covered paper. Between the trusses is 100 mm of Rockwool insulation.

The floor construction consists of 87 x 150 mm beams with exterior 12 x 150 mm boards supported by a 25 x 125 mm underboard. Between the insulation and the boards is a wind membrane of tarred paper. On top of the beams, 25 x 100 mm floorboards are connected with tongue and groove. Between the beams and the floorboards is a vapour barrier of aluminium-covered paper. Between the floor beams is 100 mm of Rockwool insulation.

Rockwool insulation 100 mm thick is used in walls, roof and floor. The level of insulation was therefore above standard at the time the house was built, but is rather low by today's standards. The lambda value of Rockwool in 1962 was approx. 0.049 W/(m·K) [22] compared to 0.037 W/(m·K) today [23].

To provide sufficient ventilation, the houses have a 150 x 150 mm ventilation inlet in each room located at the top of the window (natural ventilation). The grill is manually operated and is not completely tight when closed. The small houses often accommodated big families and cooking used to be a demanding task. All these vents kept the house sound and provided for a fine dry indoor climate, but with rather high and uncontrolled air change. And this type of ventilation is responsible for a tremendous ventilation heat loss.

Nowadays, the heating system is an oil-fired boiler which in two out of three cases would produce more energy savings if it was replaced or had more accurate control. Especially in Osvald's case because the old oil-boiler is placed in a cold storage room where in Ester's case an old oil-boiler is placed in the kitchen. In Eva's house a new condensing combi oil-boiler was recently installed in the insulated cold storage room. The heat is distributed by radiators in the living room and in the two bedrooms with the pipes laid visible on the front of the walls. Hot water comes from the oil-fired boiler and is available in the kitchen and in the bathroom. Waste water from the kitchen is led out of the house through a pipe which runs on the surface down to the gutter at the side of the street. In two of the houses, the waste water from the toilet is led to a tank outside the building, which is emptied by the local authority. In Osvald's house, it is a bucket with a plastic bag, which is emptied manually. From the bucket, there is a pipe to the outside for ventilation.

The general inspection of the three 18D sample houses shows that the construction is sound and a simple static calculation shows that the additional load from extra materials to meet the low-energy standard represents 3-4% of the capacity of the load carrying joists, so the current construction can carry the extra load with no problems. For a passive house solution, the load will be increased due to the extra amount of insulation and wood construction. For a passive house solution it could be necessary to consider transferring some of the extra load to the foundation with steel angle fittings.

The building techniques of the late 1960s had very little focus on thermal bridges, and therefore the walls, roof and floor, although insulated with 100 mm mineral insulation, are full of thermal bridges. The investigations showed that there are a lot of thermal bridges in the roof, the façades, and the floor, all of which contribute to the heat loss. The 50 x 125 mm roof trusses directly connect the exterior roof boards with the interior plasterboard and thereby create thermal bridges. In the exterior walls the vertical 100 x 100 mm posts create thermal bridges in spite of the inlaid 50 x 100 mm crossbars, because no insulation has been applied in the gap between the cladding and the posts. In the floor, the 787 x 150 mm beams directly connect the underboard with the interior floorboards and thus create thermal bridges [9].

Fig. 5. Original drawing of detailed connection of floor and wall

The vertical brick wall between the two semi-detached houses is a significant thermal bridge. Fig. 6 illustrates the thermal bridges in the walls where the 150 x 150 mm closed vent shows a high energy loss. Moreover, the construction framework is visible and causes energy loss. The thermography also indicates the poor air tightness in connecting places between wall and floor in the bathroom and between internal doors and the floor. Another problem is the air tightness of the hatch leading to the attic and air leaking between the wall and the sloped roof in the bedroom and through the closed vent.

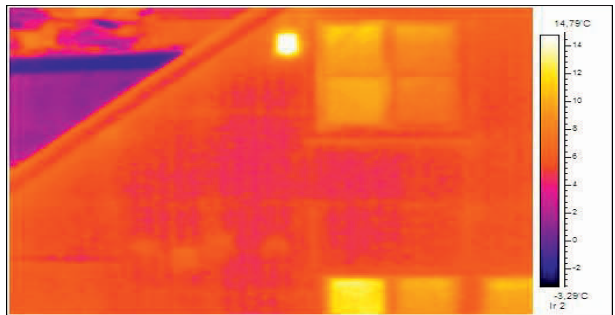


Fig. 6. Closed vents of 150 x 150 mm and the wooden framework

4.3. Temperature and relative humidity

The temperature (Temp) and relative humidity (RH) were measured over a period of 3 weeks in August 2009. The temperature graph shows that the overall average temperature in the houses is high – in the living rooms, the temperature is 23.5°C and in the bedrooms 22.8°C. The average temperature in the non-insulated attic is 6–7°C higher than the outdoor temperature due to heat loss through the hatch and the poorly insulated loft (Table 3). The significant fluctuation of approximately up to 10 degrees in the attic is caused by the periodic exposure of the roof to direct sun. The temperature in the living rooms also varies from 19–28°C (Fig.7.) and in the bedroom varies from 17–23°C in Eva's bedroom and from 22–28°C in Ester's and Osvald's bedrooms (Fig. 8).

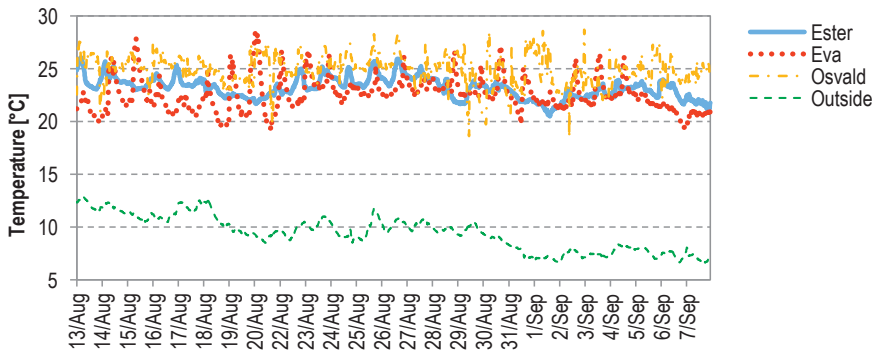


Fig. 7. Measured temperatures in Ester's, Eva's and Osvald's houses (living room and exterior) compared to outside temperature from August 13 to September 7, 2009

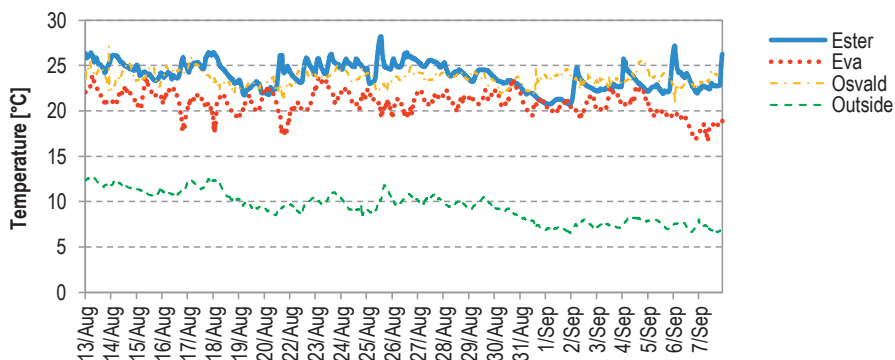


Fig. 8. Measured temperatures in Ester's, Eva's and Osvald's houses (bedroom and exterior) compared to outside temperature from August 13 to September 7, 2009

The humidity was measured in Eva's and Ester's houses, where the average humidity over 3 weeks in the attic was 42.5%, 37.6% in the living rooms and 39.3% in bedrooms (Table 3). There is no humidity problem in the current condition of the houses (no mould) because the houses are not air-tight and are well ventilated through the vents. The external humidity in grams is low in Greenland because of long periods with cold temperatures and cold air does not contain much water. Once the houses are renovated and air-tight, the moisture produced from inside sources (people, cooking, showering) will have to be removed with the help of mechanical ventilation with a heat recovery system, otherwise critical conditions such as mould growth may occur.

Table 3. Measured relative humidity inside the houses and outside

	Ester Living room	Bedroom	Attic	Eva Living room	Bedroom	Attic	Osvald Living room	Bedroom	Attic	Outside
Average Temp [°C]	23.9	18.3	23.2	17.5	22.5	20.9	24.9	23.6	16.5	9.4
Average RH [%]	41.5	39.7	44.0	33.8	38.9	41.1	-	-	-	74.5

4.4. Blower-door test

The infiltration rate is the volumetric flow of outside air into a building V_{50} or CFM50 (m^3/h), and the air change rate is the number of interior volume air changes that occur per hour ACH (h^{-1}). The blower-door test measures the air change at 50 Pa, i.e. n_{50} (h^{-1}). The air change is calculated as (3) where V_{50} is flow at 50 Pa (m^3/h) and V is the internal volume (m^3).

$$n_{50} = \frac{V_{50}}{V} \quad (3)$$

For 18D houses, the net floor area is $A = 63 \text{ m}^2$, and the internal volume is $V = 157 \text{ m}^3$. The actual infiltration is determined from an air change rate of 50 Pa as (4), where the factor "20" is estimated for leaky buildings from the "Princeton Method" [25]. This method gives reasonable average infiltration estimates, but ignores many details of the infiltration process, such as stack effect, windiness and wind shielding, and type of leaks. The infiltration n is used in the energy calculations.

$$n = \frac{n_{50}}{20} \quad (4)$$

Each house was measured according to the European Standard 13829 [16] and two sets of tests were performed. For the purpose of Method A, all vents were closed. For the purpose of Method B, all adjustable openings were closed and sealed with tape. In Method B, the hatch to the attic was also sealed and the “bag toilet” was sealed. In Eva’s house, it was not possible to seal the fire stove. Table 4 shows measured air change (n_{50}) in different units, the calculated average infiltration for further energy calculations of ventilation heat loss can be found in

Table 5.

Table 4. Blower-door test results and calculated average infiltration

House	Air change @ 50Pa n_{50} [h^{-1}]	Air change @ 50Pa n_{50} [m^3/h per m^2 of floor area]	Air change @ 50Pa n_{50} [l/s per m^2 of floor area]
Type 18D - Oscar	18.5	40.2	11.2
Type 18D - Ester	11.3	26.3	7.3
Type 18D - Eva	14.4	31.2	8.7

According to DBR 2008, the air tightness requirement at 50 Pa pressure is 1.5 l/s per m^2 floor area (Fig. 9), i.e. 5.4 m^3/h per m^2 of floor area. The results of the blower-door test are usually presented as air change at 50 Pascal in unit of h^{-1} (n_{50}), so the results can be compared to the requirements for low-energy (LEH) or passive houses (PH) where required $n_{50} \leq 0.6 \text{ h}^{-1}$ [26].

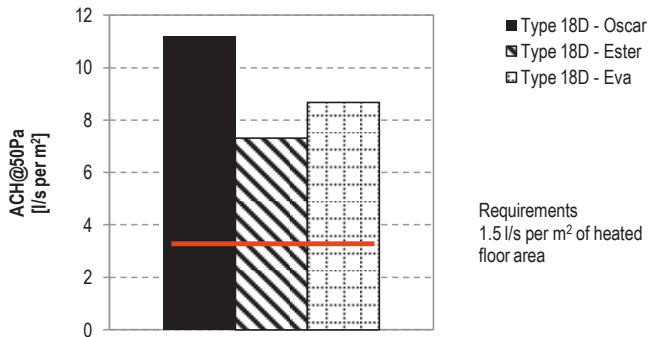


Fig. 9. Measured average air changes for 18D houses and comparison with Standards

The blower-door test shows an air change of up to 7–8 times the maximum allowed in Osvald’s house, which has the original construction, and up to 5 times in Ester’s and Eva’s houses, which have been improved with 50 mm extra insulation. According to the thermography carried out, the lack of air tightness originates from various places, e.g. the connection between the walls and the floors, and between the walls and the roof.

4.5. Actual energy consumption of 18D

Oil delivery bills were collected for a period of more than 3 years in order to determine the actual oil consumption for each house. Oswald's house had the highest consumption over the past 3 years; using approximately 2,200 litres of oil per year (

Table 5). Oswald's house is mainly orientated towards the north and it is in its original state where no renovation has been done. Eva's house had an average consumption of 1,900 litres per year for heating, and Ester's house had a consumption of 1,600 litres per year. Eva's house is mainly orientated towards the north and Ester's house is mainly orientated towards the south. Ester's house has been used over the past 3 years as occasional accommodation by Hotel Sisimiut.

4.6. Energy calculation for renovation

In the 1960s, the thermal conductivity λ of Rockwool was around 0.049 W/(m·K) due to less effective production methods then [22]. Today's mineral wool insulation generally has a lambda value of $\lambda = 0.037$ W/(m·K) [23]. The insulation material used in wooden houses from the 1950s and 1960s was Rockwool, but more recent buildings are insulated with glass wool, because its lower density allows this material to be compressed and transported in larger quantities. Other materials like paper insulation ($\lambda = 0.040$ W/(m·K)) [27] and closed cell type insulation PIR / PUR with $\lambda = 0.025$ W/(m·K) [28] have been considered but due to GBR these solutions would require more fire protection material in the construction.

GBR 2006 requires the total consumption of a type 18D house (i.e. one semi-detached house) according Eq. (2) to be below 199 kWh/(m²·a) for a house situated north of the Polar Circle where $e = 1.6$. If the location of the house is south of the Polar Circle, according Eq. (1) the Regulation would require a heating demand of below 166 kWh/(m²·a). In the standard energy calculations for interior temperature, we used $T_i = 23^\circ\text{C}$, which was obtained from the room measurements and other tests. The energy calculation of heat balance is done in accordance with Danish Standard DS 418 and SBI 184 [18, 19]. The investigated houses were all occupied and heated, and so was the adjacent house.

Oswald's house has the worst state of insulation, with only 100 mm, poor windows with an estimated U-value of 2.5 W/(m²·K), and very poor air tightness. In Eva's house the insulation has been increased to 150 mm, the thermo windows have a U-value of 1.5 W/(m²·K), and the level of air tightness is higher than in Oswald's house. Ester's house has the same U-value characteristics for walls and windows as Eva's house and has the best air tightness of all houses. GBR 2006 also requires all residential houses to have air change 0.5 h⁻¹ and exhaust ventilation totaling 45 l/s (kitchen 20 l/s, bathroom 15 l/s and utility room 10 l/s).

The results in

Table 5 show that the consumption for Eva's and Ester's houses is almost equal to the calculated theoretical consumption, but Oswald's oil consumption is higher than the theoretical calculation. One possible explanation could be that Oswald was buying oil somewhere in a non-recorded way.

Table 5. Calculated and actual heating consumption of actual state of Osvald's, Eva's and Ester's houses

Current state of houses	Osvald	Insulation thickness [mm] ($\lambda = 0.049 \text{ W/(m}^2\cdot\text{K)}$)	Eva	Insulation thickness [mm] ($\lambda = 0.049 \text{ W/(m}^2\cdot\text{K)}$)	Ester
Walls U-value [$\text{W/(m}^2\cdot\text{K)}$]	0.497	100 (0.059 ⁽¹⁾)	0.334	150 (0.059 ⁽¹⁾ ; 0.051 ⁽²⁾)	0.306
Roofs U-value [$\text{W/(m}^2\cdot\text{K)}$]	0.434	100 (0.052 ⁽¹⁾)	0.299	150 (0.052 ⁽¹⁾ ; 0.048 ⁽²⁾)	0.275
Floors U-value [$\text{W/(m}^2\cdot\text{K)}$]	0.439	100 (0.049 ⁽¹⁾)	0.293	150 (0.049 ⁽¹⁾ ; 0.044 ⁽²⁾)	0.334
Windows U-value [$\text{W/(m}^2\cdot\text{K)}$]	2.0		1.5		1.5
Infiltration [h^{-1}]	0.78		0.59		0.50
Heating requirements [$\text{kWh/(m}^2\cdot\text{a)}$]	381		276		241
Calculated total consumption [$\text{kWh/(m}^2\cdot\text{a)}$] ⁽³⁾	383		279		244
Calculated oil consumption [liters per year] ⁽³⁾	2,494		1,814		1,589
Actual oil consumption [liters per year] ⁽⁴⁾	2,200		1,900		1,600

⁽¹⁾ The λ -value includes inhomogeneous vertical and horizontal members in walls, and floor and roof. ⁽²⁾ Extra 50 mm of insulation with vertical member of 50 x 50 mm. ⁽³⁾ Calculated total consumption includes calculated heating and hot water consumption (3 $\text{kWh/(m}^2\cdot\text{a)}$). ⁽⁴⁾ Actual oil consumption equals the documented oil consumption based on collected heating bills.

The energy consumption of the three houses was calculated and average values were used to calculate the approximate status of building construction (walls, floor, roof, windows) and the average infiltration. This "Average 18D" model was chosen to represent the current status of standard houses in Greenland. The Average 18D was used to estimate energy consumption of all similar standard houses in Greenland. The average consumption of 18D houses is approximately 317 $\text{kWh/(m}^2\cdot\text{a)}$ for Zone 2 and 261 $\text{kWh/(m}^2\cdot\text{a)}$ for Zone 1 which is approximately 50% above the requirements of GBR 2006.

Table 6. 18D – Average and renovated models (description of building and constructions, infiltration and systems)

	Average 18D	Existing GBR without heat recovery	Existing GBR with heat recovery	Estimated future LEH	PH Zone 1 (2.1 W/m^2 , net area)	PH Zone 2 (2.1 W/m^2 , net area)
Wall U-value [$\text{W/(m}^2\cdot\text{K)}$] / [mm] ⁽¹⁾	0.388 (100+0)	0.202 (100+150)	0.202 (100+150)	0.126 (100+300)	0.084 (100+500)	0.072 (100+600)
Roof U-value [$\text{W/(m}^2\cdot\text{K)}$] / [mm] ⁽¹⁾	0.348 (100+0)	0.191 (100+150)	0.191 (100+150)	0.122 (100+300)	0.076 (100+550)	0.066 (100+650)
Floor U-value [$\text{W/(m}^2\cdot\text{K)}$] / [mm] ⁽¹⁾	0.341 (100+0)	0.160 (100+200)	0.160 (100+200)	0.122 (100+300)	0.076 (100+550)	0.066 (100+650)
Windows U-value [$\text{W/(m}^2\cdot\text{K)}$]	2.0	1.8	1.8	1.1	0.8	0.7
Ψ [$\text{W/(m}^2\cdot\text{K)}$]	0.25, 0.03, 0.1	0.25, 0.03, 0.1	0.25, 0.03, 0.1		<0.01	<0.01
Infiltration [h^{-1}]	0.62	0.5	0.5	0.1	0.05	0.05
Heat recovery	-	-	0.80	0.80	0.80	0.85
Indoor temperature [°C]	23.0	20.0	20.0	20.0	20.0	20.0
Floor area [m^2]	65	70	70	76	57 ⁽²⁾	57 ⁽¹⁾

⁽¹⁾ The number in brackets represents the current status of insulation in mm ($\lambda = 0.049 \text{ W/(m}^2\cdot\text{K)}$) plus additional insulation (required) for reconstruction ($\lambda = 0.037 \text{ W/(m}^2\cdot\text{K)}$). ⁽²⁾ Calculated for A_{TFA}

The model house type Average 18D was used to calculate various models in accordance with the following Standards: GBR with and without heat recovery (mechanical ventilation); estimated future low-energy house requirements (LEH) based on expected future GBR; and passive house requirements (PH). Each model was calculated using monthly weather profile data for Zone 1 (with average annual temperature -1.3°C) and Zone 2 (with average annual temperature -5.6°C) [29]. Fig. 10 shows the various models in the different locations.

The model Average 18D and GBR without heat recovery includes only heating demand and hot water consumption of 250 litres per m² of household per year. The model GBR with heat recovery and future LEH model includes heating demand, hot water consumption and electrical energy for ventilation system (1200 J/m² with factor 2.5 for electricity). And passive house model only includes heating demand per treated floor area.

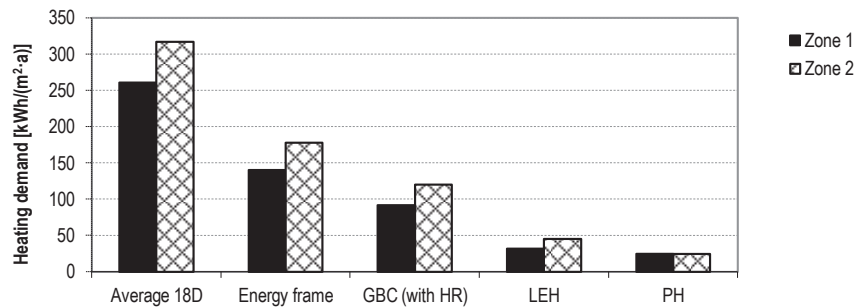


Fig. 10. Different improvements to the Average 18D standard house in location Zone 1 and Zone 2

The demonstration of applying benefits one at a time is shown on Fig. 11 starting with decreasing of interior temperature, improvement of the building construction (includes increasing the insulation and improving the thermal bridges) moving to changing the windows, improving the air tightness of a building envelope and installation of heat exchanger. Nevertheless many improvements must go hand in hand, i.e. making the building envelope airtight must be followed by a heat exchanger to provide fresh air or improvement of a building construction should be done in connection with improving thermal bridges, increasing insulation and improving air tightness.

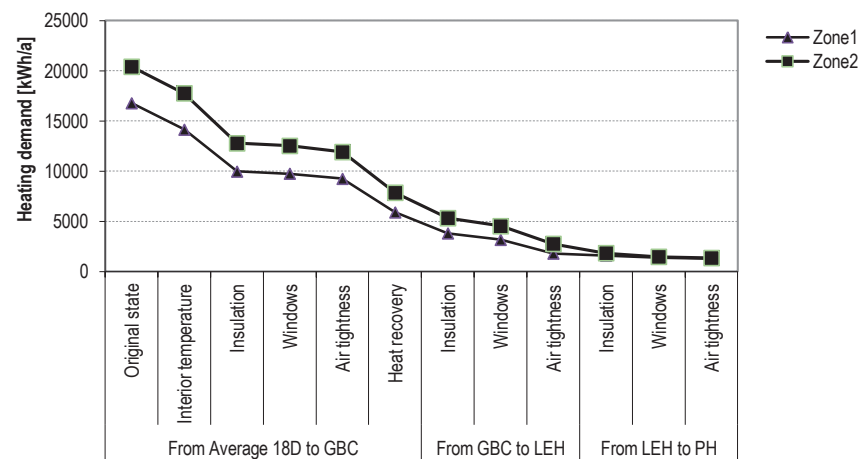


Fig. 11. Different benefits applied one at the time

4.7. Dew point in wall construction

To meet LEH requirement, a minimum of 200 mm of insulation ($\lambda = 0.037 \text{ W/(m}\cdot\text{K)}$) should be added to the existing 100 mm insulation and between those two insulation layers a new vapour barrier must be applied. This set up follows the rule of thumb that the vapour barrier can be placed up to 1/3 from the inside of the total thickness of the layer of insulation which in each case has to be supported by calculations. Fig. 12 is based on an example of initial calculation using the Glaser method [30]. When the exterior temperature is -36.4°C with relative humidity outside 100% and interior temperature $+20.0^\circ\text{C}$ with relative humidity inside 30%, the saturated pressure always is higher than actual pressure, so no condensation will occur. Although the Glaser method only requires the average temperature from the coldest month from the design reference year, the coldest hourly temperature of -36.4°C has been used for the northernmost located city Thule [29], and the interior temperature and humidity is based on measurements made in 18D. If the temperature drops below -36.4°C , this will happen only for short periods and possible condensation will not damage the construction.

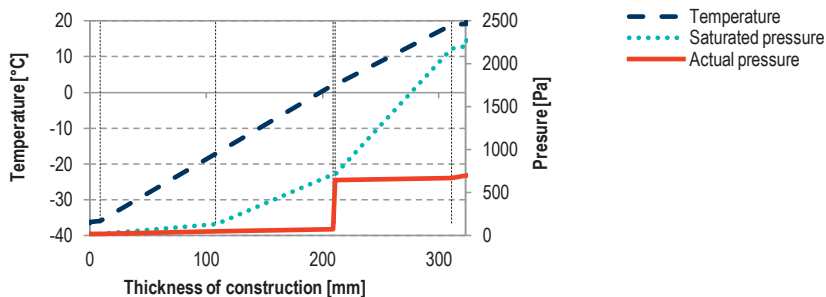


Fig. 12. Example of temperature and dew point calculation in insulated wall

4.8. CO₂ emissions

The building materials come by ship, which emits 8 g of CO₂ per km and per tonne [31]. This calculation is based on a total voyage of 3,000 km from Copenhagen to Sisimiut [31]. The calculated weight of materials is 38 kg/m² (tarred paper, gypsum, plywood, I-beams, insulation and wood and 5 kg of fittings = 39 kg/m² of envelope area), e.g. 5.9 tonnes of material per house. The CO₂ emission from production of the insulation needed for renovation is based on a Rockwool report where the manufacturing of 1 kg of insulation creates 1.2 kg CO₂ [23]. There are no accessible data yet on CO₂ emissions from the production of glass wool insulation in Denmark, so we used the reference value for Rockwool. The annual savings of 52,616 tonnes of CO₂ were calculated as the consumption of "Average 18D" as sum 317 kWh/(m²·a) for 4,787 houses in Zone 2 and 261 kWh/(m²·a) for 6,845 houses in Zone 1 multiplied by average floor area of a Greenlandic house (65.5 m²) [4].

The calculated CO₂ for the production and transportation of materials from Copenhagen to Sisimiut must be deducted from the total savings, i.e. 52,616 tonnes of CO₂ minus 1,606 tonnes CO₂ for transport of goods and minus 8,246 tonnes of CO₂ emission for the production of insulation. These deductions must be made for all 11,452 standard wooden houses, but only in the first year, which

means that the saving in CO₂ emissions in the first year is not 52,616 tonnes, but 42,761 tonnes (assuming the simplification that all the renovation is completed at the same time in the first year), but for other years the savings are 52,616 tonnes of CO₂. In the lifetime of a building, the deduction for transport and producing insulation is insignificant.

The CO₂ emission from using oil for oil boilers is 0.245 kg per kWh [32]. If all 6,845 houses in Zone 1 and 4,787 houses in Zone 2 are renovated from their current state (model Average 18D with an average floor area of 65.5 m²) to future low-energy requirements (LEH, 45 kWh/(m²·a) for Zone 2 and 32 kWh/(m²·a) for Zone 1), the total CO₂ saving will be 87% per year. To make a common standard solution for the whole of Greenland, the requirements for the coldest Zone 2 have been chosen to determine the LEH requirement of 45 kWh/(m²·a). That means that the standard solution in Zone 1 will have energy consumption for heating of 32 kWh/(m²·a).

Table 7. Total energy use and CO₂ emission in the 11,452 standard houses in Greenland

	Energy use (GWh/year)	CO ₂ (tonnes CO ₂ /year)
Today	217	53,000
Low-energy	29	6,000
Savings (%)	87	86

5 Discussion

The results show the 11,452 detached and semi-detached family houses built in or before 2006 have a potential for improvement in their building envelopes. The poor air tightness and the relatively thin insulation and the consequent large amount of heat loss through thermal bridges demand a solution. GTO's improvement program [8], which was applied to some of the older houses in the 1980s, has not solved the problem of the poor air tightness and the inadequate insulation, as is illustrated by the calculations for Eva's and Ester's house energy consumption.

LEH or PH

If the buildings are to be energy efficient for the next decades, the heat requirement needs to be lowered to the standard of either LEH or PH. LEH can be obtained with an insulation thickness totalling 300 mm in walls, roof and floor, a window U-value of 1.1 W/(m²·K), heat recovery of 80%, and infiltration of 0.1 h⁻¹. Renovation to PH standard requires thickness of insulation of 600 mm for walls and 650 mm in the roof and floor, super efficient windows, super air-tight construction, and a very well performing heat recovery system, etc, to reach 25 kWh/(m²·a) in Zone 1.

CO₂ emission

If low-energy standards were implemented in the houses investigated, the results show a potential for a reduction in CO₂ emission by a factor of 10. If these results were transferred to the total number of 11,452 Greenlandic detached and semi-detached family houses, all basically built with a wood-framed construction, floors over ventilated crawl space and a pitched roof with tarred paper, the total reduction would be 703 tonnes CO₂ per m² per year or 86% of the total CO₂ emission for heating in the building sector in Greenland.

Today Greenland produces 565,000 metric tonnes of CO₂ per year from burning fossil fuels and is aiming at a reduction of 8% before 2012 [7]. For 11,452 houses in Greenland, Table 7 shows the energy use of today and possible savings by improving houses to LEH standards. The total energy savings equals to 190 GWh/year. The reduction in CO₂ equals 47,000 tonnes of CO₂ per year or 8.0% of the total production of CO₂ emission from burning fossil fuels.

Air tightness and mechanical ventilation

GBR limits for air change have not yet been introduced but are expected to be implemented in 2010/11. To achieve LEH or PH, air tightness has to be improved. That will require the introduction of efficient central mechanical ventilation with a heat recovery system. The houses investigated have an attic, which is a suitable place to install the heat exchanger. In single story houses, it could be installed in the store room. But we also need to find a way to establish air tightness in the existing building stock. It will be too complicated and expensive to make the buildings air-tight from the inside because there are too many connecting elements like the walls, kitchens, bathrooms, etc. It is therefore preferable to add the air tightness from the outside, but that requires that the added insulation should be sufficient to avoid condensation inside the construction. The dew point calculation shows that this is possible.

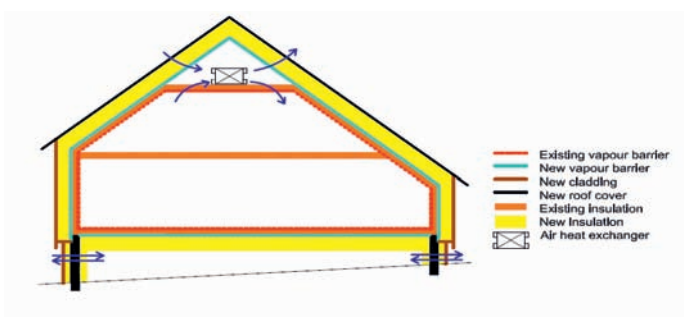


Fig. 13. Theoretical model with an exterior added air-tight vapour barrier placed up to 1/3 from the inside of the total thickness of the layer of insulation

How the extra insulation could be added

Based on our results, we have developed a theoretical model of how the extra insulation could be added. The model can be applied to all the detached and semi-detached houses built in and before 2006. In houses built before 1977, the insulation thickness of 100 mm or less represents less than one third of the total insulation layer that is required for the LEH. It is therefore possible to establish a vapour barrier on top of the existing exterior surfaces of the roofs, walls and floors and then apply sufficient insulation to the exterior side to avoid condensation in the construction. The additional construction should increase the lambda value as little as possible. The added beams could be either I-beams of wood and plywood or a beam made of wood with a core of hard insulation. The current non-insulated attics will be insulated and can thus contain a ventilation system with a heat exchanger. This solution will also be suitable for houses from the period 1977–2006, if the exterior cladding and the crossbars with part of the insulation are dismantled before applying the air-tight vapor barrier (Fig. 13).

Architectural aspect of renovation

The architectural expression of the house would be maintained by using the same roof material; the same overhang, the same cladding as the existing houses; the windows and the doors should be in the same location in the new cladding as they are in the existing one, but with the use of fittings with a low thermal bridge effect. The windows should be changed to low-energy types with frames of low transmission value and low-energy glass, and the exterior door should be changed to an insulated type. In this way, the energy renovation of the houses will be possible without any need to relocate the occupants.

6 Conclusion

The findings show a current energy consumption from 214 to 383 kWh/(m²·a) for heating and hot water. This is a high figure compared to current demand, but it is lower than the average consumption taken from Greenlandic Statistics of 416 kWh/(m²·a) which indicate that we probably will find many houses with much higher figures in the rest of the house stock, indicating that the total savings could be even higher. The figure from Greenlandic Statistics is also high compared with the Norwegian and Canadian Statistics with an average energy consumption of 181 and 231 kWh/(m²·a). The findings also show poor air tightness, a large number of thermal bridges, and high indoor temperatures. We demonstrate a potential for a reduction in energy consumption of 182 kWh/(m²·a) for Zone 1 and 338 kWh/(m²·a) for Zone 2 by using the same standard renovation method in both zones. We also demonstrate a potential for a reduction in CO₂ emission by a factor of 10. Finally, the paper describes a practical way of reducing thermal bridges significantly, increasing air tightness, upgrading insulation and adding mechanical ventilation to approximately half of the housing stock without significantly changing the architectural expression or having to relocate the occupants during the renovation.

7 Further work

To test the proposed theoretical model, a standard house should be renovated in the way described, and tests should be carried out to document the performance of the energy renovated house. This should be done in two steps. The first step would be to use the same system as used earlier when the houses were built; standard packages should be developed with membranes, insulation, new frameworks, wind barrier, fittings, cladding, a roof cover, and an air heat exchange system, etc. These packages could be manufactured at suitable places in Greenland and shipped all over the country. Finally, in order to find a technically and economically optimal solution, the second step, a full-scale experimental renovation project should be carried out.

8 Acknowledgments

We would like to thank all the people living in the houses we have investigated for their cooperation and great help in our struggle to provide information. The project is part of Technical University of Denmark and ARTEK (PhD project: Passive Houses for Arctic Climates). The project is also based on information obtained in the Lighthouse Project 2.0.

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Paper III: Low-energy house in Arctic climate - 5 years of experience

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Low-energy house in Arctic climate - 5 years of experience

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Abstract

The aim of this article is to present and disseminate the experience gained from a low-energy house in Sisimiut, Greenland, over the 5 years of operation since its inauguration in April 2005. The house was designed to test and present new low-energy technologies in the Arctic climate and to improve sustainability in Greenlandic buildings. The article presents some measurements, analyses and comparisons of theoretical simulations, and also some steps which were taken to improve the house with impacts on the energy consumption. The results include energy consumption, temperatures, and solar heating production. Also presented are the results of several investigations carried out in the house, such as blower-door tests and inspection of the ventilation system. The initial target for the heating demand of the house was that it should be restricted to 80 kWh/(m²·a), but in reality it has varied over the past 5 years from 139 to 150 kWh/(m²·a). Currently the house is on the way to present a good energy solution, and the annual energy consumption for heating in 2010 was 90 kWh/m².

Keywords

Low-energy house, Arctic climate, energy consumption, analyses, measurements

1 Introduction

A couple of decades ago, just after the oil crises, the world turned its attention towards energy-efficient housing and the implementation of building regulations that support saving of natural resources and promote the use of renewable sources. So far, building traditions in Arctic regions have not been focused on highly insulated and airtight buildings and this has resulted in houses that consume a large amount of oil (for heating and operation) and deplete limited natural resources. Arctic countries are slowly adopting the idea of using less oil for heating and thus emitting less CO₂. Compared to the European climate, the Arctic climate represents an extreme challenge for energy-efficient housing due to the extremely low temperatures, strong winds, and periods without sun or with sun at a low angle. Moreover, in the periods of the highest energy demand in the Polar Regions (winter), there is little or no available solar energy. Low solar radiation is an often mentioned faulty assumption and the potential of solar gains on/through the vertical

surfaces is neglected. The differences between the Danish climate and solar radiation profile (Copenhagen, Denmark) and the solar radiation profiles for Arctic and Antarctic locations are shown in Table 1, data source METEONORM [1].

A review of relevant literature and sources gives only a limited number of already built energy-efficient buildings located in Arctic or Antarctic regions. Examples include Polarbo (1996, Longyearbyen, Norway), built as conventional apartments with common areas [2], and I-Box 120 (2005, Tromsø, Norway), built as a prototype for the first Norwegian passive house [3]. Another example is the Belgian research station named Princess Elisabeth Antarctica (2009, Droning Maud Land, Antarctica), which is a futuristic design building that performs as a passive house in the Antarctic summer [4]. Canadian researchers have built energy-efficient houses mostly located between 50° and 66° latitude, including the Riverdale NetZero Project (built in Edmonton, Canada, 2007) as a zero energy house using passive techniques and renewable sources to fully cover heating and electricity consumption [5]. Some experimental buildings are located in high mountains, as is the Schiestlhaus (Hochschwab, Austria, 2005), which demonstrates the possibility of a sustainable and energy-efficient building in the Alps at an altitude of 2,153 m [6].

Table 1. Examples of energy efficient buildings in Arctic and Antarctic regions

Building, location	Coordinates	HDH ⁽¹⁾ [kKh/a]	Mean annual (coldest monthly) temperature [°C]	Global radiation Gh ⁽²⁾ [kWh/(m ² ·a)]	Gk 90° (South, West, North, East) [kWh/(m ² ·a)]	Targeted consumption [kWh/(m ² ·a)]
Copenhagen, DK	55°N, 12°E	83	7.8 (-0.3)	986	906; 686; 341; 673	-
Low-energy house, GL	66°N, 53°E	208	-3.9 (-14.0)	945 ⁽³⁾	1,019; 839; 442; 815	80.0
Polarbo, NO	78°N, 15°E	233	-6.7 (-16.3)	644 ⁽³⁾	786; 670; 512; 653	?
I-Box 120, NO	70°N, 19°E	150	2.9 (-3.8)	634 ⁽³⁾	705; 552; 334; 531	50.0
Riverdale, CA	53°N, 113°W	145	3.3 (-12.8)	1,313 ⁽³⁾	1,478; 991; 445; 992	-1.5
Schiestlhaus, AU	47°N, 15°E	177	-0.2 (-6.1)	1,051 ⁽⁴⁾	915; 694; 378; 694	15.0 ⁽⁵⁾
Princess Elisabeth, AN	71°S, 23°E	270	-10.8 (-18.0)	1,127 ⁽⁶⁾	696; 1,245; 1,653; 1,235	15.0 ⁽⁵⁾

⁽¹⁾ Heating degree hours with $T_{base} = 20^{\circ}\text{C}$, $HDH [\text{kKh/a}] = 0.024 \times HDD [\text{Kd/a}]$; ⁽²⁾ Gh = global radiation horizontal, Gk = solar radiation on tilted surface; ⁽³⁾ mean values of climate zone; ⁽⁴⁾ readings for Mariäzell (altitude 845 m); ⁽⁵⁾ self-sufficient/passive in summer; ⁽⁶⁾ Station Novolazarevskaya. Note: "a" defines as annual.

The literature review shows published information on building houses in Arctic and Antarctic regions documenting the process of design, initial design documentation and building reports. But rarely are the energy-efficient buildings equipped with all-year-round monitoring systems to document their performance and for long periods, as is the case with the low-energy house in Sisimiut (LEH) (Fig. 1).

The significance of this paper lies in the presentation of a comprehensive study of this LEH in the arctic region – a unique project with an ambitious goal of very low energy consumption. Not many houses have been built in an energy-efficient way in Arctic climate and then been documented by extensive and detailed measurements over a period of 5 years. The paper uses the extensive amount of collected and measured data to evaluate the house from the initial design model to the measurements of the house in practice. The LEH serves as a testing, training and experimental house where students and local people can learn valuable lessons and see the future perspective of building energy-efficient houses.



Fig. 1. Low-energy house in Sisimiut, view from the east

2 Key information about the Low-energy house in Sisimiut

2.1. Establishment of the house

Traditional buildings in Greenland are built from a timber construction with mineral wool insulation. Building traditions so far have not focused much on air tightness, ventilation systems or the elimination of thermal bridges. The houses are usually equipped with a hydronic based heating system supplied by oil and the ventilation is provided by natural ventilation openings. There are only a limited number of newly built houses with a ventilation system with heat recovery. The standard houses in Greenland usually consume up to 380 kWh/m^2 per year [7] compared to the average heating consumption of $416 \text{ kWh}/(\text{m}^2\cdot\text{a})$ for an average heated-floor area of 65.5 m^2 stated in the Greenland's Statistics [8]. It is important to apply new knowledge and technologies to reduce such high energy consumption. Therefore, the LEH in Sisimiut was designed and built in 2005 with donations from the Villum Foundation (DKK 5 million), the local authority in Sisimiut (DKK 100,000), Exhausto A/S (donation of ventilation equipment), and with help from local building companies.

The non-static definition of a low-energy house is that the house consumes only half the energy permitted by the Danish Building Regulations (e.g. a low-energy building Class 1). This poses a big challenge in the Arctic climate. The Greenlandic Building Regulation 2006 (GBR 2006) sets a target of $230 \text{ kWh}/(\text{m}^2\cdot\text{a})$ for space heating and ventilation of a single storey house without heat recovery located in Zone 2 (north of the Polar Circle) and built in accordance with standard practices [9]. Approximately $70 \text{ kWh}/(\text{m}^2\cdot\text{a})$ can be subtracted with the installation of an efficient heat recovery, so the permissible energy for heating should be only $160 \text{ kWh}/(\text{m}^2\cdot\text{a})$. A low-energy house is using only half of the energy permitted, so the annual heating target is $80 \text{ kWh}/\text{m}^2$ because the house is equipped with a highly effective heat recovery ventilation system. This is an ambitious, yet realistic, target for energy-efficient buildings in the Arctic. The house was inaugurated in April 2005 on the occasion of the Symposium on Energy-efficient Buildings [10]. The price of the house was approximately EUR 3,600 per square meter of floor area.

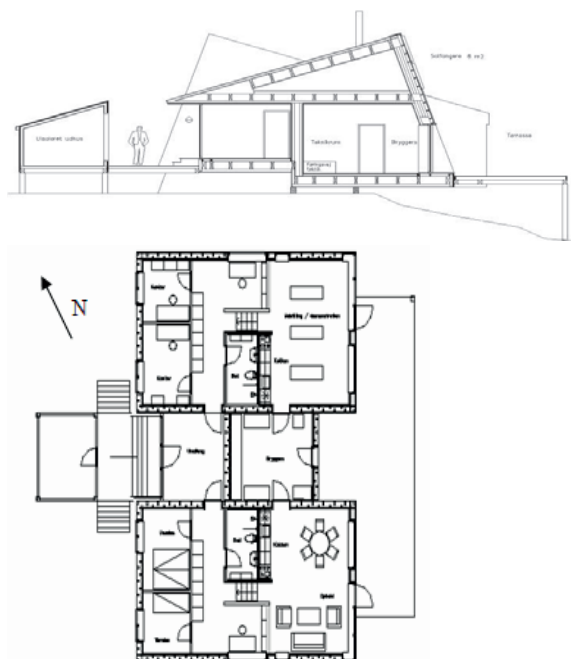


Fig. 2. Cross section and floor plan of the LEH

2.2. Description of the Low-energy house in Sisimiut

The LEH has a usable net floor area of 186 m², and it is built as a pair of single-storey semi-detached houses with a common scullery and entrance hall. One of the houses serves as accommodation to a Greenlandic family (south-western, inhabited) and the other as an exhibition centre and occasional accommodation for guests (north-eastern, guest). In the initial design, the attic space was to be insulated, as is current technical practice in cold climates. But due to economic reasons, there is a cold attic above the whole building and the heat exchanger and ducts have been post-insulated. There is an open crawl space below. The layout of the building was designed as two completely thermally separated residence units with a common unheated entrance hall and an insulated technical room containing heating installations and domestic appliances (Fig. 2).

To achieve the target of an annual energy consumption of 80 kWh/m², the house was designed to optimize frame-work energy use with reduced heat loss and an orientation to exploit the sun. The external walls are made from insulated wooden members with minimum thermal bridge effect (calculated linear thermal transmittance $\Psi = 0.015 \text{ W/(m}\cdot\text{K)}$), with each wooden member separated into an external and an internal part (Fig. 3). The calculated U-values including thermal bridge effects for the building envelope ($U_{\text{floor}} = 0.14 \text{ W/(m}^2\cdot\text{K)}$ with 350 mm of insulation, $U_{\text{wall}} = 0.15 \text{ W/(m}^2\cdot\text{K)}$ with 300 mm of insulation, and $U_{\text{roof}} = 0.13 \text{ W/(m}^2\cdot\text{K)}$ with 350 mm of insulation) are below the demands of GBR 2006 [9].

Windows were installed in the house with low-energy glazing designed to achieve a positive net gain from low-angle sun. The Velux windows in bedrooms are in inclined walls with 2-layer glass with vacuum ($U_{\text{window}} = 1.1 \text{ W/(m}^2\cdot\text{K)}$, $U_{\text{glass}} = 0.7 \text{ W/(m}^2\cdot\text{K)}$) with an annual net energy gain of -59.3 kWh/m^2 . And everywhere else there are Velfac windows, with 2-layer glass plus one single glass ($U_{\text{window}} = 1.1 \text{ W/(m}^2\cdot\text{K)}$, $U_{\text{glass}} = 0.8 \text{ W/(m}^2\cdot\text{K)}$) with an annual net energy gain of 67.1 kWh/m^2 [11].

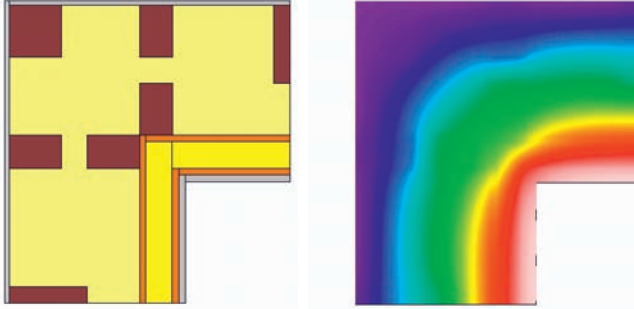


Fig. 3. Thermal bridge effect of outer wall corner with temperature effect in the LEH (horizontal cross-section)

The house is equipped with a balanced ventilation system with an experimental heat exchanger. Ventilation systems in cold climates usually preheat the inlet air before the heat exchanger to avoid ice blockage, but this is not an optimal energy solution, so a new prototype of a heat recovery unit with defrosting mechanism and no preheating was developed and tested in the house. The entire ventilation system is located in a cold attic and consists of a heat exchanger, two low-energy ventilators with additional heating coil 40 kW (after-heater), and air terminal devices. The heat exchanger unit consists of two aluminum counter-flow heat exchangers coupled in a serial connection to avoid freezing problems during cold periods [12]. The order of exchangers can be switched by a damper, so that the colder exchanger, where the frost formation may appear, can intermittently be defrosted by warmer air passing through it (Fig. 4). The damper is controlled by a timer, so it switches at the certain time. In theory, the temperature efficiency of a counter-flow heat exchanger could reach 90% and, with the coupling of two units in series, it could reach 95% [13]. The laboratory measurements of the heat exchanger designed for the LEH were simulated at a temperature of -8°C proving that the active defrosting system functioned as intended [12]. The heat exchanger is located in an insulated box with $2 \times 50 \text{ mm}$ of Rockwool insulation. The ventilation ducts are wrapped in insulation (total thickness 150 mm).

The floor heating was an experimental design choice for the extreme climate to introduce low-temperature heating. The heating system is an oil-fired boiler ($\eta = 0.9$) supplying the floor heating and the hot water, which is also partly covered by the solar collectors (solar combi-system). The flat plate collectors are placed on the south-east façade with a slope of 70° from horizontal and a total surface area of 7.4 m^2 . Furthermore, the house is equipped with a detailed monitoring system [14], [15], [16], [17].

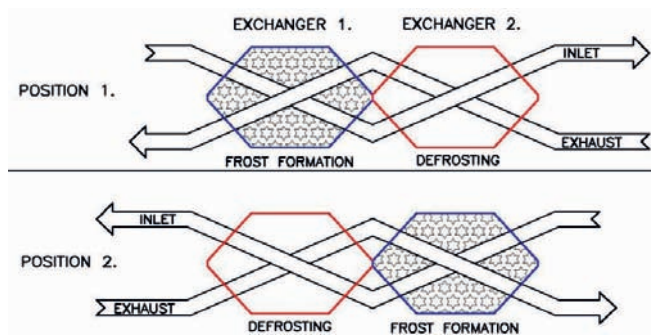


Fig. 4. Scheme of heat exchanger

2.3. Energy balance of the designed house

In 2004, an initial design model was created and simulated in BSim with the initial values stated in Table 4. The test reference year of Sisimiut used in the BSim model was based on weather data measured from 1991 to 2004 by ASIAQ (Sisimiut.dry) [18], [19]. The total simulated heating demand for the LEH with a gross heated floor area of 197 m² (not including the entrance area, which was originally designed not to be heated) was approximately 15,500 kWh/a, corresponding to 78 kWh/m² per year or 1,500 litres of oil for the entire building). The theoretical consumption of the LEH was calculated to be 3,000 kWh/a for electricity and 3,000 kWh/a for hot water, of which 1,700 kWh/a should have been covered by solar heating (Fig. 5). With the oil price in Greenland at EUR 0.33 per litre in 2004, this corresponded to an annual payment for heating of EUR 485 per year. The savings compared to the actual world price for oil would be considerably larger, i.e. EUR 1.48 per litre equals an annual payment for heating of EUR 2,200 per year. The subsidized Greenlandic price for oil has an impact on delivering energy and these prices do not encourage the development of low-energy housing in Greenland – one of many non-technical impediments to energy efficiency. For comparison: an ordinary new house of the same size would consume 230 kWh/(m²·a) for heating, i.e. 15,000 kWh/a for an average house size of 65.5 m² [8], and 3,000 kWh/a for hot water, i.e. 4,500 litres of oil per house (~ EUR 1,485 per year for heating and hot water consumption using the subsidized oil price, or EUR 6,660 per year for world price oil) [11].

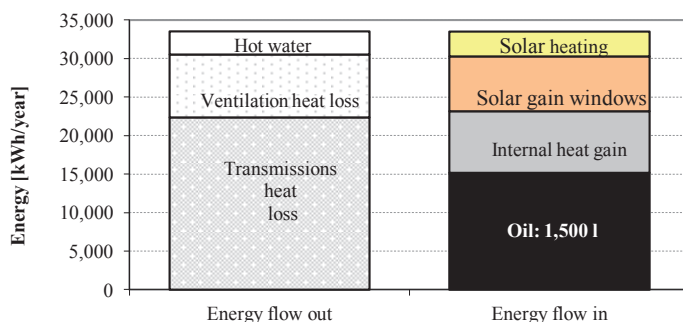


Fig. 5. Initial design consumption of the LEH in Sisimiut

3 Methods of investigations

The following methods of investigation were used to determine the existing conditions of the LEH, the problems causing large energy consumption, and several possible principles of improvement based on data from energy monitoring, investigations and theoretical analyses.

3.1. Indoor climate and energy consumption

Using measurements for heating consumption and indoor climate data, the connection between the oil consumption and temperatures indoors and outdoors was established. The solar energy and excess of solar energy were measured and evaluated. The main actions taken to improve the LEH were documented.

The degree days (DD) indicate how the heating is used in a climate-controlled building comparing one year to another, i.e. how cold the years were, and how much heat the building needed each year. The monthly oil consumption per degree day is expressed in equation (1), where D is the number of days in a month, T_{base} is the base design indoor temperature (19°C) and $T_{ambient}$ is the outdoor temperature (°C). The consumption of oil (litres of heating oil per degree day) is calculated using equation (2) where O is the oil consumption in each month (litres).

$$DD = (T_{base} - T_{ambient}) \cdot D \quad (1)$$

$$Q_{for_heating_oil} = \frac{O}{DD} \quad (2)$$

3.2. Air tightness, infiltration heat loss and thermography

The air tightness was investigated twice using a blower-door test (February 2009 and March 2010). The LEH was measured in accordance with the European Standard 13829, method B [20]. The air change rate n_{50} @ 50 Pa (h^{-1}) with net floor area A_{net} (m^2), and w_{50} @50 (l/s m^2) with gross heated area A_{gross} (m^2) was calculated in accordance with EN 13829. The calculated results at 50 Pa obtained from the blower-door test were converted to air change at normalized pressure state using the SBi method with q_{inf} as in (3) where q (l/s m^2 of heated floor area) is airflow and q_{50} (l/s m^2 of heated floor area) is a leakage rate calculated from the blower-door test [21]. Then an infiltration rate can be calculated in (4) that is a representation of a steady state from the SBi method based on European conditions.

$$q = 0.04 + 0.06 \cdot q_{50} \quad (3)$$

$$q_{inf} = \frac{q \cdot A_{gross} \cdot 3.6}{V_{net}} \quad (4)$$

The results from the blower-door test were used to calculate the real infiltration for comparison with the initial design infiltration. Infiltration heat losses constitute a large part of the total losses, so the annual infiltration heat loss through the building envelope was calculated using the values from the

blower-door test (average value from two tests) and the following equations. The total infiltration throughout the year Q_{inf} (kWh/a) is expressed in (5) where V is the internal insulated volume of the building (m^3), q_{inf} is the calculated infiltration air change (h^{-1}), c_p is the thermal capacity of the air ($1,005 J/(kg \cdot K)$), ρ is the air density ($1.2 kg/m^3$), and HDH is a yearly sum of heating degree hours from the design reference year for Sisimiut (208 kKh/a) [22].

$$Q_{inf} = V \cdot q_{inf} \cdot \frac{c_p \cdot \rho}{3,600} \cdot HDH \quad (5)$$

Thermographic pictures were taken during the blower-door test to examine the thermal bridges and air leakages. The analyses of the thermographic pictures help us to understand whether there is an air leakage or a thermal bridge that is caused by missing insulation or defect materials.

3.3. Efficiency of ventilation system and insulation of ducts

An investigation of the performance of the ventilation system was carried out to establish the efficiency, set-up modes and failures of the heat recovery system. The temperature efficiency of the heat recovery was calculated using temperature and pressure data from the monitoring system. Temperature efficiency η_t is one of the describing parameters for measuring the energy performance of a heat exchanger. The efficiency is calculated using expression (6), which is related to the supply side, where T_{supply} is the temperature of the supply air after the heat exchanger ($^{\circ}C$), $T_{ambient}$ is outdoor temperature ($^{\circ}C$) and $T_{extract}$ is the extract air temperature ($^{\circ}C$) [23].

$$\eta = \frac{T_{supply} - T_{ambient}}{T_{extract} - T_{ambient}} \quad (6)$$

The effect of heat loss from ventilation and from insulated pipes in the cold attic was determined. The U-value of the insulation around ducts is expressed in (7) where d is the outer diameter of non-insulated pipe (201 mm), λ_{is} is the thermal conductivity of the insulation ($0.035 W/(m \cdot K)$), \emptyset is the diameter of insulated pipe (301 mm and 501 mm respectively) and α_e is the heat transfer coefficient on the outer surface ($10 W/(m^2 \cdot K)$). The equation ignores the effect of the metal parts of the ducts.

$$U = \frac{\pi}{\frac{1}{2 \cdot \lambda_{is}} \ln \frac{\emptyset}{d} + \frac{1}{\alpha_e \cdot D}} \quad (7)$$

3.4. Modelling in BSim

Based on the results from investigations and monitoring in the LEH, analyses of the theoretical models (the initial design model and the model with actual values) were carried out in BSim [24]. The BSim program calculates the energy balance for a building model from input data about the building design, construction, windows, internal systems, and weather climate data. The initial design model of the LEH was created in accordance with the design proposal: building design, construction and windows characteristics [11]. The set-ups for internal systems are listed in Table 4. When the model was constructed, only the south-western half of the building was created for

analyses due to symmetry, with each room as a separate zone with its own controls. The entrance area was considered not to be heated. The second model was constructed for comparison, with input values (Table 4) that correspond to the actual values in the LEH as realized, based on the measured conditions of infiltration, efficiency of heat recovery system, indoor temperature, etc. The model represents the complete LEH, and the two apartments were treated as one sector, in which each room is one thermal zone with its own set-up of systems connected via the entrance and technical room with no internal doors. The entrance is part of the heated area with internal gains and connected to the heating/ventilation system.

4 Results

4.1. Measurements in the house

4.1.1. Indoor climate and heating consumption

The interior temperatures ranged from 20.0°C to 27.0°C (**Error! Reference source not found.**). The highest monthly average temperatures were in July 2008, when the average indoor temperature in the guest apartment (north-east) was 26.8°C and in the inhabited apartment, where windows are mainly oriented towards south-west, 27.4°C. At the time, the ambient monthly average temperature was 9.6°C, which was considered a very warm summer (highest monthly mean ambient temperature in 5 years).

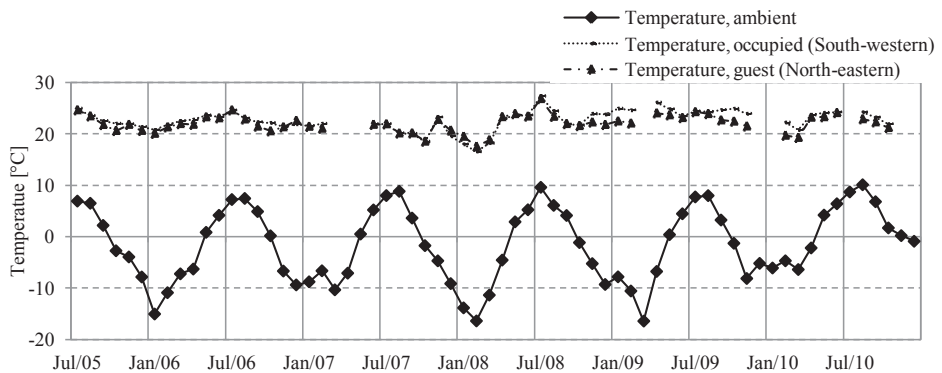


Fig. 6. Measured indoor climate (indoor temperature in both apartments) and ambient temperature over 5 years

Comparisons of the real measured consumption (over 5 years) and the initial design heating demand of 23°C (values periodically repeating each year) show the effect of higher indoor temperatures on the real heating consumption (Fig. 7). The peaks in the monthly consumption indicate that the building consumes most energy in the winter months where the real measured consumption is often 3 times greater than the design values, especially in the months November, December and January. The building acts in accordance with the design from January to September. The improvements after December 2009 and April 2010 can be seen where the measured heating consumption is lower than the design heating demand, but the year 2010 was exceptionally warm. The results (Fig. 7) show that the LEH uses more energy on heating,

especially from 2006 onwards, when the after-heater was installed and monitored. The electricity consumption is measured from January 2006. The total electricity is also 3 times that expected, and ranges from 7,100 kWh/a in 2007 to 9,000 kWh/a in 2009.

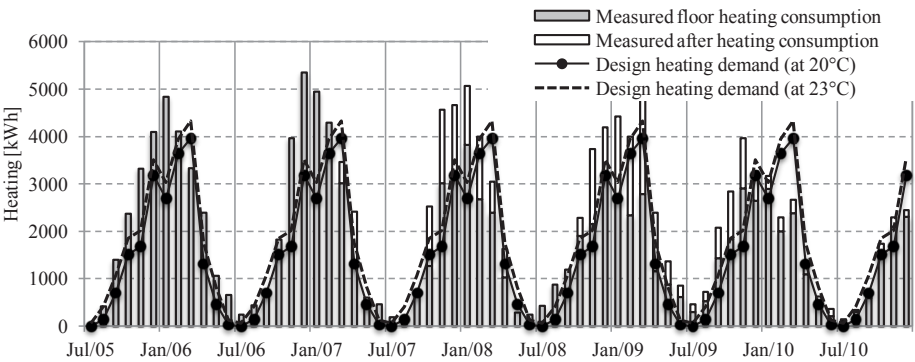


Fig. 7. Monthly MEASURED values of heating consumption (in kWh) compared to DESIGN values of heating demand (at 20 and 23°C) over 5 years (DESIGN values do not include the heating needed for the entrance area). MEASURED heating consumption includes the floor heating and the after-heater.

The LEH was not inhabited between June 2007 and March 2008, but still consumed lots of oil for heating because houses in Greenland are usually heated even when no one is present in the house. The monthly values (Fig. 7) show the progress in improving the house, especially in December 2009, when the after-heater (defect) and the heat recovery (switching damper valve) were repaired, and thickness of insulation on ducts in the cold attic was increased. The results show that only a small amount of energy was required for after-heating of supply air to the rooms and there was an overall decrease in the use of heating oil.

Calculations were made to establish the amount of oil used per degree day. Until end of 2009, the LEH consumed almost 0.6 liter of oil per degree day in each month in winter periods, and only 1/6 of this amount is used in summer periods because of solar gains (Fig. 8).

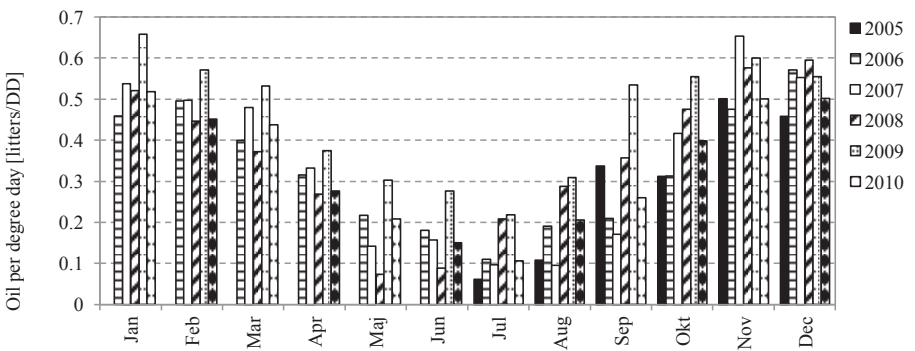


Fig. 8. Monthly summary of oil consumption per degree day over 5 years

Energy produced in the LEH from solar collectors connected to the hot-water tank covers approximately 50% of the hot water consumption. The energy produced by the solar collectors was in question as the measurements showed them producing heat even in cold winter, but this was due to the solar collector fluid circulating backwards through the solar collector loop (thermo-siphoning) in periods with a high driving force due to a strong cooling of the fluid in the solar collector. The issue was solved with the installation of a magnetic valve (2009-2010). In 2010, the solar energy supplied to the hot water tank was measured as 1,859 kWh/a. There was also a significant surplus of solar energy, e.g. from March to December 2009 the excess energy was 823 kWh and from April to September in 2010 the excess was 682 kWh.

The design heating consumption in the LEH was simulated to be 80 kWh/(m²·a) with the design heated floor area of 197 m² including heat generated by the solar collectors. The heating consumption measured over the past 5 years shows that, on average, the LEH consumes 56% of heating in the first half of the year, and 44% in the second half of the year. From January to end of June 2010, the consumption in the LEH was 10,400 kWh, which is equal to 50 kWh per m² of heated floor area. The consumption for the period from July to the end of December in year 2010 was 7,670 kWh, i.e. ~ 40 kWh/m². The total consumption was about 90 kWh/(m²·a), calculated with 208 m² of actual heated floor area including the heated entrance area in contrast to the design heated floor area. If the measured heating consumption is calculated against the design heated floor area of 197 m², it comes out at 95 kWh/(m²·a). The values in this paragraph include heat generated by the solar collectors.

4.1.2. Air tightness of the building envelope

The results of the air tightness measurements show that the LEH would not fulfill the certification conditions of the upcoming Greenlandic Building Regulation 2011 ($q_{50} < 1.5$ l/s m² @ 50 Pa) or Passive house Standards ($n_{50} < 0.6$ h⁻¹ @ 50 Pa). The LEH was designed to have an infiltration rate of 0.1 h⁻¹, but its current rate is 0.29 h⁻¹, calculated under steady weather conditions (Table 2). This makes the infiltration heat loss 3 times greater than the initial design value.

Table 2. Blower-door test results at 50 Pa and under normalized pressure

Method / Date	Pressure at 50 Pa				Normalized pressure
	Airflow V_{50} [l/s]	Air change rate W_{50} [l/(s m ²) @ 50 Pa]	Air change rate n_{50} [h ⁻¹ @ 50 Pa]	Leakage rate q_{50} [l/(s m ²)] of A_{gross}	Infiltration rate q_{inf} [h ⁻¹]
Blower-door, Feb 2009	474	2.55	3.35	2.28	0.30
Blower-door, Mar 2010	436	2.35	3.07	2.10	0.28

Internal building volume $V_{net} = 450$ m³, net floor area $A_{net} = 186$ m², heated floor area $A_{gross} = 208$ m².

During the thermography investigation, three-dimensional thermal bridges were identified at floor/wall joints, ceiling/wall joints, and around windows. Significant thermal bridges were also identified at the door thresholds for terrace doors made of aluminium. Air leakages were also identified between floor/wall in the entrance hall and between the kitchen and the horizontal ventilation shaft. The joint sealing of the vapour airtight layer around the windows in the inclined wall has also been leaking air (Fig. 9).

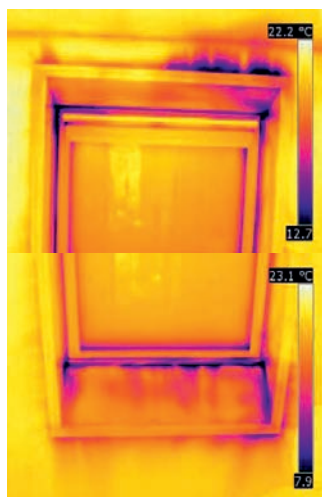


Fig. 9. Thermo image of a window in an inclined wall and leakage of airtight barrier (Blower-door test by Lars Due, 2009) identifying areas of high air leakage with dark colour

The annual infiltration heat loss was calculated from the average results of two blower-door tests and for the required value of $q_{50} = 1.5 \text{ l/s m}^2$ of gross heated area permitted by future GBR (Table 3). These results were calculated for the internal insulated envelope of the LEH (V_{net}) that includes the volume of the whole building (two apartments, entrance, technical room, installation shafts). The design infiltration was 0.1 h^{-1} at normal pressure, but the average infiltration 0.29 h^{-1} calculated from the blower-door tests gives almost three times the expected infiltration loss. Moreover, the calculated infiltration is only under steady conditions, so the effects of wind, snow and temperature are not taken into account.

Table 3. Infiltration heat loss through the whole building envelope

	Leakage rate q_{50} [l/(s m ²)] of heated floor area ⁽²⁾	Infiltration q_{inf} [l/(s m ²)] of heated floor area ⁽²⁾	Infiltration q_{inf} [h ⁻¹]	Q_{inf} [kWh/a]
Design infiltration ⁽¹⁾	-	-	0.10	2,900
Air tightness (GBR 2011) ⁽²⁾	1.50	0.13	0.22	6,800
Real infiltration ⁽²⁾	2.19	0.17	0.29	9,000

⁽¹⁾ Design infiltration heat loss from the BSim model for the whole LEH (not including entrance) with $V = 410 \text{ m}^3$ was 2,900 kWh/a with a design infiltration of 0.1 h^{-1} ; ⁽²⁾ Heated gross area $A_{gross} = 208 \text{ m}^2$, internal volume of the whole building $V = 450 \text{ m}^3$.

4.2. Ventilation system

4.2.1. Condensation, freezing and efficiency of heat recovery unit

The box plot (Fig. 10) shows a distribution of measurements of heat exchanger efficiency in different years. The bottom and upper parts of the boxes are the 25th and 75th percentiles of the data, whereas the ends of the whiskers represent the lowest and highest data, but still within 1.5 times the interquartile range. The bands inside the boxes are medians and the crosses beyond the whiskers are the outliers.

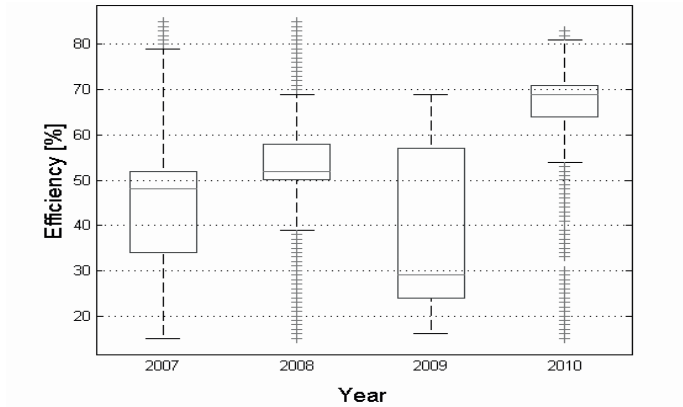


Fig. 10. Efficiency of heat exchanger (distribution of valid measurements with efficiency 15–85%)

Based on the measurements in the LEH [25], the calculated temperature efficiency during the first years of operation was low. After a broken damper was fixed in December 2009, the temperature efficiency increased significantly. The temperature efficiency dropped down close to zero in some periods where there was no airflow (Fig. 11). The switching of the damper also affected the temperature efficiency, with a significant drop in efficiency of as much as 18% just after the switching (Fig. 12), when the outdoor temperature was -8.5°C on average. Due to the switching, the annual temperature efficiency varies from 50% to 66% (Fig. 12). After approximately one hour, equilibrium is reached again.

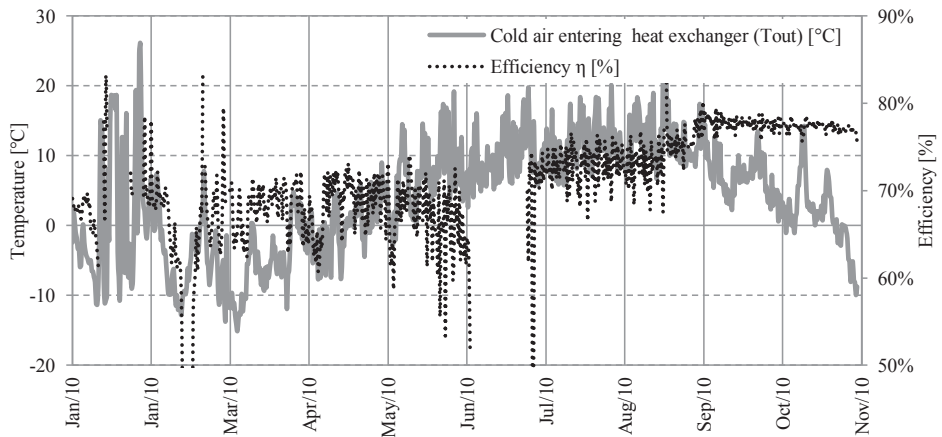


Fig. 11. Temperature efficiency from beginning of January 2010 to end of November 2010

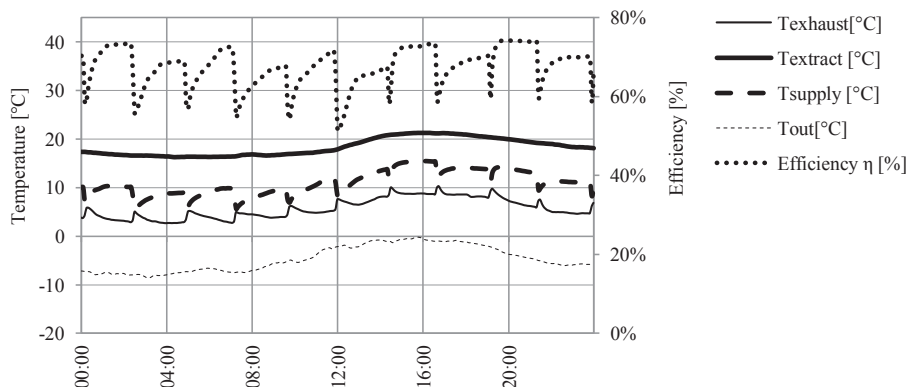


Fig. 12. Temperature and efficiency during damper switching every two hours on March 23, 2010, with an average outdoor temperature of -8.5°C

4.2.2. Heat recovery modes

In the winter of 2009/2010, the heat recovery was investigated in eight different modes: with the timer set to 1, 2, 3 and 4 hours and with the additional electrical heater in the insulated box turned on and off, respectively. Temperature efficiency, volume of condensation, airflows, pressure loss and thus possible ice formation and the heat exchanger's blockage were all monitored. The increased pressure loss in the exhaust part of the heat exchanger in the period with outdoor temperatures below -10°C indicated that there might have been frost formation partly blocking the heat exchanger. Nevertheless, there was no condensation going out of the unit during the entire testing period. This means that the dry air stream was able to remove all of the moisture from melting ice after the temperature increased. The temperature efficiency of the different modes varied between 62% and 70%.

4.2.3. Insulation of ventilation ducts in attic

Until the end of autumn 2009, the ventilation ducts were insulated by only 50 mm of mineral wool, which led to high transmission losses since the ducts are located in a cold attic where the temperature was just slightly higher than outdoors. The temperature of the exhaust air entering the heat recovery unit was therefore approximately 8 K lower than the room temperature. This decreased the unit's efficiency. An extra 100 mm thermal insulation was added in December 2009, which improved the thermal resistance of the ducting. The heat loss along the duct and thus the temperature drop between room temperature and heat exchanger should be approximately 44% less than before the additional insulation was installed (insulation of ducts before August 2009: $U_{50} = 0.545 \text{ W}/(\text{m}\cdot\text{K})$; and today's insulation: $U_{150} = 0.241 \text{ W}/(\text{m}\cdot\text{K})$). The measurements on site show that the temperature drop is now approximately 4 K.

4.2.4. Analyses of theoretical models in BSim

The analyses of the two models in BSim (Fig. 13) show that the heating demand for the initial design model is 78 kWh/(m²·a) while for the model with actual values it is 130 kWh/(m²·a). The effect on heating consumption based on air tightness of the building envelope indicates that the infiltration is 3 times greater in the real situation than is the initial design. The high indoor temperature creates overheating in the south-western apartment, where the hourly temperature during the summer gets above 25°C, unlike the north-eastern apartment with hourly summer temperatures approximately between 22-23°C. Furthermore, the detailed results from comparison of the two models indicate that the initial design model of the south-western apartment has an extra 360 kWh/a of solar gains compared to the north-eastern apartment. Due to the extra ventilation in the entrance hall and low heat recovery efficiency, the ventilation heat loss in the model with real values is 4 times greater than in the initial design model. Moreover, user behavior will affect energy consumption.

Table 4. Input values for BSim model: Initial design model and model with actual values

Values	Initial design model with design values	Model with actual values
Indoor temperature	20°C	23.2°C ^(X)
Infiltration	0.10 h ⁻¹	0.29 h ⁻¹ ^(X)
Heat recovery efficiency	80%	60% ^(X)
U _{window}	0.8 W/(m ² ·K)	1.2 W/(m ² ·K) ^(X)
Zoning	Each room is one zone	Whole building is one zone, no internal doors
Entrance	Not heated, not part of the house, no internal gains	Heated, part of the house, internal gains 5 W/m ²
Gross floor area	197 m ² (not including entrance)	208 m ² (including entrance)

Note on ventilation system for half of the house: exhaust from kitchen 20 l/s, bathroom 15 l/s and technical room 5 l/s; inlets to bedrooms 5 l/s, to working place 10 l/s, to living area 20 l/s. Venting when $T_i > 25^\circ\text{C}$; internal gains 5.0 W/m²; ^(X) average values as measured. Weather data: Sisimiut.dry.

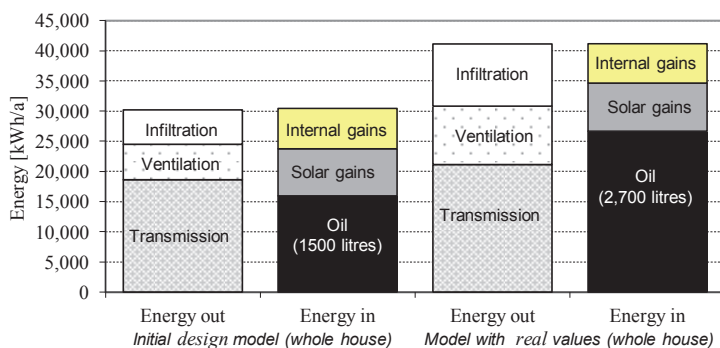


Fig. 13. Analyses of initial design model and model with real values in BSim (1 litre of oil = 10 kWh)

4.3. Challenges in the Low-energy house in Sisimiut

The design of the LEH was a complicated process that had to overcome many challenges starting from the initial design decisions right through the 5-year operation of the house. In the initial design, the heat recovery was located in an insulated attic but, due to the costs, this was changed to an un-insulated attic with a simpler layout of insulation on top of the ceiling. Later on, the heat recovery

unit needed to be placed in an insulated box equipped with an electrical heater, and ducts in the attic were clad with more insulation. In 2005, when the building was constructed, the importance of air tightness had yet to be introduced to the Greenlandic craftsmen. The complexity of the framework building, its windows and building services resulted in many errors, e.g. the vapour airtight barrier and sealing at penetrations were not ideal.

The LEH has lacked a commissioning process that would validate the completeness and accuracy of all systems and components in the building, including the design, installation, testing, operation and maintenance, in accordance with the operational requirements set. A commissioning methodology would involve the quality control of the design project to discover possible errors, follow-up on the building site during the building process, and monitoring of the system's operation during the first year. The adoption of such a process for new projects in the Arctic would yield more knowledge of the building process and how to reach the designed performance of a building and would also educate the craftsmen.

5 Discussion

The analysis shows that the LEH has not quite reached its initial design target yet. It has been struggling with many issues that are exacerbated by the severe climate of Greenland. Some sources of large heat losses have been identified: insufficient air tightness, operational problems of the experimental heat exchanger, floor heating in the entrance hall, the unqualified craftsmanship, and user behavior related to the operation of the house.

Measured indoor climate in the inhabited apartment shows that the living rooms often get overheated in the summer months due to the large south-facing windows with insufficient shading from the south. Better utilization of solar gains could be implemented, and the house should have been equipped with movable shadings to block the low-angle solar radiation. The **target heating consumption** of 80 kWh/(m²·a) calculated for the design heated-floor area of 197 m² has not been reached yet, but the results from year 2010 are very promising for the actual heated area of 208 m². The most significant improvements were made at the end of 2009 and in the spring of 2010, with the reduction in energy consumption due to the mending of the heat exchanger and improved air tightness. Only the **hot water consumption** is the same or even below the targeted value of 3,000 kWh/a, because only half of the LEH is inhabited throughout the year. The electricity consumption is three times greater than expected, and therefore investigations of the electricity system and appliances are needed. The **solar-collector production** covers the hot-water consumption in summer, and even yields a surplus of energy. This immediate solar energy could perhaps be utilized in a more efficient way, e.g. stored in an additional hot-water tank for later use in floor heating or used for a ventilation system.

The results from blower-door tests show that the LEH has some air leakages through the building envelope. The **air tightness** has been somewhat improved, which shows the need to make the air-tight layer a focus from the very beginning of the building process.

The realized temperature efficiency of the **heat exchanger** over the past 5 years averages 60%, fluctuating between 55% and 80% due to insufficient insulation of the ventilation system and

problems with defrosting operation. The switching mode after 4 hours to prevent freezing of the heat exchanger should be in action only when defrosting is necessary. More efficient control of the switch would greatly improve the overall temperature efficiency; e.g. it could be put into effect if the ambient temperature is below 0°C or if frost is detected in the heat exchanger. For future measurements of low flow-velocities, the difference pressure sensors could be located in the pipe with 1 m length with a decreased diameter.

The results from **BSim simulations** show that the models for calculating heating demand have a high accuracy. The results give ideas on what are the most important aspects of the LEH and where it fails. The half of the model used as a design model was constructed well, but the overheating and larger solar gains in the south-western apartment were not considered. The high infiltration rate and the temperature efficiency of the heat recovery being lower than designed have a significant impact on the heating demand in the building.

Experience and lessons learned

The LEH was a university project with the aim of demonstrating an energy-efficient building documented with all-year-round measurements. The experience from the LEH shows that integrated design is necessary, starting from the beginning with careful design modeling and continued follow-up on the building site. Very great attention needs to be paid to details such as thermal bridges, air tightness, and workmanship, as well as the work on finishing details. Experimental materials get thoroughly tested in severe climates, so there is a higher risk of material failure, and extra attention needs to be paid to preheating, efficiency and execution of installation. The heat recovery unit must be placed in a heated room; otherwise it will be difficult to insulate the ducts and the heat recovery unit properly, with undesirable heat losses as a consequence.

Our improved understanding and use of passive and solar gains needs to be put into practice in the Arctic regions, especially from to avoid the risk of overheating in a house. The house has to be designed carefully on paper and built on site, avoiding changes of plans at later stages of the project. Making unusual design choices in conflict with common practice can lead to difficulties in the building and use of houses (e.g. floor heating in cold entrance area, open doors from/to an insulated envelope, saving on insulation in the attic). The design of the LEH is different from the traditional Inuit houses; so the social and cultural needs and expectation of local people need to be taken into account.

6 Conclusion

Focus of the article is on the building envelope, ventilation heating systems and overall performance of the LEH in Sisimiut and the paper also lists some problems with building practice in the Arctic. Although the initial design target for heating consumption was not reached until the end of the 5-year trial period, the measurements obtained have high value and contribute to our knowledge about the behaviour of a low-energy building in the Arctic climate. The LEH tells a significant story of an ambitious project in an Arctic climate that is slowly achieving success.

The future in Arctic construction lies in building energy-efficient houses using an “integrated design, building and monitoring process”. The buildings must have highly insulated and airtight building

envelopes, window solutions with positive net energy gains whenever possible and highly efficient heat recovery systems that can provide a good indoor climate with low heat consumption. Such houses would constitute good examples of energy-efficient buildings in the Arctic climate. In the Arctic, the design of an energy-efficient house needs to focus on detailed solutions with more site training and emphasis on the importance of each building component and system to reach the desired performance. In the Arctic, the commissioning methodology is an extremely important process that has to evaluate all details and systems in a building to ensure that the performance intended is realizable in the extreme climate.

The LEH in Sisimiut will continue to serve as a learning, exhibition and knowledge centre for everyone interested in the Arctic region of Greenland. The building has become a spin-off project for other projects, e.g. *"Models of energy performance of low-energy houses"* in DTU's Mathematics Department and has inspired the making of an energy-efficient dormitory in Sisimiut.

7 Acknowledgment

We would like to thank the Villum Foundation for supporting the development of the LEH, Lars Due, of Isolink ApS, for carrying out the blower-door tests in the house, and all the people and companies in Sisimiut who have contributed to the LEH. The article is part of the PhD project *"Passive Houses for Arctic Climates"* at the Technical University of Denmark.

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Paper IV: Passive houses in the Arctic. Measures and alternatives

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Passive houses in the Arctic. Measures and alternatives

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Abstract

The Arctic areas have an extreme weather, low humidity in winter and limited energy resource. Also the big problems are the remote areas in Arctic or Antarctic areas. The local building traditions have not been changed for past several decades, the new information with technologies/techniques do not reach the areas fast or even at all, the transportation costs are often the largest number on the bill. The first task is to use a fundamental definition of Passive house and implement it in a challenging arctic climate in Greenland. A hypothesis of using Passive house in Arctic will be introduced where the focus will be put on possible ways of achieving heating energy consumption of maximally 15 kWh/(m²·a) or heating load of maximally 10 W/m²; together with the overall primary energy demand maximally 120 kWh/m².year. In principle, the fundamental concept of Passive house in such a challenging climate could be achieved and this paper will suggest measures to reach this goal, but will also consider the initial energy spent and the investment costs (building material and transportation costs). Secondly it is considered, what could be “the” energy- and cost optimal concept in Greenland, accepting it might not necessarily be the passive house concept.

Keywords

Passive house, Arctic climate, internal gain, energy consumption

1 Introduction

Passive houses were designed and successfully implemented in Germany and other European countries as a highly insulated, air-tight, and healthy construction where thermal comfort can be achieved solely by post-heating (post-cooling) of the fresh air mass. Currently the Passive house is being implemented also in colder regions. This paper summarises what it takes to build Passive house with the same fundamental definition in Arctic climate zones and discusses alternatives to the Passive house for extreme climates.



Fig. 1. Arctic, roughly (Arctic Polar Circle – blue colour, tree line – green colour, and permafrost – red colour) and Sisimiut

The Arctic is described by either a geographical or a climatological definition [1]:

1. The geographical definition is by *Polar Circles* (Arctic and Antarctic), which are at $66^{\circ}33'38''$ Northern respectively Southern latitude.
2. In climatology is used a more “functional” definition, as the Arctic is defined in terms of the *treeless zone of tundra* and the regions of *permafrost* in Northern Hemisphere. These are the locations where the average daily summer temperature does not rise above 10°C , the edge of the habitat at which the trees are capable to growing, and the soil is below 0°C for two or more years.



Fig. 2. Settlement in Greenland, Iltoqqortoormiit with about 500 inhabitants. Photo: Hannes Grobe, AWI / Wikipedia

For calculation later is used climate data for Würzburg in Germany (longitude 9.57°E , latitude 39.48°) and for Sisimiut in Greenland (old name: Holsteinsborg, longitude -53.40°E , latitude 66.55°). Weather data were obtained from Meteonorm [2].

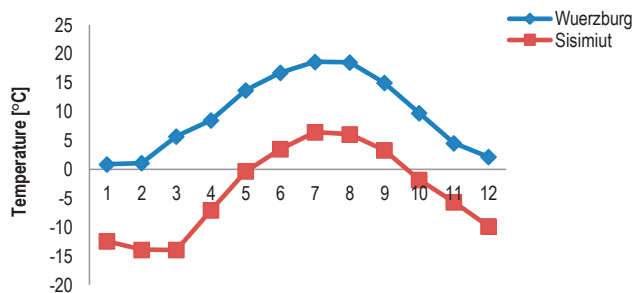


Fig. 3. Temperature in Würzburg, Germany and Sisimiut, Greenland

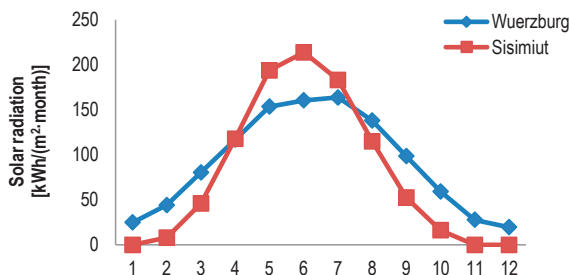


Fig. 4. Solar radiation (global horizontal) in Würzburg, Germany and Sisimiut, Greenland

2 Passive house - functional definition

The fundamental concept of delivering all space heating just by heating the fresh air (no conventional active heating) [3] can only work if even the highest immediate heat demand is very low.

To illustrate the influence of the climate, we look at the well-documented row houses in Darmstadt-Kranichstein (end of terrace). In standard German climate they reach a space heating demand of 14 kWh/(m²·a) and heating load of 10 W/m²; but when placed in Sisimiut, Greenland, the specific space heat demand raises up to 52 kWh/(m²·a) and heating load is 21 W/m². In order to reach the same space heat demand and heat load in Sisimiut, it would take increased insulation thickness etc.:

Table 1. Passive house Kranichstein construction for Germany and Greenland

Kranichstein house	Darmstadt, Germany	Sisimiut, Greenland
Wall insulation	275 mm with $\lambda=0.040$ W/(m·K)	600 mm with $\lambda=0.033$ W/(m·K)
Roof insulation	400 mm with $\lambda=0.040$ W/(m·K)	800 mm with $\lambda=0.040$ W/(m·K)
Floor insulation	250 mm with $\lambda=0.040$ W/(m·K)	400 mm with $\lambda=0.040$ W/(m·K)
Windows	$U_g=0.7$ W/(m²·K) $U_i=0.59$ W/(m²·K) $g=0.5$	$U_g=0.33$ W/(m²·K) $U_i=0.36$ W/(m²·K) $g=0.39$
Heat recovery efficiency	83%	92%
Window area to A_{TFA}	28%	18%

With these significant changes (e.g. total thickness of outer wall then 0.81 m), the Passive house in Arctic according the fundamental concept could in principle be implemented.

The building materials with the best thermal conductivity suitable for Arctic might be e.g. vacuum insulation panels with $\lambda = 0.004 \text{ W/(m}\cdot\text{K)}$ or polyurethane foam with gypsum boards with $\lambda = 0.020 \text{ W/(m}\cdot\text{K)}$, and the Arctic could be used as a “laboratory” for more temperate climates with testing of buildings materials and technologies, as it is already a test facility for cars!

Anyhow for the single building project it might still, economically, be more feasible to use cheaper insulation materials and take advantage of the fact that the regions are so scarcely populated that the thicker insulation will also fit.

Note: The article is primarily focused on residential dwellings and on specific heat demand of $15 \text{ kWh/(m}^2\cdot\text{a)}$ and heating load of 10 W/m^2 . The total specific primary energy demand (limit $120 \text{ kWh/(m}^2\cdot\text{a)}$) is less influenced by the climate.

3 Importance of circumstances

The internal heat gains are important factors in Passive houses. In e.g. Greenland different circumstances might justify a different number for the internal heat gains:

- The dwelling area per person is significantly smaller than in e.g. Denmark and Germany and thus internal heat loads are distributed on less area.
- The smaller dwelling area also means that ventilation per area ideally is higher.
- The need for artificial lighting might be different, though different factors pull in different directions: The outside ground surface in Greenland would usually be snow-covered in winter and thus highly reflective. The sun will be above the horizon for fewer hours. Cloud cover varies for each location. Due to reduced living area there will be less area to light. Table 2 shows some central numbers to the dwelling area.
- We believe that there might be significant differences in the contribution from *cooking* to the internal heat load but we lack concrete references to confirm this belief.
- Different use patterns – are people in Greenland more or less indoor at home?
- There might be different *expectations* for indoor climate though indoor climate research has proved that ideally the sense of thermal comfort is the same for all people (adaptive thermal comfort).
- Different sources already claim different numbers for the internal heat load, varying from 2 to 8 W/m^2 [4], [3], [5], [6]

It is not clear how precise all of these numbers are and it more points to the fact that the internal heat gain must be considered carefully for different locations with different circumstances.

Table 2. Reference Statistic for Germany [7] and Greenland [8]

	Total	Germany	Greenland
Total	Living area [m ²]	3,421,384,000	1,445,900
	Number of people	80,060,200	57,500
	Number of dwellings	38,971,200	22,100
Per unit	Living area [m ² /person]	41.6	25.1
	Average floor space [m ² /dwelling]	86.1	65.5
	Average no. of inhabitants per dwelling	2.1	2.6

4 Example

Based on PHPP we do a little model calculation.

- The positive internal heat gain is divided in: occupancy, cooking, lighting and household appliances (and DHW, cool down tank, electricity, waste heat).
- At a norm contribution of 80 W/person, and presence 55 % of the time for 8 760 hours a year, Table 3 gives the approximate internal heat gain from people.
- Use for cooking 0.20 kWh/use (frequency 500 times per person per year). Lighting - norm demand 21 W, 8 hours per day.
- Lighting frequency is calculated using luminance data for Sisimiut from Meteonorm. The standard of required hours (per person and day) for Greenland (Sisimiut) is calculated as the sum of hours per year and the inside minimum luminance is set to be 200 lux by a daylight factor of 2 % (below 200 lux the lighting is assumed to be switched on). The hours, when inside luminance is lower than 200 lux, are summed up and subtracted 8 hours per day for zero demand when the inhabitants are asleep. This sum is for Sisimiut 3 285 hours per year or some 9 hours a day. (For Würzburg the total hours is 2 799 per year or some 8 hours a day).
- The household appliances are assumed to be the similar as in Europe.

Table 3. Internal heat gain – People, Cooking and Lighting

	Location	Number of persons [p]	Living area [m ²]	Availability [-]	Specific heat demand [W/m ²]
PEOPLE	Germany	2.1	86.1	0.55	1.073
	Greenland	2.6	65.5	0.55	1.747
COOKING	Germany	2.1	86.1	500	0.174
	Greenland	2.6	65.5	500	0.283
LIGHTING	Germany	2.1	86.1	2.920	0.171
	Greenland	2.6	65.5	3.285	0.278

Table 4. Internal heat gains [W/m²]

Internal heat gain	Germany	Greenland
Household appliances	0.651	1.060
Persons	1.073	1.747
Cooking	0.174	0.283
Lighting	0.171	0.278
Total	2.069	3.368

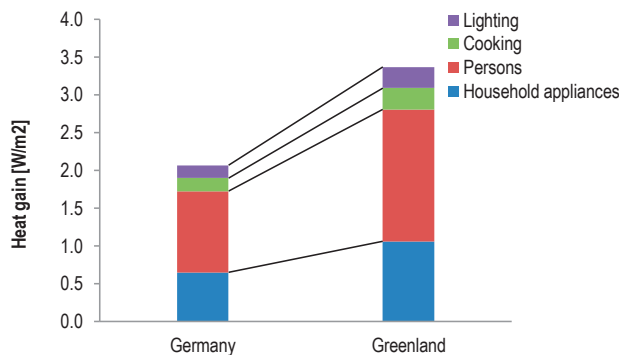


Fig. 5. Heat gain for Germany and Greenland

5 Alternative optimizations

We have looked at what it takes to implement the fundamental passive house concept in the case of the end row house from Kranichstein if it were relocated to Sisimiut in Greenland. Closer studies of the internal heat load and ventilation demand might justify a higher heat demand and heat load, but it is not a natural law that this would also be optimal in such different locations. Not only might internal heat load, use and expectations be different, but also energy supply, security, tax structure and energy distribution grid can be very different. For instance the population in Greenland is very scarce and there are numerous small electricity grids. It might therefore also make sense to look at optimisation of these whole, small systems, including hydro power, wind and geothermal heat sources or heat storage. We suspect that such an optimisation would not give precise guide lines as to insulation level of the single houses, but some minimum level will be advisable to take thermal comfort as well as security by unsteady supply into account.

6 Discussion

What can influence on the understanding of what is a passive house? We might not mind smaller differences in dwelling area between e.g. France, Germany, Denmark and Finland but just agree that a passive house as a standard is calculated with 35 m² net area per person as in the certification scheme. But with bigger differences, perhaps even cultural, from Denmark to Greenland, what could or should this imply?

A passive house can in principle be possible to make everywhere, but the climate in e.g. Greenland is so different that it is not given that the passive house concept is the most optimal concept there, regarding insulation level and payback time for saved energy is high considering the local prices for energy.

Therefore, a more pragmatic solution would be reasonable where the fresh air heating has to be combined with a more conventional type of heating (depending on available renewable sources). Using optimum of insulation and best available Passive house technologies and materials and with

clever and compact structure with minimum ventilation loss and still maximum facade expose to solar radiation, good and practical solutions could be reached.

What about political climate, and the individuals' expectations for the indoor climate? How does extreme outdoor climate influence on the acceptance of variations in indoor climates? And how does "adaptive comfort" apply to very cold climates.

7 Acknowledgment

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Paper V: The energy potential from the building design's differences between Europe and the Arctic

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The potential for energy efficient building design - differences between Europe and the Arctic

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Abstract

The design of a highly energy efficient building is closely connected to the climate conditions. The article deals with the way of designing buildings for the Arctic where very often the knowledge and experiences from European conditions are adopted. The aim is to investigate which design parameters can be adopted in the Arctic, what needs to be altered to reach an energy efficient building, and what is the sensitivity of various design parameters to the potential on energy savings.

A new and energy efficient dormitory called "Apisseq" has been constructed in the town of Sisimiut, Greenland, as an ambitious project which will focus on minimal energy consumption. This will be documented using an extensive monitoring system with energy meters, indoor climate sensors and sensors built-in to constructions. The model of a dormitory is used for the investigation of key parameters that could decrease the energy demand, and inspiration and comparison are made with a passive house model such as a passive house Kranichstein in Darmstadt, Germany. Several investigations are performed: the necessity of air-tight constructions which are free of thermal bridges and the potential to use gains from sun that shines at shallow angles. Furthermore, the investigation of optimized energy consumption is analyzed in order to reach the most suitable solution for energy efficient building for Arctic climate.

Keywords

Building design, Arctic, Europe, energy potential, passive house

1 Introduction

The design of buildings in the Arctic Greenland is influenced by the climate characteristics, availability of building materials, and knowledge of building technologies and techniques. The natural resources are very scarce in Greenland and everything must be imported and delivered to the building site by ship or plane due to the long distances and no roads. The Greenlandic Building Regulations are derived from the Danish Building Regulations and applied with a delay of some years and not entirely taking into account the climatic differences between Greenland and

Germany. For building of energy efficient buildings it is essential that skilled labour is employed but the education in energy efficient building technologies is not widespread in Arctic countries. For the region north of the Polar Circle, the current Greenlandic Building Regulations [1] stipulates a maximum annual consumption of energy for heating of 185 kWh/(m²·a) or requirements on maximum U-values for walls, doors and windows as in Table 2 and a maximum window/floor area of 22%.

When designing the energy efficient buildings for the Arctic the conditions needs to be considered regarding outdoor temperature, solar pattern, local building techniques and user habits. The weather in Sisimiut, Greenland (latitude 66.6°N, longitude 53.4°E), is quite different from Darmstadt, Germany (latitude 49.5°N, longitude 8.4°E). The heating degree hours calculated using the PHPP formula [2] with $T_{base} = 16^{\circ}\text{C}$ for Sisimiut are 146.3 kKh/a compared to 79.8 kKh/a in Darmstadt. The monthly average temperatures varies between from -14.0°C to 6.3°C in Sisimiut while for Darmstadt the variation is from 0.7°C to 18.9°C making roughly Sisimiut climate as “twice as cold” as Darmstadt. In the Arctic, there is significantly more radiation on vertical surfaces because of the shallow solar angle (Table 1). In Sisimiut there are days in winter where the sun does not dawn, while the summer has days where the sun does not set. This facilitates good possibilities for passive solar gains through (vertical) windows in Arctic buildings in other seasons than the winter.

Table 1. Annual solar radiation on a vertical surface

	Solar radiation on a vertical surface [kWh/(m ² ·a)]			
	South	East	West	North
Darmstadt	949	652	653	362
Sisimiut	1,019	815	839	442

2 New dormitory Apisseq

The dormitory “Apisseq” (which means “polar bear’s pit”) was inaugurated in November 2010. The energy monitoring of the dormitory starts in the beginning of 2011. The new dormitory has a gross heated floor area of 1,435 m² (A_{gross}) and accommodates 40 students, mainly in single-room apartments but also with a few three-room apartments with the treated floor area is $A_{TFA} = 1,134 \text{ m}^2$ calculated in accordance with [3] and the gross volume of the building is $V_{gross} = 4,382 \text{ m}^3$. The building consists of three quarters of a ring that circumscribe a protected courtyard (Fig. 1). In the centre of the building, facing the inner courtyard is a glazed atrium which contains a main staircase and common facilities. Access to the apartments is from canopied balconies made from a suspended steel structure, which also faces the courtyard.

The building has a load bearing structure of inner concrete walls and floors. The external walls are lightweight insulating constructions made from vertical wooden I-beams of 150 mm and mineral wool in between, which are fastened so they pass on the outside of the concrete structure. Furthermore, the exterior walls have on the inside 2 x 70 mm of insulation. On the exterior wall 9 mm gypsum is placed as wind breaking layer behind a ventilated cavity, and on the interior side is

the vapour air tight barrier. The external floor of the insulated building envelope is made from 50 mm of mineral wool and below is an unventilated space for horizontal installation of another 100 mm mineral wool insulation. The ceiling to the cold attic is made from 2 layers of 150 mm of insulation lying on the top of concrete ceiling of 180 mm. The windows are 2 layers glazing with U-value 1.1 W/(m²·K), with “warm edge” frames supplemented with third removable glass layer from inside. The exterior doors have the U-value of 1.8 W/(m²·K). The building’s heating is delivered by a floor heating system, by radiators, and from the town’s district heating system. The ventilation system supplies the building with fresh air with after-heating up to 18°C and for exhausting the used air, and the heat is recovered with an efficiency of 75%. Solar energy contributes to heating the domestic hot water as well as partly to the room heating.



Fig. 1. Dormitory Apisseq in Sisimiut, Greenland

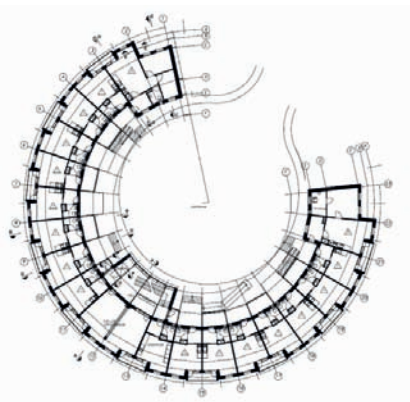


Table 2. Calculated U-values of different constructions compared to GBR 2006 [1]

Construction	Insulation thickness [mm]	U-value calculated [W/(m ² ·K)]	U-value demand [W/(m ² ·K)]
Floor	50+100	0.13	0.15
Wall	290	0.15	0.20
Roof	2*150 mm	0.13	0.15

2.1. Energy demand

The annual heat loss is calculated to be approximately 150 kWh/(m²·a) based on the Danish Standard DS 418 [4] for calculating design heat loss and the heating degree hours that closely follows the the method [5]. Hot water consumption is calculated to be approximately 80,000 kWh/a, or 52 kWh/(m²·a). Annual production of solar energy is calculated to be 400 kWh per m² of the solar collector, or 40 MWh/a for the whole dormitory.

2.2. Monitoring system

A monitoring system is set up to continuously log the energy consumption, indoor climate, moisture in constructions, and the meteorological situation. A LonBOX system gathers the data about the building performance. A total of 9 Kamstrup energy meters are installed to measure the following: production of solar energy, energy transported from solar collectors to storage tanks and from

the tanks to the domestic hot water system, hot water consumption, circulation heat loss, hot water contribution to heating, district heating contribution and energy delivered from tanks to heating, and total heating consumption. Honeywell and Vaisala CO₂ sensors were chosen for registering the indoor climate (combined sensors for temperature and relative humidity, and CO₂). A total of 15 Vaisala sensors are built in to monitor the temperature and relative humidity at various places in the constructions. For meteorological measurements, a sunshine pyranometer is installed on the roof.

3 Methodology

The methodology of investigation is based on comparing two models: a model for the passive house “Kranichstein” located in Darmstadt, Germany, and a model “Aphisseq” for the dormitory located in Sisimiut, Greenland. The Kranichstein house [6] was built in 1991 and is an example of asuper-insulated, airtight house that utilises solar and internal gains so that only a very small amount of space heating is necessary, i.e. space heating demand of 15 kWh/(m²·a) when located in Darmstadt, Germany. The Kranichstein has $U_{\text{wall}} = 0.14 \text{ W/(m}^2\cdot\text{K)}$, $U_{\text{roof}} = 0.1 \text{ W/(m}^2\cdot\text{K)}$, $U_{\text{floor}} = 0.13 \text{ W/(m}^2\cdot\text{K)}$, and has triple pane glazing filled with krypton with $U_{\text{window}} = 0.7 \text{ W/(m}^2\cdot\text{K)}$, and the house is equipped with air-to-air heat exchanger with efficiency 80% and the measured air tightness of a building envelope is $n_{50} = 0.3 \text{ h}^{-1}$. That small amount of heating is supplied to the fresh air through the ventilation system with heat recovery, where the target for a passive house is to have a heating load that does not exceed 10 W/m² per treated floor area (A_{TFA}).

The passive house Kranichstein and the dormitory Aphisseq are used in a sensitivity analysis of separate parts of the dormitory’s building envelope to investigate if it could be enhanced to reach up to the passive house standard. The following is comprised in the analysis: level of insulation, air tightness and heat exchanger efficiency. Each parameter is improved to reach the equivalent effect as a passive house in the Arctic, and the potential energy savings is noted. Since the windows have influence on the heat loss, and at the same time contribute solar gains, the investigation of solar radiation potential is made for two geographical locations with different solar patterns: Darmstadt and Sisimiut. The task is to identify important design characteristics in the building design as key figures in the design. An optimized solution for an energy efficient building in the Arctic is proposed.

4 Results

4.1. Annual space heating demand

The building’s characteristics are important design factors including the amount of insulation, air tightness of the building envelope, performance of windows, and the ventilation and heating systems. As the insulation is one of the main parameters in the building design, the amount of insulation is investigated using the annual energy balance. Insulation thickness in the thermal bridge free construction is an important factor concerning the heating demand of the building. The amount of insulation necessary to reach a passive house requirement of annual space heating demand of 15 kWh/(m²·a) is investigated using the annual energy balance with the distribution of gains and losses (Fig. 2).

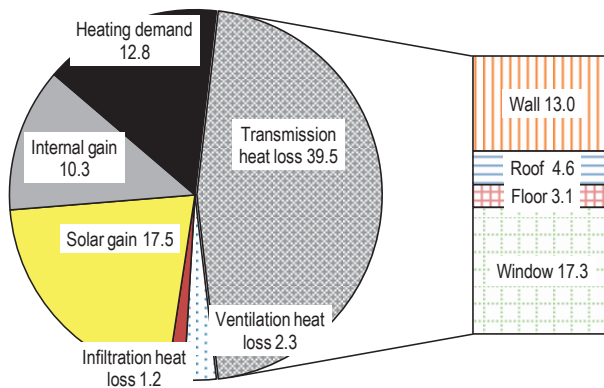


Fig. 2. Energy balance in kWh/(m²·a) with distribution of gains and losses of a passive house Kranichstein in Darmstadt

An example for the external wall is shown in Fig. 3, where for a passive house in Darmstadt, the transmission heat loss through the insulated building wall equals to 13.0 kWh/(m²·a) with $U_{wall} = 0.138$ W/(m²·K). If the Kranichstein house were located in Sisimiut and should obtain a transmission heat loss for the wall of 13.0 kWh/(m²·a), the wall U-value would need to be as low as 0.075 W/(m²·K). Due to the larger surface area of the building envelope, the equivalent U-value to reach a passive house standard for the Apisseq dormitory in Sisimiut would be 0.067 W/(m²·K).

Table 3 shows the same methodology applied to other of the building's components and systems. The energy savings for Apisseq show that the biggest potential to save the energy lies in minimizing the heat loss through the building envelope including windows, and improving the wall's characteristics is most beneficial.

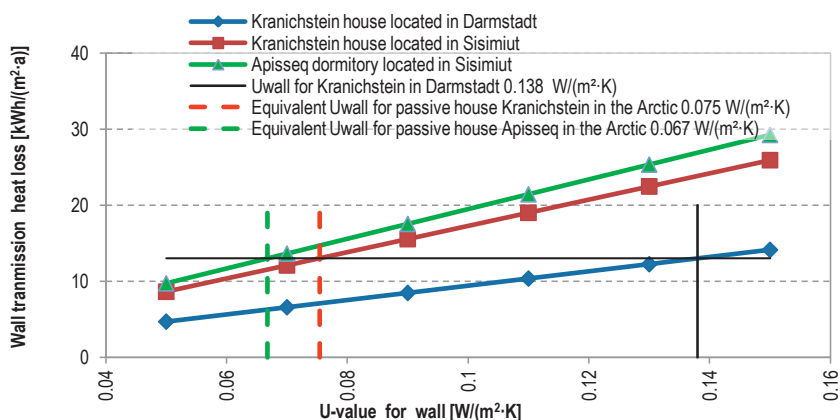


Fig. 3. Level of insulation for Apisseq compared to level of insulation for Kranichstein, and equivalent effects with values for locations in Darmstadt and Sisimiut

Table 3. Equivalents for improvement to a passive house standard and energy improvements for Apisseq from current state to passive house standards

State Location	Current state		Passive house		Energy improvements for Apisseq [kWh/(m ² ·a)]
	Kranichstein Darmstadt	Apisseq Sisimiut	Kranichstein Sisimiut	Apisseq Sisimiut	
U_{wall} [W/(m ² ·K)]	0.138	0.150	0.075	0.068	12.8
U_{floor} [W/(m ² ·K)]	0.131	0.130	0.041	0.038	6.1
U_{roof} [W/(m ² ·K)]	0.108	0.130	0.069	0.059	4.8
$\Psi_{\text{window/foundation}}$ [W/(m·K)]	0.010	0.03/0.25	0.010	0.010	4.5
Air tightness [h ⁻¹]	0.022	0.135	0.022	0.012	3.0
Heat exchanger [%]	80	75	90	90	4.1

The windows must have the best thermal performance, i.e. the lowest possible thermal heat transfer (U-value), but at the same time be able to obtain the highest amount of solar radiation, i.e. the window area should be optimal in size and orientation regarding transmission loss and solar heat gain. In the current situation, the balcony windows/doors are embedded in the façade in Apisseq with orientation of 22° distributed over various orientations on the façade of the circular building, and they contribute to the energy balance with 7,600 kWh/a of solar gains, and at the same time they have a total transmission heat loss of approximately 32,800 kWh/a with $U_{\text{window}} = 1.1 \text{ W/(m}^2\cdot\text{K)}$ and g-value = 0.56 with a shading factor F_s of 0.56. Fig. 4 illustrates the utilization of solar gains obtained from embedded window/door in balconies and other windows in a passive house Kranichstein located in Darmstadt and compare it to different levels of improved windows in Apisseq in Sisimiut for all window orientations.

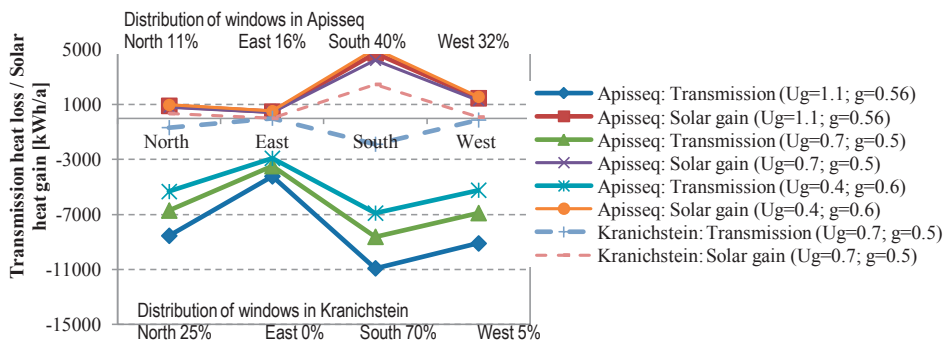


Fig. 4. Comparison of solar heat gains and transmission losses of the passive house Kranichstein in Darmstadt with similar values for the windows of the Apisseq dormitory in Sisimiut analyzing different scenarios for U_{glazing} and g-value

For the selection of windows it would be desirable to obtain the same amount of solar gain as what is lost by transmission through the windows. Full compensation of the transmission heat loss through windows can be done only in the European locations with current technologies, e.g. the transmission heat loss through a window with $U_{\text{window}} = 0.78 \text{ W/(m}^2\cdot\text{K)}$ in Darmstadt can be covered by using a glass with g-value 0.45-0.65 for south oriented windows. To cover fully the transmission heat loss in Sisimiut, i.e. to have a positive net energy gain, a super window with $U_{\text{window}} \leq 0.44 \text{ W/(m}^2\cdot\text{K)}$ with g-value ≥ 0.57 would have to be used for the south orientation (for

west and east orientation the g-value should be ≥ 0.95) and higher. The embedded balconies in Apisseq shade the solar gain with the resulting shading factor 0.56 while the windows on the outer façade have a shading factor F_s of 0.9.

The internal gain is calculated with 2.1 W/m^2 and for a Kranichstein it equals to $10.3 \text{ kWh}/(\text{m}^2 \cdot \text{a})$. The national standard for Greenland prescribes use of an internal gain of 5.0 W/m^2 and for Apisseq it equals to $24.5 \text{ kWh}/(\text{m}^2 \cdot \text{a})$. If the value 5.0 W/m^2 is used, the calculated annual internal gains can almost cover the missing solar gains.

4.2. Heating load

A passive house utilizes solar and other passive gain in the super insulated and airtight buildings so the heat peak heating load of the building is 10 W/m^2 . The design heat load in a passive house is calculated for the two special days: “Day 1” - a cold day with clear sky and “Day 2” - a moderately cold day with overcast sky. On such two design days there would be significant or moderate solar radiation in a European location, but in an Arctic location such days would have no solar radiation and could be represented as one day. Therefore the heating load has to be covered only by the internal gain, which in a passive house equals just 1.6 W/m^2 to represent the worst case situation when nobody is present in the house [2]. Fig. 5 shows the proportion of heat loss and gains when calculating the heat load and showing the contribution of different parameters.

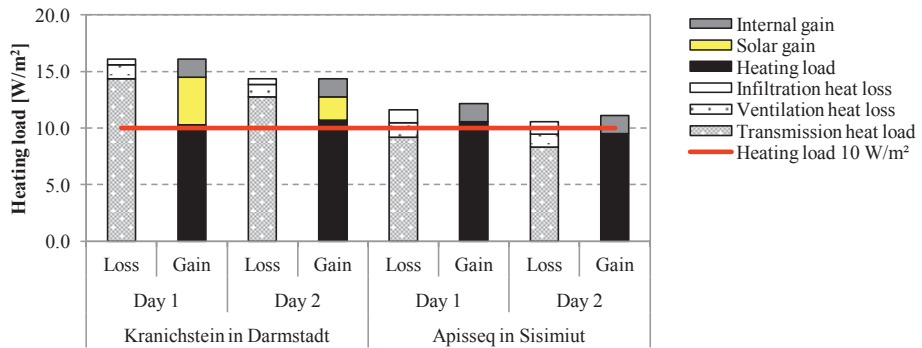


Fig. 5. Distribution of losses and gains for calculation of peak heating loads for the houses located in Darmstadt or Sisimiut

In the Arctic location, in order to reach a heating load as low as 10 W/m^2 on a design day without solar radiation, the transmission heat loss through the building envelope has the major impact. The most significant building parts are the windows and walls (Table 4). An unrealistically well insulating window with $U_{\text{window}} = 0.492 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ with shading factor $F_s = 0.56$ would have to be used due to the current building design with embedded windows in balconies or heat mirror windows together with the insulation thickness of 550 mm with thermal conductivity $\lambda = 0.025 \text{ W}/(\text{m} \cdot \text{K})$ or with traditional mineral wool insulation with $\lambda = 0.037 \text{ W}/(\text{m} \cdot \text{K})$ and insulation thickness of 900 mm.

Table 4. Building characteristics needed in order to reach a passive house standard of heating load 10 W/m^2

Location / Characteristics	Kranichstein in Darmstadt		Apisseq in Sisimiut	
	Day 1	Day 2	Day 1	Day 2
Design temperature [$^{\circ}\text{C}$]	-11.4	-7.5	-32.2	-26.9
Solar gain (North, East, South, West) [W/m^2]	11, 35, 90, 35	15, 20, 40, 25	0, 0, 0, 0	0, 0, 0, 0
U_{wall} [$\text{W}/(\text{m}^2\cdot\text{K})$]	0.138		0.042	
U_{roof} [$\text{W}/(\text{m}^2\cdot\text{K})$]	0.108		0.035	
U_{floor} [$\text{W}/(\text{m}^2\cdot\text{K})$]	0.131		0.035	
U_{window} [$\text{W}/(\text{m}^2\cdot\text{K})$]	0.777		0.492	
Infiltration [h^{-1}]	0.019		0.030	
Heat exchanger efficiency [%]	80		91	

4.3. Optimized energy design and consumption

Fig. 6 gives an insight into the current situation presenting the energy balances for a typical Greenlandic house, “Illoput” located in Sisimiut [7] and the Apisseq dormitory, compared to a passive house (located in Darmstadt, Germany). Typical new residential buildings in Sisimiut have only the insulation levels required by GBR 2006 and are usually not equipped with a ventilation system with heat recovery. Heating is provided by an oil-boiler, ventilation is secured by venting and exhausts fans in kitchen and bathroom, and the air tightness of the envelope is probably not very good. The passive house model of Kranichstein has a super insulated and very air tight building envelope, and the ventilation heat loss is reduced by efficient heat recovery system. The initial calculation of the energy efficient dormitory Apisseq shows that there is a potential for improvement if the building is made more air tight and the amount of insulation is increased. The annual space heating demand for a typical house is $230 \text{ kWh}/(\text{m}^2\cdot\text{a})$ [1], for a passive house $15 \text{ kWh}/(\text{m}^2\cdot\text{a})$ and for the dormitory Apisseq $150 \text{ kWh}/(\text{m}^2\cdot\text{a})$ as shown in Fig. 6.

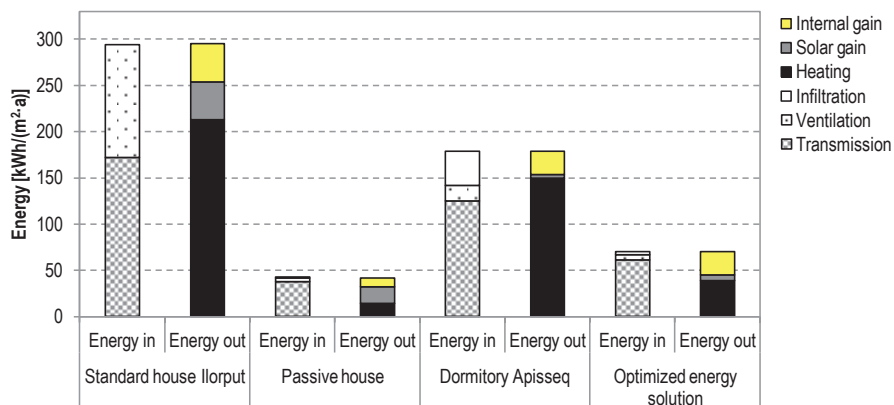


Fig. 6. Energy balance for a typical residential house, a new dormitory Apisseq and a passive house compared to an optimized energy solutions for the Arctic

The Apisseq investigations show that the largest potential lies in improvement of the building envelope. The question is to what limit the improvement of the building envelope should go. The optimized building solution from Section 4.2 would reach an annual heating demand $40 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ that would require the ventilation 90% with air change rate 0.3 h^{-1} (improvement of $12 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ from the current state), improved air tightness 0.135 h^{-1} to 0.021 h^{-1} (improvement by $33 \text{ kWh}/(\text{m}^2 \cdot \text{a})$), improved windows moved to the outer surface of the façade with $U_{\text{window}} = 0.8 \text{ W}/(\text{m}^2 \cdot \text{K})$ and $g = 0.6$ and $U_{\text{door}} = 0.8 \text{ W}/(\text{m}^2 \cdot \text{K})$ (improvement by $2 \text{ kWh}/(\text{m}^2 \cdot \text{a})$), and improved insulation properties to $U_{\text{wall}} = 0.07 \text{ W}/(\text{m}^2 \cdot \text{K})$, U_{floor} and $U_{\text{roof}} = 0.08 \text{ W}/(\text{m}^2 \cdot \text{K})$.

5 Discussion

The first step when building in the Arctic is to minimize the heat loss with the most optimal use of a building shape and insulation level. Often the cost of insulation governs the decision of what amount of insulation will be used rather than making decisions from a wider perspective. For example, a passive house offers more energy savings when using more insulation. The calculations show that the calculation of energy balance with annual method to fulfil the space heating demand of $15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ can be accomplished in the arctic city Sisimiut in Greenland. But the peak heat load of no more than $10 \text{ W}/\text{m}^2$ is more difficult to achieve on the design days as there is no solar gain, and therefore there will have to be used unrealistically high amounts of insulation to achieve it.

The investigations show that it is possible in the Arctic to fully cover the annual transmission heat loss with solar gains obtained from solar radiation only with very efficient windows that are not on the market yet. The most beneficial orientations for windows are also in Sisimiut that they are facing south, east and west. The dormitory building investigated in the paper has windows which are embedded behind balconies and in windows recesses. Putting the windows to the front of the facades would enhance the solar gains, but on the other hand the window's characteristics would be affected by high storms and the transmission heat loss would increase. Also the vertical shadings have to be installed to minimizing the risk of overheating and glare in the summer from the low angle sun.

6 Conclusion

A solution for a passive house may depend on the choice if one should focus on reaching the specified space heating demand of $15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$, or the demand that the peak heat load must not exceed $10 \text{ W}/\text{m}^2$ to be able to heat the building just by the air ventilation system. However, this solution would present an extreme solution in the Arctic as it would require using some unrealistic technical solutions. Nevertheless, whichever ambitious goal is chosen, the first step when designing a building in the Arctic should be to minimize the heat loss by applying highly efficient insulation. Along with insulation there must also be good air tightness of the building envelope, although this has hitherto not had enough focus in Arctic constructions. Other key elements are the utilisation of passive solar and internal gains, and the installation of a mechanical ventilation system with heat recovery. The heat recovery system is still not a normal part of the usual design strategy in the Arctic. When mechanical ventilation systems with heat recovery are used, it is critical that the

installations are properly carried out, and frost problems are avoided. The last key element of the building design is solar radiation which may offer a free heat gain that may be significant compared to the potentially large transmission heat loss through the windows. These key elements are well-known from buildings in other climates, but they are not less important for energy efficient buildings located in the extreme climates.

The passive house's qualities offering maximum comfort with minimum energy use are very desirable in the demanding climate of the Arctic, thus the specific target of a passive house is transferred to the Arctic. The further investigation has to focus on minimizing lifecycle costs and cost-effectiveness of a passive house in the Arctic. Technical and economical optimizations of efficient building elements for the Arctic could spin off further development of super energy efficient buildings for any climate.

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Paper VI: The study of an appropriate and reasonable building solution for the Arctic climates based on a passive house concept

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The study of an appropriate and reasonable building solution for Arctic climates based on a passive house concept

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Abstract

A passive house is a highly insulated building with an efficient ventilation system with heat recovery providing heating and a good indoor climate. The building is designed to utilize solar and internal gains in an effective way. Heating fresh air provided by a ventilation system means there is no requirement for a conventional hydronic heating system. The passive house concept has been successfully implemented in latitudes 40° to 60°, mainly in Europe. The most interesting locations for a passive house in the Arctic region were selected based on cross-investigation of population, location and weather data. The passive house was evaluated in various Arctic locations with regard to definition, boundary conditions and design parameters. The possible energy designs for a passive house were investigated with a view to use in the Arctic region. The optimal energy-efficient house for the Arctic was found by making building modifications to adapt the passive house to the Arctic climate.

Keywords

Passive house, Arctic climate, fundamental definition, optimization

1 Introduction

In the temperate climate countries, buildings currently account for approximately 40% of overall energy consumption. A substantial part of this energy consumption is used for heating. The average heating consumption amounts to about 160 kWh/(m²·a) in the existing building stock of central Europe [1]. For latitudes above 66°, the Greenlandic Statistics [2] show that the heating consumption for all buildings averages 416 kWh/(m²·a), and the Canadian Statistics [3] state that an average of 231 kWh/(m²·a) is used for heating in residential building in Canada. So it is not surprising that there is increased focus on energy efficiency in the design and use of buildings. There are many kinds of energy-efficient buildings: low-energy, 0-energy, energy+, active, ultra and passive houses (Fig. 1), among many others.

Passive houses (PH) have been successfully implemented in locations latitude 40° to 60°N. Examples include a semi-detached family house built in 1990 in Kranichstein (Darmstadt,

Germany, latitude 49.5°N) following a conventional passive house principle [4]. This house design will be used for comparison later in the article where it will simply be referred to as the “Kranichstein” passive house. Most examples of passive or energy-efficient houses in Arctic climates can be found around latitude 66°N. The I-Box 120 built in Tromsø (2005, Norway, latitude 69.4°N) was a prototype for the first Norwegian certified passive house [5], and the Talo Salomaa built in Littoinen (2009, Finland, latitude 60.0°N) was the first certified passive house in Finland [6]. Another example is the futuristically designed Belgian polar research station, the Princess Elisabeth Antarctica (2009, Antarctica, latitude 70.4°S), which functions as a passive house in the Antarctic summer [7]. Two examples of experimental buildings situated high in the mountains are the Schiestlhaus (2005, Hochschwab, Austria, latitude 47.4°N) demonstrating the possibility of a sustainable and energy-efficient building in the Alps at an altitude of 2,153 m [8], and the new eco-hut Monte Rose (2009, Zermatt, Switzerland, latitude 45.5°N), which is equipped with several different energy systems at an altitude of 2,795 m [9].

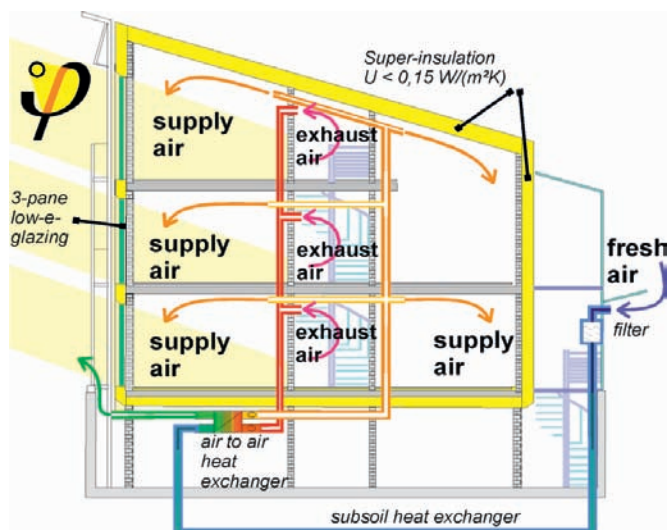


Fig. 1. Scheme of a passive house principle (source www.passivhausgestaltung.de [4])

Our research is focused on building design and building practices in cold climates, passive houses at various latitudes, and the implementation of the passive house concept in extremely cold climates. We reviewed the technical and non-technical aspects described as measurable and qualitative objectives. These investigations and calculations constituted the basis for our analyses comparing the actual Kranichstein passive house [4] with traditional residential buildings in the Arctic, such as detached and semi-detached family houses, and multi-family residential houses. The research did not focus on a specific building design or end-solution, but on analyses from various different angles and on discussion of the possibilities of using a passive house solution. Our basic motivation is not to define something new and call that a “passive house”, but actually to take relevant experience and implement them in building construction in the Arctic.

2 Information on the Arctic and Antarctica

2.1. The Arctic and Antarctic regions

The Arctic and Antarctica are described as *geographical locations* with certain *climatological definitions* [11]. The geographical locations are defined by the *Polar Circles* of the Arctic and Antarctic, both are at latitude 66°33'44". The areas above / below the Polar Circles constitute 5.6% of the surface area of the Earth, and have 0.06% of the population of the world, i.e. 3,997,400 in the Arctic and 1,000 to 5,000 in Antarctica. In climatology, the Arctic is defined in terms of the *treeless zone of tundra* and regions of *permafrost* in the northern hemisphere. These are regions where the mean daily temperature does not rise above 10°C, and where the line of the habitat is defined by the trees which are capable of growing, and the soil temperature is below 0°C for two years or more. If we combine the geographical and climatological definitions, the Arctic consists of Greenland, Iceland, and northern parts of Finland, Sweden, Norway, Russia, Canada, and the United States (Alaska), as well as the North Pole with the surrounding Arctic Ocean. The Antarctic region is represented by Antarctica including the South Pole.

The Arctic climate is characterized by a high spatial and climate variability. The coastal continental regions are influenced by the ocean, and the winters in these areas are cold and stormy. The summers are cloudy but mild with mean July temperatures around 10°C. Annual precipitation is generally between 60 cm and 125 cm, mostly falling as snow. The inland continental regions have more severe winters with less precipitation. The land is mostly covered by a great depth of permafrost, which often thaws only down to 2 metres in summer. Temperatures can rise above 10°C in the three summer months, but in the period of the highest energy demand in the Polar Regions (winter), there is little or no available solar energy.

Table 1

Selected locations between 66°–75° in the Arctic and Antarctic regions compared to selected locations between 40°–55° latitudes, listed by latitudes

Location	Coordinates [°]	HDH [kKh/a] ⁽¹⁾	Mean annual (coldest monthly and daily) temperatures [°C] ⁽³⁾			Global radiation horizontal Gh [kWh/(m ² ·a)] ⁽³⁾	Solar radiation on vertical surface (South, West, North, East) [kWh/(m ² ·a)] ⁽³⁾				
		PHPP [kKh/a] ⁽²⁾									
Würzburg, GE	49.5°N, 9.6°E	95 / 80	9.6	0.9	-10.6	1,087	914	695	371	692	
Harbin, CH	45.5°N, 126.4°E	149 / 140	2.8	20.3	-32.3	992	1,534	980	494	992	
Fairbanks, USA	64.5°N, 147.4°W	199 / 170	-2.9	-23.4	-43.8	1,040	1,336	885	409	877	
Oulu, FI	65.1°N, 25.3°E	156 / 124	2.1	-11.0	-29.8	841	927	667	354	673	
Sisimiut, GL	66.6°N, 53.4°E	209 / 146	-3.9	-18.5	-32.0	945	1,019	839	442	815	
Sodankylä, SE	67.3°N, 26.3°E	183 / 143	-1.0	-15.1	-37.6	816	883	648	310	644	
Kiruna, SE	67.8°N, 20.3°E	185 / 138	-1.1	-13.9	-33.2	748	616	438	295	411	
Inuvik, CA	68.2°N, 133.3°W	256 / 206	-9.3	-28.5	-47.5	923	1,193	866	464	870	
Murmansk, RU	68.6°N, 33.0°E	177 / 132	-0.3	-11.6	-31.7	724	824	618	348	610	
Barrow, USA	71.2°N, 156.5°W	233 / 163	-12.5	-27.7	-44.1	725	397	700	447	695	
Uummannaq, GL	70.4°N, 52.1°E	211 / 145	-4.1	-16.2	-33.5	779	726	623	379	641	
Resolute, CA	74.4°N, 94.5°W	319 / 233	-16.5	-33.0	-45.3	921	1,314	1,023	670	1,017	

⁽¹⁾ HDH = heating degree hours calculated as HDD [Kd/a] = 0.024 x HDH [kKh/a] ($T_{base} = 20^{\circ}\text{C}$); ⁽²⁾ PHPP method (16°C and 10°C); ⁽³⁾ representative collection of data from PHPP, DRY, METEONORM; grey colour is inland

The combination of population, climate profiles and location data indicates the most interesting climates and regions to focus on, i.e. the areas between latitudes 66° and 70°N with some 90% of the permanent inhabitants of the Arctic region. The remaining 10% of the population lives in latitudes 70° to 75°N. Due to their very cold climate, inland locations between latitudes 60° and 66°N also represent the potential locations of interest with a population of 15 million. Locations such as Harbin in China and the high altitude mountain locations have extremely cold climate too, but only a limited number of inhabitants. Antarctica also has a very small population. So locations between latitudes 60° and 75°N seem most relevant for passive houses designed for Arctic conditions. Table 1 lists selected locations at these latitudes providing basic information about climate along with heating degree-hours (*HDH*) and data using the PHPP method [12].

2.2. Building practices in the Arctic regions

The Arctic and Antarctic regions have few natural resources which can be used as building materials and limited skilled labour. The building practices and codes are usually transferred from developed regions, e.g. from Denmark to Greenland and from central Russia to northern Russia, often depending on the sources and distances involved. The design approach for building in the Arctic region is based on designing the house for outdoor winter temperatures, i.e. the lowest temperature expected at the building location. Furthermore, the building design focuses on minimizing heat loss before exploiting possible gains (solar, internal), elevated foundation due to permafrost settlement, and the use of a cold entrance as an “air lock” to protect the heated area from cold air entering, amongst other things.

There is limited focus on sealing the windows to the envelope of the building, the quality of the insulation, and the details of the building cladding. Heating and hot water are usually supplied by an oil-fired boiler or, alternatively, an electric heating system is installed. Very common is the use of traditional natural ventilation through openings or micro ventilation. The use of mechanical ventilation systems with heat recovery is not common, because a heat exchanger needs to be able to deal with defrosting and preheating of supply inlet air. The characteristics of a traditional building envelope and its technical systems clearly indicate that some existing practices need to be changed and/or the level of quality needs to be improved.

3 The passive house

3.1. Definition of a passive house

The idea of a passive house originates from the research carried out by Bo Adamson in the late 1980s. In China, some areas have limited access to fuel, so some of the buildings had no heating system and were called “passive houses” [21]. The concept of a passive house was worked out by Wolfgang Feist, the founder of the Passivhaus Institute (PHI) in the 1990s [4]. The term “passive house” (*Passivhaus* in German) describes a super-insulated building with highly insulated windows, no thermal bridges, and an airtight building envelope. The building has a balanced heat recovery ventilation system, and is equipped with energy-efficient building services supplied with renewable energy [13]. The notion of passiveness refers to a fundamental concept of delivering all the space heating with fresh air via a ventilation system with efficient heat recovery, thus, saving the installation costs of a traditional heating system [14, 21].

3.2. Requirements of a passive house

The usual passive house requirements apply in Central Europe and countries with similar climates. The definition itself does not depend on climate and applies for latitudes between 40° and 60°N. The requirements of a passive house are an annual heating / cooling energy demand of $\leq 15 \text{ kWh}/(\text{m}^2\cdot\text{a})$ for a new building and, for conversions to passive-house standard, $\leq 25 \text{ kWh}/(\text{m}^2\cdot\text{a})$. The heating / cooling load must be $\leq 10 \text{ W}/\text{m}^2$ and the total primary energy demand must not exceed $120 \text{ kWh}/(\text{m}^2\cdot\text{a})$. All values refer to the so-called “treated floor area” (A_{TFA} [15]). The documented air change rate of a building envelope must $n_{50} \leq 0.6 \text{ h}^{-1}$ @ 50 Pa.

There are boundary conditions and design rules for passive houses that do not depend on climate, including an interior design temperature of 20°C with a frequency of overheating $\leq 10\%$ ($T_i = 25^\circ\text{C}$), and an internal heat gain of $2.1 \text{ W}/\text{m}^2$ (people, household appliances, lighting). Ventilation has to be provided by a balanced mechanical system with highly efficient heat recovery $\geq 75\%$, minimal electrical consumption, and an air change rate $\leq 0.4 \text{ h}^{-1}$ (the average air flow rate per a room must be 20–30 m^3/h or national requirements if higher). The air temperature supplied has to be $\leq 52^\circ\text{C}$ and be delivered through well insulated ventilation ducts.

The fundamental PH definition for central European and central US climates (latitudes 40°–60°N) makes the following recommendations for the building envelope in temperate climates: $U_{\text{envelope}} < 0.15 \text{ W}/(\text{m}^2\cdot\text{K})$ for ceiling, wall and floor, and $U_{\text{window}} < 0.8 \text{ W}/(\text{m}^2\cdot\text{K})$ for windows, with insulated frames and triple pane glazing with low-e coatings, insulated frames, and window glazing with solar transmittance $g \geq 0.5$ along with required air tightness of the building envelope. The indoor climate, heating and ventilation has to be provided by a ventilation unit with heat exchanger with a temperature efficiency of $\eta \approx 80\%$. The total primary energy demand must be below $120 \text{ kWh}/(\text{m}^2\cdot\text{a})$, including hot water consumption of $10\text{--}15 \text{ kWh}/(\text{m}^2\cdot\text{a})$ and electricity $10\text{--}15 \text{ kWh}/(\text{m}^2\cdot\text{a})$.

4 Methodology and scope of investigations

To optimize the *performance* of a passive house designed for the Arctic climate, we used *single-objective*, *multi-criteria* and *qualitative* methods. We distinguished between *measurable* and *qualitative objectives*. *Measurable objectives* are the energy performance values that can be improved to achieve energy-efficient buildings. These are: heating demand, minimizing heat loss and maximizing solar gains via relevant building elements within the practical limits of the construction, air heating, and ventilation efficiency. *Qualitative objectives* are more subjective, but they can still be measured: lifestyle preferences, thermal indoor comfort, temperature stability, and the sustainability value of the insulation, socio-economic conditions, culture gap, and energy supply.

We put the focus on a building in a specific climate, building boundaries and design solutions, and other non-technical factors. The results show the special challenges for a passive house in the Arctic climate, such as the heating load and the possible necessity of having a heating system, and we discuss the need to establish the proper level of the solar and internal gains. We also discuss to what extent building elements should be used that can deliver the extreme improvements essential

for normal passive-house standards to be fulfilled. And we point out the possible adaptations needed for a passive house to achieve the most reasonable solution in the Arctic.

5 Results

5.1. Passive houses in the Arctic

5.1.1. Performance of a passive house in the Arctic

We investigated the performance of a passive house by using the “Kranichstein” model in various locations characterized by different climates. This included analysis of the distribution of the space heating demand, transmission, ventilation and infiltration heat losses, and solar and internal gains in accordance with EN 13790 [16]. An investigation of what it would take to enable a passive house in Greenland to achieve $15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ and/or $10 \text{ W}/\text{m}^2$ was carried out for several Arctic locations and for two models: the first with the values and parameters of passive houses, and the second using Danish / Greenlandic national standards and building techniques. The Danish / Greenlandic national values selected were representative of houses in the Arctic region and involved adequate building techniques using lightweight building structures on elevated foundations, limits on window / floor area ratios, increased ventilation rate and internal heat gains.

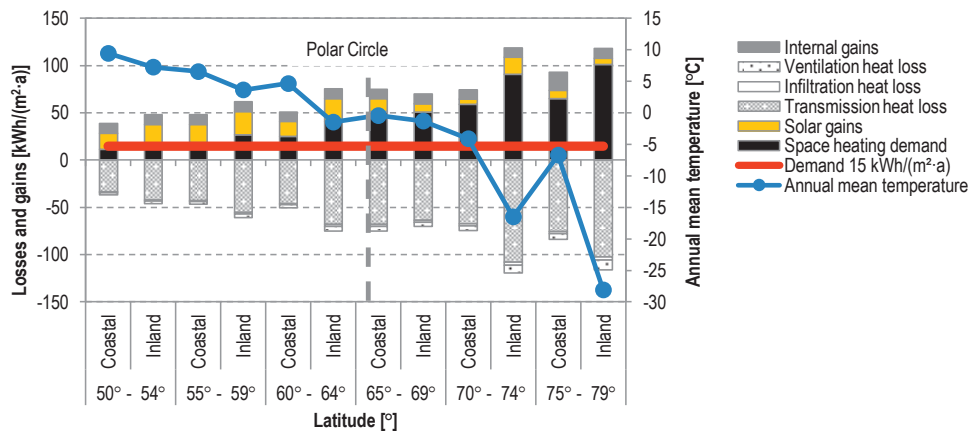


Fig. 2. Annual energy balance and space heating demand of the Kranichstein passive house in different latitudes

At latitudes between 55° and 79°N , there is a marked temperature difference between coastal and inland locations. A coastal location usually has a milder climate than an inland location. As we move north, this difference results in much higher transmission losses for inland locations (Fig. 2). In northern locations, windows also need to be designed for the different solar pattern of sun rays at a shallow angle and the absence of solar radiation in winter. The size, orientation and thermal properties of the windows must give the lowest possible transmission losses. The standard value of $2.1 \text{ W}/\text{m}^2$ for internal gains in a passive house will vary due to the different climate and lifestyle in the region.

The investigation of the heating load (W/m^2) calculated in accordance with EN 12831 [17] for a “Kranichstein” passive-house model shows (Fig. 3) that above latitude 65°N there are almost no possible solar gains on the design days. The heating load is mainly due to the transmission heat loss, which has the greatest impact on the results, while the ventilation and infiltration heat losses are very low, once the internal gain contribution of 1.6 W/m^2 has been subtracted. There is a need for a low temperature heating source capable of delivering more than 10 W/m^2 and to use the passive house in the Arctic.

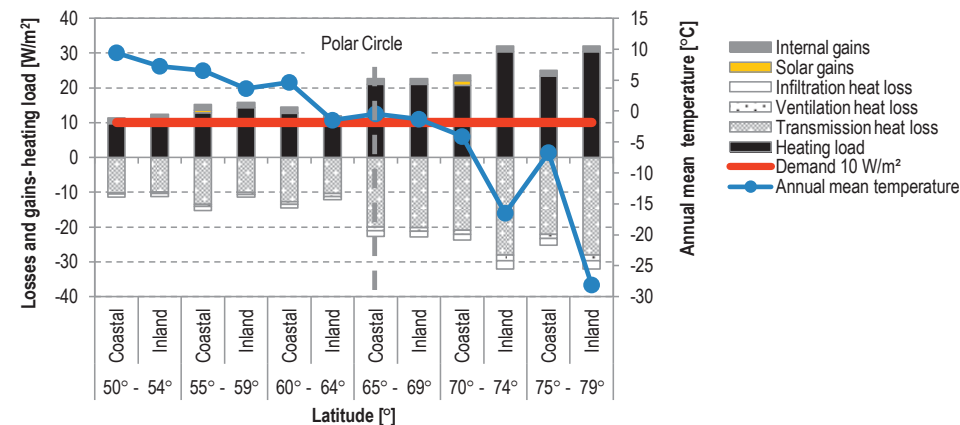


Fig. 3. Peak power balance and heating load of the Kranichstein passive house at different latitudes, shown as the maximum of the two design days

5.1.2. Passive house in the Arctic in accordance with the fundamental definition

The design of buildings in the Arctic is based on the calculation of transmission and ventilation heat losses with an interior design temperature and an outdoor design temperature. This calculation is similar to the PHPP method of calculating the heating load, apart from including the additional internal gains of 1.6 W/m^2 and any possible solar gains [18]. Since the ventilation heat load has very low power, of the same magnitude as the internal gains, the total transmission heat load must not be above $10\text{--}12 \text{ W/m}^2$ if the heating is to be covered by heating the air in the ventilation system. Furthermore, the result of the calculation of the heating load must be below 10 W/m^2 . The heating load in PHPP is calculated for two design days defined with a mean daily temperature and an available daily solar radiation [19]. In the Arctic (above latitude 66°N), the coldest day or the moderately overcast day may often happen to coincide with the lowest two-day average temperature achieved at least 10 times in the past 20 years (i.e. the outdoor design temperature) and without solar gains. For selected locations, the similarity between the outdoor design temperatures and the two design days are shown in Table 2, where the two design days are represented by the average and extreme values obtained from METEONORM 6.0 [20].

Table 2

Design day characteristics for a passive-house calculation

Location / Outdoor design temperature [°C]		Mean values					Extreme values				
		Design day 1:			Design day 2:		Design day 1:			Design day 2:	
		Cold, clear day			Moderate, overcast		Cold, clear day			Moderate, overcast	
		Mean daily temperature [°C], Mean daily solar radiation (N, E, S, W, global) [W/m²]									
Würzburg, GE	-12.0	-6.6	11; 20; 47; 18; 30	-1.5	6; 8; 16; 9; 15	-10.0	9; 14; 31; 13; 23	-7.0	8; 10; 16; 11; 19		
Sisimiut, GL	-30.0	-27.6	0; 0; 0; 0; 0	-22.9	0; 0; 0; 0; 0	-32.2	0; 0; 0; 0; 0	-26.9	0; 0; 0; 0; 0		
Barrow, AK,USA	-40.0	-35.5	0; 0; 0; 0; 0	-30.2	0; 0; 0; 0; 0	-39.3	1; 5; 20; 4; 3	-33.2	0; 0; 0; 0; 0		
Resolute, CA	-44.0	-40.2	0; 0; 0; 0; 0	-34.2	0; 0; 0; 0; 0	-44.3	0; 0; 0; 0; 0	-36.5	0; 0; 0; 0; 0		

First, we investigated designing a “Kranichstein” passive-house model in the Arctic in accordance with the fundamental definition to achieve 15 kWh/(m²·a) and/or 10 W/m². Here, the fundamental values applied on the European passive house were left unchanged, i.e. internal gain 2.1 W/m² (and 1.6 W/m² when the house is without any habitants), unrestricted size of windows as a percentage of the floor area, and a ventilation air change of 0.3 h⁻¹. The results are shown in Table 3 for several locations expressed in terms of the mean annual temperature and solar radiation.

Table 1

The passive house in Arctic locations based on the fundamental values and techniques, and with Danish / Greenlandic national standards

Techniques	Fundamental values and techniques			Danish / Greenlandic national standards		
Location / Ambient temperature	Sisimiut Latitude 66.4° $T_{amb} = -3.9^{\circ}\text{C}$	Barrow Latitude 71.2° $T_{amb} = -12.5^{\circ}\text{C}$	Resolute Latitude 74.4° $T_{amb} = -16.5^{\circ}\text{C}$	Sisimiut Latitude 66.4° $T_{amb} = -3.9^{\circ}\text{C}$	Barrow Latitude 71.2° $T_{amb} = -12.5^{\circ}\text{C}$	Resolute Latitude 74.4° $T_{amb} = -16.5^{\circ}\text{C}$
$U_{wall, floor, roof}$ [W/(m ² ·K)] ⁽¹⁾	0.055; 0.050; 0.050	0.035; 0.030; 0.030	0.033; 0.030; 0.030	0.070; 0.065; 0.065	0.044; 0.040; 0.040	0.040; 0.035; 0.035
$U_{glazing}$, g-value [W/(m ² ·K)], [-]	0.33; g=0.60	0.25; g=0.60	0.23; g=0.60	0.55; g=0.60	0.33; g=0.60	0.32; g=0.60
Infiltration air change [h ⁻¹]	0.019	0.014	0.010	0.019	0.014	0.010
Heat exchanger η [%]	92	95	95	85	87	88
Window / floor area [%]	22	18	18	22	18	18
Energy demand for heating – annual method [kWh/(m ² ·a)]	15.4	15.4	15.2	14.9	15.4	15.0
Energy demand for heating – monthly method [kWh/(m ² ·a)]	16.6	15.8	17.4	14.7	14.5	15.5
Peak power demand – heating load [W/m ²]	9.6	9.3	10.1	12.8	12.3	12.7

Secondly, we investigated the building design parameters adjusted to meet Danish / Greenlandic national standards, including internal gains 5 W/m², window / floor area $\leq 22\%$, increased ventilation air change of 0.5 h⁻¹, and the changes related to the building structure from medium to lightweight, i.e. a wood-framed structure with mineral wool insulation, and elevated foundations. The results can be found in Table 3 along with the distribution of heat losses and gains as well as space heating demand of such a passive house for three selected locations (Fig. 4, Fig. 5 and Fig. 6).

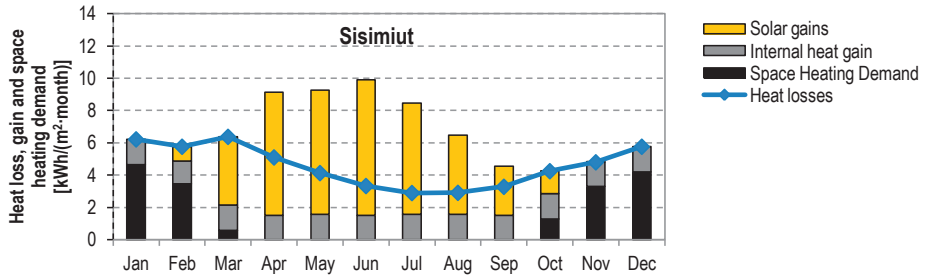


Fig. 4. Distribution of heat loss and gains with space heating demand in a passive house in Sisimiut

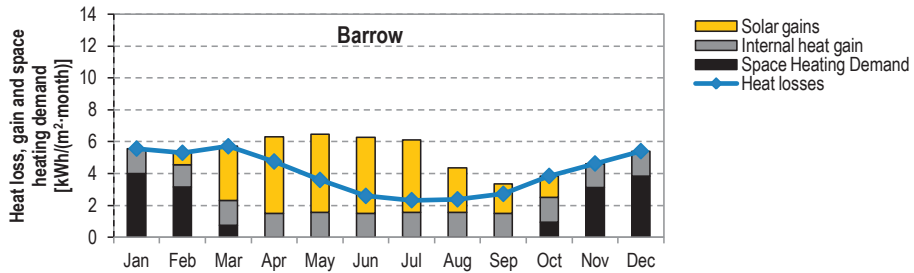


Fig. 5. Distribution of heat loss and gains with space heating demand in a passive house in Barrow

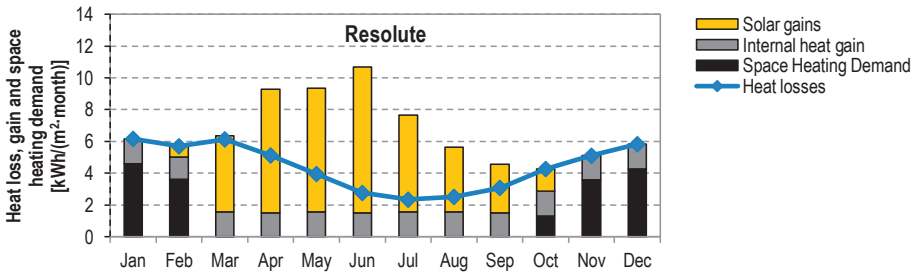


Fig. 6. Distribution of heat loss and gains with space heating demand in a passive house in Resolute

Our investigation of these methods for calculating the heating demand shows that the annual heating demand varies significantly on a monthly basis compared to space heating demand of $15 \text{ kWh}/(\text{m}^2\cdot\text{a})$. The monthly figures also reveal the lack of solar gains in several winter months and especially for the design day, which is essential to calculate the peak power load for heating. A space heating demand of no more than $15 \text{ kWh}/(\text{m}^2\cdot\text{a})$ is easier to achieve. To achieve the heating load of $10 \text{ W}/\text{m}^2$ seems to be more difficult; this is mainly due to the absence of solar radiation on the design day in winter. The figures (Fig. 4, Fig. 5 and Fig. 6) show that these Arctic locations have a significant amount of solar radiation from April to July.

5.2. Evaluation and optimization of a passive house in the Arctic using measurable and qualitative objectives

5.2.1. The characteristics of the building envelope

Two of the main design parameters are the thickness and thermal conductivity (λ) of the insulation material. The compact shape of a building affects the transmission heat losses through the areas of the floor, roof and walls. The normal insulation materials used in the Arctic have a thermal conductivity of 0.037–0.040 W/(m·K) (mineral wool insulation), but the efficiency of the insulation can be increased by using a material with a lower thermal conductivity (e.g. PUR 0.022–0.025 W/(m·K)) or vacuum insulation panels (VIP 0.005–0.010 W/(m·K)) [21]. Moreover, this could decrease the thickness of the building envelope. The optimum insulation thickness is a strong point in the building design and observation of the heat flow shows where the potential improvement of a building element is proportional to the heating degree hours. The marginal savings for additional insulation will decrease with increased insulation (Fig. 7). To achieve passive-house standard and reduce heat loss through building envelope down to approximately 10–15 W/m², would require an extensive amount of insulation ranging from 700 mm to 1,100 mm depending on a thermal conductivity of insulation.

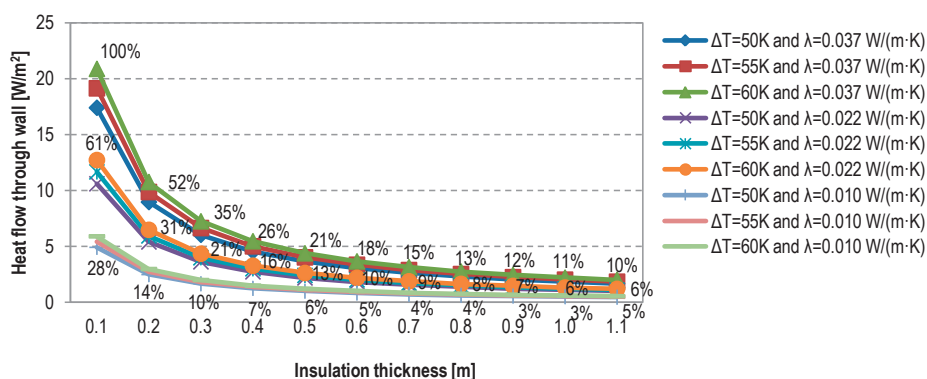


Fig. 7. Heat flow per m² with increasing insulation thickness for various temperature differences and thermal conductivities

The air tightness is ensured in a passive house by making the building envelope into an airtight barrier. In a cold climate, air leakages cause extreme discomfort for users and problems like icicles on the exterior façade, corrosion of metal parts, high wood moisture content and rotting. In normal houses in a temperate climate such as Würzburg, the infiltration heat loss can be up to 23 kWh/(m²·a) with air leakage of 4 h⁻¹ at 50 Pa. In a cold climate, it can be up to 150 kWh/(m²·a) with n_{50} ranging from 15 to 20 h⁻¹. In passive houses, the infiltration heat loss via the building envelope comprises only a small part of the total balance of heat losses and gains in the calculation of the heating demand, e.g. with an infiltration air change rate of 0.019 h⁻¹ ($n_{50} = 0.22$ h⁻¹), the infiltration heat loss is just 1.3 kWh/(m²·a) for a passive house in a temperate climate, while it would be 2.3 kWh/(m²·a) in Sisimiut, 3.2 kWh/(m²·a) in Barrow, and 3.7 kWh/(m²·a) in Resolute.

Passive-house windows are designed to bring net energy gains into the building. Usually, the glazing has a low-emission coating to reduce the heat loss by radiation, triple or quadruple glazing filled with argon or krypton, which reduces conductive heat transfer, and the window frame might be made of composite or synthetic materials such as fibreglass or PVC with warm edge spacers to reduce thermal bridging. Table 4 shows various window characteristics in the three locations, with results from windows facing in different directions. With very improved characteristics, windows facing south, east and west can bring positive gains to the energy balance of the building. However, it should be noted there are no windows on the market today which have U -values as low as $0.3 \text{ W}/(\text{m}^2\cdot\text{K})$, although such windows may be realistic one day.

Table 4

Net energy gain (kWh/m^2) for various windows with different orientations in the three locations

Windows characteristics / orientation		Sisimiut Latitude 66.4° $T_{\text{amb}} = -3.9^\circ\text{C}$	Barrow Latitude 71.2° $T_{\text{amb}} = -12.5^\circ\text{C}$	Resolute Latitude 74.4° $T_{\text{amb}} = -16.5^\circ\text{C}$
$U_{\text{window}}/g\text{-value}$ 0.8 / 0.6	South	17	-20	10
	East	-36	-97	-83
	West	-36	-96	-84
	North	-76	-147	-146
$U_{\text{window}}/g\text{-value}$ 0.5 / 0.6	South	61	42	80
	East	8	-35	-13
	West	8	-33	-14
	North	-32	-85	-76
$U_{\text{window}}/g\text{-value}$ 0.3 / 0.6	South	90	83	127
	East	37	6	34
	West	37	8	32
	North	-3	-43	-29

5.2.2. Ventilation and heating system

A properly designed ventilation system with heat recovery provides good indoor air quality and recovers more energy than it takes to run the fans. So it saves a great amount of energy compared to the situation of having a leaky house. The heat recovery system ensures interior temperatures between 18° and 21°C with relative humidity ranging from 30% to 50%, which is considered both achievable and healthy in the Arctic (Buildings in Alaska, 2004). In a temperate climate, the ventilation heat loss with an appropriate air change rate will be between 20 and $30 \text{ kWh}/(\text{m}^2\cdot\text{a})$ without heat recovery while, with heat recovery with efficiency $\eta = 75\text{--}85\%$, it can be reduced to $2\text{--}7 \text{ kWh}/(\text{m}^2\cdot\text{a})$. In a cold climate, the ventilation heat loss adds up to $60\text{--}90 \text{ kWh}/(\text{m}^2\cdot\text{a})$ without heat recovery, and with heat recovery, it can be reduced to $7\text{--}12 \text{ kWh}/(\text{m}^2\cdot\text{a})$. Achieving heat recovery efficiency of 90% is difficult in a cold climate due to the problems with freezing and moisture in the heat exchanger unit, and this means additional energy is needed for the preheating of the inlet air where defrosting is assumed to be necessary if $T_{\text{amb}} < -3.5^\circ\text{C}$ (Fig. 8).

In a cold climate, the building regulations often require higher air change rates, e.g. 0.5 h^{-1} compared to 0.3 h^{-1} in the passive-house standard. The need for higher air change rates in the Arctic is due to the different lifestyle, e.g. more dense occupation of the buildings due to the climate, socioeconomic conditions, or different habits with regard to cooking food. An increased air

change rate and higher indoor temperature lead to more energy being consumed for heating and ventilation, e.g. increasing the air change rate in a passive house from 0.3 to 0.5 h⁻¹ leads to an additional 2–3 kWh/(m²·a) and so does increasing the interior temperature from 20° to 23°C leads to an additional 2–3 kWh/(m²·a).

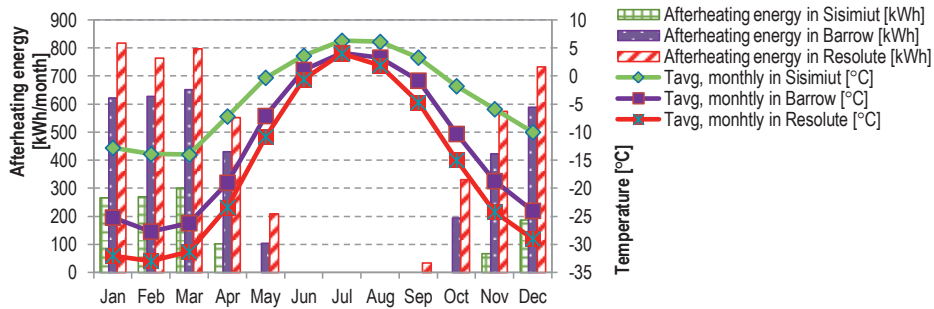


Fig. 8. The energy needed for preheating in a passive house situated in the three different cold climates to achieve required energy efficiency of heat exchanger

5.2.3. Primary energy demand

Primary energy is another parameter in a passive house. The specific primary energy demand calculation includes: domestic hot water, heating, cooling, and auxiliary and household electricity [22]. The Kranichstein passive house uses approximately 2,350 kWh/a for space heating $A_{TFA} = 156 \text{ m}^2$, which is 15 kWh/(m²·a) [4]. The hot water consumption amounts to 25 litres/person/day at 60°C (equivalent to 2,400 kWh/a) and the additional energy for a household dishwasher and washing machine of 400 kWh/a. This is usually with at least 50% covered by solar hot water production. The electricity demand equals 1,800 kWh/a, with a primary energy factor of 2.7 for Germany, and the recommended maximum value is 18 kWh/(m²·a) in a passive house.

In a cold climate, the space heating demand varies from 12,000 kWh/a for a house with a floor area of 190 m² to 19,000 kWh/a for a house with floor area of 63 m² (from 80 up to 300 kWh/(m²·a), respectively) depending on the age of the building, amount of insulation, and air tightness [10, 23, 24]. The heating is usually from an oil-fired boiler with an efficiency of 90% with an energy factor 1.1, or from electrical heating with an energy factor of 2.7. The hot water consumption is assumed to be 250 litres/m² per household per year, or 4,000 kWh/a. In a typical house, a total of 4,000 kWh/a is used for electricity for lights, appliances and mechanical equipment with a primary energy factor of 2.7.

The total specific primary energy calculated for a typical existing house in Greenland varies from 183 to 429 kWh/(m²·a) compared to 64 kWh/(m²·a) for the Kranichstein passive house in Germany. So energy-efficient houses in the Arctic have to be equipped with more efficient systems, such as a condensing oil-fired boiler coupled with solar heating or photovoltaic to cover part of the hot water consumption and/or electrical consumption. Other sources of renewable energy, such as hydropower or wind power, could be used to achieve even more optimized results. Highly efficient appliances are needed to operate and maintain a low-energy house.

5.3. Challenges and obstacles in comparison to regions with a temperate climate

The calculation of payback time using traditional methods would lead to an unacceptably long payback period because of the very low price of energy due to the absence of Value Added Tax. Prices may not be comparable because prices in the Arctic are influenced by many factors, such as availability of building materials, knowledge and labour, which often create a monopoly and increases in prices. Instead, the CO₂ emission factor can be used to compare the embodied energy in insulation materials and savings on heating for a passive house compared to traditional housing. The energy savings and emission production for the building stock in selected cold regions was calculated based on the average floor area, number of dwellings, and average heating consumption obtained from the relevant national Statistics [2, 3, 25]. The current building stock in the selected Arctic countries of Greenland, Norway and Canada emits approximately 10.6 megatons of CO₂/year due to oil-based heating if we use the conversion factor of 0.245 kg CO₂/kWh [26]. If the whole building stock could be upgraded to passive houses using 15 kWh/(m²·a) for heating, the potential savings in consumed energy and, thus, emission would be approximately 90%.

Table 5

Indoor temperature drop and stabilization in lightweight buildings in Arctic climates obtained from BSim

Location and temperature characteristics	Temperature drop and stabilization	
	Normal house (lightweight structure)	Passive house (lightweight structure)
Sisimiut, Greenland, latitude 66.6° Tamb, monthly = -3.6°C, Tamb,daily,min = -27.6°C	15.0°C in first 24h, and within a week follows profile of Tamb with +4.0°C difference	1.8°C in first 24h, drop of 2.0°C every next 24h, and slowly stabilizes to Ti = 8.0°C with Tamb = -20.0°C
Barrow, USA, latitude 71.2° Tamb, monthly = -12.5°C Tamb,daily,min = -40.3°C	17.0°C in first 24h, and within a week follows profile of Tamb with +2.0°C difference	2.1°C in first 24h, drop of 2.4°C every next 24h, and slowly stabilizes to Ti = 5.0°C with Tamb = -28.0°C
Resolute, Canada, latitude 74.4° Tamb, monthly = -16.5°C Tamb,daily,min = -42.6°C	16.0°C in first 24h, and within a week follows profile of Tamb completely	2.5°C in first 24h, drop of 2.8°C every next 24h, and slowly stabilizes to Ti = 0.0°C with Tamb = -38.0°C

Building a passive house requires a significant amount of insulation, so the CO₂ emission of traditional building insulation has to be taken into account. The insulation material for the construction of a passive house in the Arctic, with an average mineral wool thickness of 700 mm, would equal 31.1 tons CO₂ emission per house and 455.5 megatons of CO₂ emission for the total number of houses in the selected cold regions of Greenland, Norway and Canada if we use the conversion factor of 1.2 kg CO₂ for manufacturing 1 kg of Rockwool insulation [27]. If we compare the insulation material to the heating savings expressed in emission factors, the payback period in the selected cold regions would be approximately 40–45 years. If we take into account the use of new building materials depending on the type of the building structure, super energy-efficient windows, and new building systems, the payback time in terms of CO₂ could be reduced even more.

Sociological and cultural differences play a significant role in the Arctic regions. Socio-economic factors include the social impacts of economic changes in society and the behavioural interaction of groups in which lifestyle and culture are connected to the climate through the eco-system, people and housing. The cultural gap [28, 29] and socio-economic factors are among the non-technical

aspects which need to be reviewed and have a significant influence on building developments in the Arctic region, especially with regard to passive houses.

Survival in an extremely cold climate depends on retaining warmth, which is closely connected to the energy supply. When the energy supply is limited or suddenly interrupted, the current practice is to relocate the inhabitants, which can take up to 2–3 days depending on the means and options for transportation. Today's poorly insulated lightweight building constructions are only just able to withstand the extremely cold temperatures even with a powerful heating source. The passive house has the ability to provide for the survival of the individual by retaining the interior temperature for a longer period with very slow cooling down, if the energy supply or heating system is interrupted. Table 5 shows the temperature drop and stabilization of the interior temperature in a normal house compared to a passive house, as calculated in hourly dynamic simulations using BSim [30] carried out for the coldest day / week at selected locations where the weather data was obtained from the design reference year for each location.

5.4. Adaptation of a passive house for the Arctic

The concept of the passive house in the Arctic is based on the fundamental goal of reducing costs by using a more energy-efficient design that will make it possible to use heating with a peak load of 10 W/m^2 . Solving this problem using an air supply heating system is difficult in the Arctic because the design days for the calculation of heating load have no available solar gains and internal gains are limited to 1.6 W/m^2 . To cover this heating load, the envelope of the building has to be overdimensioned, especially in terms of the thickness of the building insulation and the super energy-efficient technical properties of the windows.

One simple optimization is to use the increased value for internal gains in a passive house in the Arctic because, in the 3–4 months of winter without solar gains, people live mostly in their homes which have more densely populated living areas. Furthermore, Arctic social and cultural habits can be assumed to cause more internal gains, compensating for the lack of solar gains, with a national value for an internal gain of 5.0 W/m^2 . With an achievable heat recovery efficiency of 85% with an average air change rate of 0.5 h^{-1} and an infiltration air change rate 0.020 h^{-1} , passive houses could be built with $U_{\text{walls}} = 0.055 \text{ W/(m}^2\cdot\text{K)}$, $U_{\text{floor,ceiling}} = 0.050 \text{ W/(m}^2\cdot\text{K)}$ and with efficient windows $U_{\text{glazing}} = 0.7 \text{ W/(m}^2\cdot\text{K)}$, with g -value 0.6. These parameters applied to a Kranichstein model built in the climate of Sisimiut would fulfil the space heating demand of $15 \text{ kWh/(m}^2\cdot\text{a)}$, but the heating load would be 13.1 W/m^2 . This means there would be a need for a low temperature heating system of approximately 3–5 kW which could work in the cold periods without solar radiation. Due to the limited availability of renewable resources and current usage of heating systems based on the fossil fuels, this heating system would have to be supplied from non-renewable resources.

Another possible optimization of a passive house in the Arctic would be to combine the energy requirements for a passive house, i.e. primary energy demand of $120 \text{ kWh/(m}^2\cdot\text{a)}$ for variation of $15 \text{ kWh/(m}^2\cdot\text{a)}$ and 10 W/m^2 . If we assume that the heating and half of the hot water consumption would be supplied by an oil-fired boiler, 50% of the hot water consumption could be covered by solar energy, the domestic appliances could be of class A or higher, lighting could be supplied by electric power, the ventilation system could be operated by low-energy fans, etc. The hot water

consumption, auxiliary and household electricity could amount to approximately 60 kWh/(m²·a); that is 50% of 120 kWh/(m²·a). This means that instead of limiting the space heating demand, almost 45 kWh/(m²·a) could be used for heating of the building, i.e. a space heating demand of 120 kWh/(m²·a) and subtracting 15 kWh/(m²·a) for space heating and finally deducting 60 kWh/(m²·a) of the energy for domestic hot water, auxiliary, electricity and preheating of inlet air. Applying the above mentioned assumptions to the consumption of a passive house, the only additional energy needed would be for preheating.

6 Discussion

Moving a passive house from a temperate climate to the Arctic is a strong application of the main design rule in cold climates, where the focus is on minimizing the heat loss before maximizing heat gains, followed by an optimization of essential building elements. With current building traditions in the Arctic regions, the fundamental definition of a passive house would be hard to fulfil because the peak heat loss through the building envelope would have to be reduced to approximately 10–15 W/m², where the thermal conductivity and thickness of the insulation in the structure and the thermal quality of the windows would be the main factors. Adding more insulation would have only a non-linearly declining effect on reducing the *U-value*, and to achieve the passive-house standard in coastal locations at the Arctic Circle would require an extensive amount of insulation, ranging from 700 mm and up to 1,100 mm at 70° latitudes using the traditional building material of mineral wool $\lambda = 0.037$ W/(m²·K), or a replacement with better thermally performing insulation materials with less thickness.

The windows in a passive house must have a good solar heat gain coefficient to be able to deliver the energy gains at any point in the room without the conventional hydronic room heating system; especially on design days with extremely low temperatures. In the Arctic region, with great temperature differences between inside and outside, and very different solar distribution, this seems hard to achieve and the heat transfer coefficient would have to be 0.23–0.40 W/(m²·K) with a solar heat gain coefficient above 0.6 for windows facing mainly south, east and west. At the same time, suitable vertical or horizontal shading would have to be available to block the low-angle sun in the summer months and ensure a good thermal comfort for the inhabitants. To provide sufficient thermal comfort in winter, insulated shutters could serve as additional insulation to decrease the heat loss and prevent possible condensation and radiant heat exchange. Yet, there will still be up to 3–4 months every winter without the possibility of obtaining sufficient solar gain.

Air tightness is crucial in a passive house and it has a paramount significance in the Arctic where the airtight barrier on the outside and the vapour retarder on the inside of the walls not only help save energy due to the lower infiltration heat loss through the building envelope, but also protect the building envelope from the penetration of moisture from the interior with incidents of condensation and subsequent destruction of the properties of the building envelope. Mechanical ventilation with heat recovery units in the Arctic could provide good indoor air quality and good thermal comfort with heat recovered from the exhaust air to reduce heating consumption. To implement a passive house in the Arctic, very efficient heat recovery systems would have to be developed with efficiency in the range of 90–95%, but solutions will be needed to avoid problems

with ice formation; otherwise, extra energy would be needed for preheating the inlet air or after heating.

Primary energy demand can be used as a parameter to express the overall performance of a passive house. This parameter should be implemented based on the building regulations in the cold region in combination with the necessity to base the annual heating consumption of buildings on a monthly calculation method to be able properly to interpret the results with regard to utilization factor, and solar and internal gains. To ensure that the passive house fulfils the requirements in accordance with the PHPP calculations, building commissioning should be implemented as a method to follow-up on the construction and operation of the house. Blower-door tests and measurements at least for the first year of operation should be the standard procedure for a successful implementation of a passive-house concept in the Arctic.

In theory, it is possible to fulfil the fundamental definition of a passive house in the Arctic fully and, therefore, to save the cost of traditional heating, but that would lead to high costs for the building materials and the provision of technical solutions of an extremely high standard, which would not pay back within the lifetime of a building. The passive house offers a sustainable solution with regard to heating and consumption of electricity, but the energy needed, money investment, and the CO₂ footprint incurred for building such a house would be demanding.

7 Conclusion

The baseline of a passive house lies in the idea of an energy-efficient house which utilizes free heat gains in the building with only a small supplementary heating source in the periods of the highest energy demand. The adaptation of the passive-house concept to the Arctic needs to take into account various circumstances, such as resources available for heating, building materials and building knowledge, along with the different solar patterns and shading methods for low-angle sun, more focus on the limitation of transmission heat loss, and the use of highly efficient heat recovery systems. The ventilation system needs to accommodate the need for high air change rates to provide good indoor air quality while still retaining good thermal comfort. The passive house itself represents an alternate backup system necessary for any building constructed in an extreme climate.

An optimized application of the passive-house concept would have to be based on a new definition of a passive house for the Arctic, but using the existing passive-house components on the market at sensible prices. The baseline of the fundamental definition of a passive house is achievable in the Arctic only at economic costs that are too high, but the idea of a highly energy-efficient building in the Arctic, even in this small market, could give a rise to the development of the highly efficient materials and building systems needed for an energy-efficient building in any climate.

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During the past few decades, there has been quite some development of energy efficient buildings with low energy heating consumption; one of these buildings is a passive house which has been successfully implemented in locations 40° to 60° Northern latitudes. Nowadays, there is a focus on implementation of a passive house in more demanding climate of the Arctic regions. The analyses presented in this thesis offer a theoretical possibility of building a fundamental passive house in the Arctic and an improvement of the technical solutions in a full sense of definition. Furthermore, a discussion of the new definition is presented based on the optimization of building construction products and adaptation of a passive house in the Arctic.

The adaptation of a passive house in the Arctic is based on the best combination of building design aspects, climate characteristics, the material availability and energy resources combined with ecological impacts.

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