LICENTIATE THESIS

Energy efficiency strategies for residential buildings in a subarctic climate: Impacts on energy use and indoor thermal climate

Shimantika Bhattacharjee

Construction Management and Building Technology

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Shimantika Bhattacharjee

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Division of Industrialized and Sustainable Construction
Department of Civil, Environmental and Natural Resources Engineering
Luleå University of Technology
SE - 971 87 LULEÅ
www.ltu.se/research/subjects/Byggproduktion-och-teknik?l=en

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Abstract

Adopting energy efficiency strategies in residential buildings are beneficial as these not only improve the energy performance but also improves the indoor thermal climate and minimizes the greenhouse gas emissions. There exist numerous studies on energy efficiency strategies and their influence on indoor thermal climate in residential buildings in cold climates. However, there is a lack of documented and systematic studies that explicitly investigated the selection of appropriate energy efficiency strategies and their impact on the indoor thermal climate in residential buildings in a subarctic climate. Moreover, the impact of such energy efficiency strategies on the life cycle energy use of buildings has not been given appropriate attention in the existing literature. Due to the extreme climate conditions in a subarctic climate – severe cold and dark winter with heavy snow and mild short summer – buildings require a considerable amount of heating energy to maintain a comfortable temperature indoors. Therefore, it is important to adopt energy efficiency strategies that can help obtain operational and life cycle energy savings along with a better indoor thermal climate.

The aim of this study is to evaluate the impact of different energy-efficiency strategies on energy use and thermal indoor climate of three selected case study residential buildings in a subarctic climate. Three research questions were formulated: (1) What is the impact of evaluated energy-efficiency strategies on the operational energy use?, (2) What is the impact of evaluated energy-efficiency strategies on the life-cycle energy use?, and (3) What is the impact of evaluated energy-efficiency strategies on the thermal indoor climate? To address research questions 1 and 3, implemented energy-efficiency strategies in two low-energy buildings were evaluated using measured energy data and dynamic building energy and indoor climate simulations. To address research question 2, different combinations of energy efficiency strategies were explored using a multiobjective optimization method to identify optimal retrofitting solutions in terms of life cycle energy savings for a 1980s building.

Results show that besides an airtight and highly insulated building envelope, a well-functioning heating system is important to achieve low operational energy use. Findings highlight that the role of occupants is vital both in regard to the proper functioning of the heating system and to reduce the need for active heating in an airtight and highly insulated building. The occupants are also important in terms of maintaining a comfortable indoor thermal climate, especially during summer since manual airing and shading can help moderate temperatures indoors. Furthermore, findings show that applying glazed balconies is not necessarily a favorable strategy in terms of operational energy use and indoor thermal climate for a building in a subarctic climate. In comparison, using double instead of single pane balcony glazing and lowering the window to wall ratio improved the operational energy and indoor thermal climate performance. A combination of energy efficiency strategies including the addition of insulation on walls and roofs, the replacement of windows from double pane to triple pane ones and the installation of heat recovery ventilation were found optimal to achieve considerable savings in both operational and life cycle energy use. In many cases, the fundamental aim of adopting energy efficiency strategies is to reduce operational energy use, while impacts on life cycle energy use and indoor thermal climate are less prioritized. The findings illustrate the importance of considering impacts on operational energy use, life cycle energy use and indoor thermal climate simultaneously to select energy efficiency strategies that ensure a better and more sustainable built environment.

Sammanfattning

Att implementera energieffektiviseringsstrategier i bostadshus är fördelaktigt eftersom det inte bara förbättrar energiprestandan utan också det termiska inomhusklimatet, samtidigt som det minskar utsläppen av växthusgaser. Det finns ett stort antal studier om energieffektivitetsstrategier och deras inverkan på det termiskt inomhusklimat i bostadshus i kalla klimat. Det råder dock brist på dokumenterade och systematiska studier som explicit undersökt valet av lämpliga energieffektiviseringsstrategier och deras inverkan på det termiska inomhusklimatet i bostadshus i ett subarktiskt klimat. Dessutom har effekterna av olika energieffektiviseringsstrategier på byggnadernas livscykelenergianvändning inte uppmärksammats tillräckligt i den befintliga litteraturen. På grund av de extrema klimatförhållandena i ett subarktiskt klimat – kalla, mörka och snöiga vinter och milda korta somrar – krävs en betydande mängd värmeenergi för att upprätthålla en behaglig temperatur inomhus. Därför är det viktigt att välja energieffektiviseringsstrategier som kan ge både drifts- och livscykelenergibesparingar liksom ett bättre termiskt inomhusklimat.

Syftet med denna studie är att utvärdera effekten av olika energieffektivitetsstrategier på energianvändning och termiskt inomhusklimat för tre utvalda bostadshus i ett subarktiskt klimat. Tre forskningsfrågor formulerades: (1) Vilken inverkan har utvärderade energieffektivitetsstrategier på den operativa energianvändningen?, (2) Vilken är effekten av utvärderade energieffektivitetsstrategier på livscykelenergianvändningen?, och (3) Vilken påverkan har utvärderade energieffektivitetsstrategier på det termiska inomhusklimatet? För att besvara forskningsfrågorna 1 och 3 utvärderades implementerade energieffektivitetsstrategier i två lågenergibyggnader med hjälp av uppmätta energidata och dynamiska byggnadsenergi- och inomhusklimatsimuleringar. För att besvara forskningsfråga 2

utforskades olika kombinationer av energieffektivitetsstrategier med hjälp av en multiobjektiv optimeringsmetod för att identifiera optimala renoveringslösningar för att nå livscykelenergibesparingar för ett 1980-talshus.

Resultaten visar att, förutom ett lufttätt och välisolerat klimatskal, är ett väl fungerande värmesystem viktigt för att uppnå en låg driftenergianvändning. Resultaten visar att de boende kan ha en avgörande roll både för värmesystemets funktion och för att minska behovet av aktiv uppvärmning i en lufttät och högisolerad byggnad. De boende är också viktiga när det gäller att reglera det termiska inomhusklimatet, särskilt under sommaren, eftersom manuellt styrd vädring och solavskärmning kan hjälpa till att hålla nere inomhustemperaturen. Vidare visar resultaten att användning av inglasade balkonger inte nödvändigtvis är en fördelaktig strategi när det gäller driftenergianvändning och termiskt inomhusklimat för en byggnad i ett subarktiskt klimat. I jämförelse ledde dubbla i stället för enkla glas på balkongen och lägre andel fönster i yttervägg till bättre energiprestanda och bättre termiskt inomhusklimat. En kombination av energieffektivitetsstrategier – tilläggsisolering av ytterväggar och tak, byte från två- till treglasfönster och installation av ventilation med värmeåtervinning – visade sig vara optimalt för att nå både stora driftenergibesparingar och stora livscykelenergibesparingar. I många fall är det grundläggande syftet med att implementera energieffektiviseringsstrategier att minska driftenergianvändningen, medan påverkan på livscykelenergianvändningen och det termiskt inomhusklimat prioriteras lägre. Resultaten av denna studie illustrerar vikten av att beakta påverkan på driftenergianvändning såväl som livscykelenergianvändning och termiskt inomhusklimat för att välja energieffektivitetsstrategier som säkerställer en bättre och mer hållbar byggd miljö.

Appended papers and authors' contribution

Paper 1:

Bhattacharjee, S., Lidelöw, S., & Schade, J. (2019). Performance evaluation of a passive house in sub-arctic climate. In Cold Climate HVAC 2018: Sustainable Buildings in Cold Climates (pp. 145-157). Springer International Publishing.

As the main author, I formulated the main idea of the research and wrote and compiled most of the parts along with the data analyses. Lidelöw developed the discussion part and contributed by editing and providing feedback to improve the overall paper. Schade assisted with data compilation, reviewed the analysis work, and helped develop the discussion part in dialogue with Lidelöw.

Paper 2:

Shadram, F., Bhattacharjee, S., Lidelöw, S., Mukkavaara, J., & Olofsson, T. (2020). Exploring the trade-off in life cycle energy of building retrofit through optimization. Applied Energy, 269, 115083.

Shadram was the main author. The framework "multiobjective optimization" was developed and implemented through the collaboration of Shadram and Mukkavaara. As a second author, I identified and described the construction details with help from Lidelöw and developed the building energy simulation model. I formulated the retrofitting strategies, which were tested in the multiobjective optimization framework, in dialogue with Lidelöw. I provided input to relevant literature for the introduction part. Lidelöw, Mukkavaara and Olofsson contributed by reviewing and commenting on the paper

Paper 3:

Bhattacharjee, S., Lidelöw, S., Shadram, F. (2023). Energy and indoor thermal performance analysis of a glazed façade high-rise building under various Nordic climatic conditions. Submitted to an international peer reviewed journal.

As a main author, I formulated the main idea of the research. I wrote the paper in close collaboration with Lidelöw. Shadram developed the introductory part and provided feedback on the writing. I identified and described the construction details together with Lidelöw, developed the simulation model, performed the energy and indoor thermal simulations, and compiled the results. Lidelöw collected and compiled measured energy data for validation of the model. Lidelöw also provided the climate data for the studied building locations. Shadram provided feedback regarding modelling in the energy simulation software.

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1. Introduction

1.1. Background

The building sector is one of the leading energy consumers around the globe, corresponding to approximately 40% of the final energy use in Europe, which generates a substantial amount of greenhouse gas (GHG) emissions (IPCC report, 2018). A large share of the European building stock represents old buildings with poor energy performance resulting in high energy use. According to the Swedish National Board of Housing, Building and Planning (Boverket), the building envelope and technical installations of 75% of the buildings in Sweden must be improved to reduce energy consumption (Boverket, 2016; La Fleur et al., 2019).

Different energy-efficiency strategies can be adopted to increase energy efficiency in the building sector. In a subarctic climate, heating energy use is generally high, especially during the cold and dark winter when passive heat gains from solar irradiation are small. Both active and passive strategies can be used to reduce the heating energy use of a building (PHI, 2016). Active strategies include improving the heating, ventilation and air conditioning (HVAC) system, whereas passive strategies mean improving the building envelope through (inter alia) additional insulation or installation of low-energy windows (Sadineni et al., 2011). This thesis focuses on how implementing active and passive energy-efficiency strategies affect energy use and indoor thermal climate in new and existing residential buildings in a subarctic climate.

Energy and indoor thermal climate performance of residential buildings in cold climates have been performed in many studies. However, relatively few of them have considered a subarctic climate. Among the few studies, thermal performance and energy-saving evaluations of buildings in a subarctic climate with highly efficient insulation materials such as phase change material (PCM) and vacuum insulation panels (VIP) are notable (Kenzhekhanov et al. 2020; Mukhopadhyaya et al. 2014). Rohdin et al. (2014) investigated the impact of energy-efficiency strategies on indoor thermal climate in nine passive houses in southern Sweden. They found that the indoor thermal climate in the passive houses was usually good compared to the traditional residential buildings; however, issues regarding cold floors and higher operative temperature during summer were detected. Furthermore, Lin et al. (2016) investigated the influence of energy efficiency measures on indoor thermal environment in residential buildings under a hot summer cold winter climate zone in China. Their findings show that stringent requirements to obtain better energy efficiency implicated the use of higher insulation levels and increasing airtightness levels of the buildings, which eventually led a warmer indoor environment.

Previous studies have also mentioned the risk of higher operative temperature or overheating in passive houses or low-energy buildings that are more airtight and insulated than conventional residential buildings. Even in a cold and subarctic climate, overheating has been detected as a potential problem for residential buildings (La Fleur et al., 2018; Lundqvist et al., 2019). The study by La Fleur et al. (2018) shows that improving the airtightness and insulation level of the building envelope generated higher temperatures indoors that led to overheating. Therefore, there is a need to understand better the impact of energy-efficient strategies on both energy performance and the indoor thermal climate of residential buildings in a subarctic climate.

When it comes to adopting energy efficiency strategies in buildings, a significant part of the literature has focused on reductions in operational energy use. However, more recent studies have emphasized the importance of adopting a life cycle perspective while considering energy efficient strategies for existing and new buildings. Shadram & Mukkavaara (2018) investigated the trade-off between embodied and operational energy use in a newly built passive house using multiobjective optimization. Their results show that selecting appropriate materials and quantities is essential as this might contribute to considerable savings in both operational and embodied energy use. Ramírez-Villegas et al. (2019) showed that deep energy-efficiency strategies lead to substantial energy use reduction and lower environmental impact from materials and construction. On the contrary, implementing heat recovery ventilation as a renovation strategy significantly reduced operational energy use but higher carbon emissions from the material and construction process was found. A similar study by Nydahl et al. (2019) assessed various refurbishment strategies from a life cycle perspective. Among other things, the results showed that installing energy-efficient windows yields a moderate reduction in operational energy use and relatively high embodied energy use. The above- mentioned studies illustrate the importance of considering energy efficiency from the perspective of both operational and life cycle energy use.

This study considers the application of active and passive strategies - installing mechanical ventilation systems with heat recovery, building envelope upgradation through more thick and efficient insulation materials in external walls and roofs, and energy-efficient windows – on existing and new residential buildings in a subarctic climate. Literature shows that such energy-efficiency strategies have been tested and used for residential buildings in various cold climates, which is elaborated on in Section 3, Frame of references. Due to the relatively high heating demand of buildings in cold climates, emphasis is commonly placed on improving their energy efficiency through improved airtightness and insulation of the building envelope and more energy-efficient windows. However, there is a lack of documented studies that explicitly address energy-efficiency strategies and the implications of such strategies on both energy use and indoor thermal climate in residential buildings in a subarctic climate. This study contributes to filling this gap.

1.2. Aim and Research Questions

The aim of this study is to evaluate the impact of different energy-efficiency strategies on energy use and thermal indoor climate of selected residential buildings in a subarctic climate. The evaluation considers both individual or combinations of energy-efficiency strategies applied to three case study buildings (cases 1, 2 and 3) and is guided by three research questions:

Research question 1: What is the impact of evaluated energy-efficiency strategies on the operational energy use?

Research question 2: What is the impact of evaluated energy-efficiency strategies on the life-cycle energy use?

Research question 3: What is the impact of evaluated energy-efficiency strategies on the thermal indoor climate?

1.3. Research Scope

The study considers the active strategy of installing a mechanical ventilation system with heat recovery and the passive strategies of increasing passive solar gains through increasing the window-to-wall ratio, adding insulation, and applying more energy-efficient windows and glazing's. In terms of operational energy use, the study considers energy use for heating but not cooling buildings since buildings in a subarctic climate are generally not equipped with systems for active cooling.

2. Frame of references

This chapter provides a frame of references for the study developed to identify the research gap and support conclusions about the study outcomes.

2.1. Strategies to reduce operational energy use

Operational energy is the energy required to operate the heating, ventilation and air conditioning (HVAC) system, electrical appliances, lighting, and domestic hot water (DHW). It is needed to run the daily maintenance and comfort conditions of buildings. This section introduces the building concepts aiming to reduce operational stage energy use in buildings and the types of energy-efficient strategies considered in this study. Low-energy buildings are built according to particular design criteria to reduce the building's operational energy use compared to a traditional building. For example, passive houses and near zero energy buildings (NZEB) are generally regarded as types of low-energy buildings.

2.1.1. Passive House

According to the German passive house institute, the definition of a passive house is "A passive house is a building which thermal comfort can only be achieved by the use of post heating or post cooling and indoor air quality must be sufficiently good without the need of a recirculated air (PHI, 2016)**; Jansson, 2010).** A passive house is a well-insulated and airtight construction that must be free from thermal bridges and equipped with a mechanical ventilation system. The construction must be airtight enough to minimize any infiltration. According to the Swedish Forum for Energy Efficient Buildings (FEBY, 2018), the target for achieving passive house standard is classified as "gold level". In FEBY, obtaining a gold level is regarded as the most stringent criterion for obtaining the highest level of energy performance for new and retrofitted buildings. Based on the criteria, buildings situated in the subarctic climate have the allowance for a maximum heat loss factor of 16 W/m2 heated floor area on the coldest day during winter. This study focuses on upgrading the building envelope by adopting different energy-efficiency strategies such as thicker insulation on external walls and roofs, energy-efficient windows, and heat recovery ventilation. However, minimizing thermal bridges was not considered in this study.

2.1.2. Net Zero Energy Buildings

The term net zero energy building (NZEB) was introduced by the Energy performance of buildings directive 2010/31/EU(EPBD) by the EU. According to the EPBD directive, a building with a high energy performance can be considered a NZEB. It means that the nearly zero or very low amount of energy required for building operation can be covered to a large extent through nearby or onsite renewable energy production (Kurnitski, 2013; Kurnitski et al., 2012; Magrini et al., 2020). A NZEB produces energy when the conditions are favorable and uses the delivered energy for building operation. The EPBD Directive emphasizes that all the new buildings should be nearly zero energy by the end of 2020. The aim of such a prospect is to improve the energy performance of buildings by adopting energy-efficiency strategies and installing renewable energy sources. The numerical indicator for primary energy use in NZEB is kWh/m2,year. The EPBD also declares that the guidelines for NZEB can differ in the member states based on their local, regional, or national conditions since European countries have different approaches towards their national policy framework (Annunziata et al., 2013). In Sweden, the building's energy performance must comply with the Swedish building code (BBR). The mini energy standard classified as "Silver class" is a near zero energy criterion. It stands between the newly built energy standard classified as "Bronze" and the passive house standard classified as "Gold class". The maximum allowed heat loss factor during the coldest winter day is 21 W/m2 heated floor area for a building located in the subarctic climate.

2.2. Strategies to reduce life-cycle energy of buildings

LCEA stands for all the energy inputs in a building during its life cycle. The system boundaries include the manufacturing, use and demolition phase of buildings and their associated energy use (Cabeza et al., 2014; Chastas et al., 2016; Ramesh et al., 2010). Embodied energy refers to the materials used in the building and the energy required for renovation, new construction and technical installations. Energy used during the end-of-life phase for demolition and transportation of materials for final waste treatment is also included in the embodied energy. On the other hand, the energy required for maintaining daily activities to run buildings, such as HVAC, lighting, electrical appliances, and DHW, is defined as the operational energy use of buildings.

Investigation on life cycle energy use for existing residential buildings reveals that operational energy has the majority share ranging from 80-90% and, conversely, embodied energy contributes to only 10-20% of the total life cycle energy use (Ramesh et al., 2010). Since operational energy constitutes the major share of the total energy use, most of the studies performed in recent decades emphasized the operational energy use reduction of buildings through adopting different energy-efficient retrofitting techniques. Few studies have discussed the importance of embodied energy in residential buildings. However, Thormark et al. (2002) found that the share of embodied energy contributes to a significant part of total energy use in low energy buildings compared to conventional buildings.

2.3. Tools for energy performance evaluation

The influence of technical and physical factors such as ventilation systems, insulation, windows, and human-influenced factors such as the indoor thermal climate of case study buildings can be explored using building energy simulation. IDA Indoor Climate and Energy (IDA ICE) has commonly been used to assess buildings' energy performance, especially in European case studies. According to the reviewed literature, it is one of the four main building energy simulation tools applied in research. Previous studies have evaluated energy performance using IDA ICE (Hilliaho et al., 2015; Kalamees, 2004; Karlsen, 2015). Energy plus has also been used to evaluate energy performance in previous studies (Ascione et al., 2015, 2016, 2017; Brun et al., 2009; Fumo et al., 2010). Multiobjective optimization methods for analyzing energy efficiency and LCEA has been widely used in previous literature (Diakaki et al., 2008; Fan & Xia, 2015).

2.4. Previous research on residential buildings in a subarctic climate

Table 1 presents an overview of previous studies on the energy performance of traditional and newly built low energy buildings in an arctic and subarctic climate. Many studies investigated the energy efficiency issue of newly built residential buildings in subarctic climates, e.g. Dehlin et al. (2018) and Banister et al. (2018). Results from Banister et al. show that a well-functioning heating and ventilation system was required to maintain an optimum temperature indoors in an energy-efficient building located in the Canadian subarctic, especially when the outdoor temperature recorded was low at -40°C. Dehlin et al.'s findings emphasized the impact of energy-efficiency strategies such as mechanical ventilation systems and highly insulated building envelopes on energy performance in a Swedish subarctic climate.

Other studies regarding thermal performance were found, such as Mukhopadhya et al. (2014), who studied the impact of VIP insulation in a retrofitted building. Risberg et al. (2015) evaluated different heating systems in a low-energy building. Lundqvist et al. (2020) assessed the impact of an air heating system in a low-energy building. Kenzhekhanov et al. (2020) evaluated the thermal performance of a PCM in a multifamily building. Results show that VIP and PCM are excellent options for reducing operational energy use of residential buildings in subarctic climates. Previous studies such as Lundqvist et al. (2020) have mentioned overheating as a potential problem in a passive house situated in a subarctic climate and Vladykova et al. (2012) detected indoor temperatures as high as 27 °C in an arctic climate. Results from Lundqvist et al. (2020) showed that occupants were experiencing overheating in some parts of the building during winter due to an uneven distribution of heat. Other studies regarding the energy performance of low-energy houses for arctic climates, such as Vladykova et al. (2012), were found insightful in terms of energy use, ventilation system and indoor climate. Fleur et al. (2019) investigated energy use and indoor environment before and after renovating a Swedish multifamily residential building. Before the renovation, the indoor thermal climate showed lower temperature and draught in the investigated building. On the other hand, the average indoor temperature after the renovation was considered good, with a range showing 20-21 °C. On the contrary, during summer, the operative temperature was as high as 30 °C. Lundqvist (2022) evaluated the indoor thermal climate after implementing energy efficiency strategies in a residential building under a subarctic climate. Findings show that the installation of heat recovery ventilation (HRV) reduced energy use in a residential building but did not improve the indoor thermal climate of a residential building. On the contrary, additional insulation on the building envelope not only enhanced the energy performance but also contributed to a comfortable indoor thermal climate. This is because the radiators provided adequate heat to provide an optimum indoor temperature. Vladykova & Bjarløv (2012) study emphasized the importance of passive solar gains potential and suggested the installation of movable shadings to obstruct the low-angle solar irradiation. Results of the study show that an apartment equipped with southwest-facing windows generated high temperatures indoors (27.4 °C). In comparison, the outdoor temperature remained low (9.6 °C) in a single-family detached house in an arctic climate. The findings also suggest that heat recovery ventilation is an excellent option for residential buildings in arctic climates. The summary of these results helped to identify appropriate energy-efficient strategies for buildings in subarctic climates.

Various studies have investigated the strategies for obtaining NZEB levels in residential buildings through retrofitting. A study by Hachem et al. (2014)

showed that passive design strategies such as replacing existing windows with triple-glazed windows, airtight construction and large south-facing windows for maximizing the potential of solar energy could help attain NZEB level in a multifamily building located in Montreal, Canada. Another study by Hamburg et al. (2020) showed potential barriers and challenges of obtaining NZEB level in a multifamily residential building in Tallinn, Estonia. Different reasons were stated, such as the average indoor temperature being higher than the standard, circulation losses from the DHW system, and DHW energy from solar collectors being lower than the standard required were regarded as the reasons for not attaining NZEB level.

Ramírez-Villegas et al. (2019) applied different renovation strategies in a simulated building. The renovation strategies included improving the external wall insulation, window replacement by low emissivity pane, attic insulation and implementing a mechanical ventilation system with heat recovery. Results show that adopting different levels of refurbishment strategies can reduce energy use by 27-43 %. The result can be applicable to a typical multifamily residential building located northwest of Stockholm, which is under a cold climate. Lidberg et al. (2018) assessed the impact of energy refurbishments, including a combination of different ventilation systems, such as a Mechanical Ventilation System With Heat Recovery (MVHR) and an Exhaust Air Heat Pump (EAHP), in the same multi-family building. The study gives an overview regarding the application of different ventilation systems and the environmental impact of such systems in a refurbished building in a subarctic climate. Nydahl et al. (2019) evaluated energy-efficiency measures from a life cycle perspective, including operational and embodied energy in a multifamily residential building in Umeå, Sweden, situated around 455 km south of the Arctic Circle. Results show that changing the existing windows to three-pane windows helped to obtain energy savings in terms of operational energy use. Shadram & Mukkavaara (2018) studied the trade-off between embodied and operational energy use in a low-energy building located in a subarctic climate using multiobjective optimization.

Table 1: Overview of research studies on the energy performance of traditional and newly built low-energy buildings in an arctic and subarctic climate.

Author (year)	Clima te type	Location	Focus of study	Method	Case study buildin g type and status	Simulation tool/ measurement/ calculation method
Rode et al. (2009)	Arctic	Sisimiut, Greenland	Design and construction	Design consideration -s and energy performance assessment using simulation and measured data	Low energy house	IDA ICE
Rode et al. (2010)	Arctic	Sisimiut, Greenland	Test and visualize the application of low-energy building technology	Performance evaluation through energy simulation and measured data	Low energy house	BSim and blower door test
Vladykova & Bjarløv (2012)	Arctic	Greenland	Insulation and non-airtight building envelope with a combination of uncontrolled air change	Energy and indoor climate assessment	Low energy house	Measured energy use
Vladykova et al. (2012)	Arctic	Sisimiut, Greenland	Comparative analysis and evaluation of indoor climate parameters on energy use	Evaluation of two case study buildings using measured data	A tradition al house and a newly built low-energy house	Measured data for indoor temperature and relative humidity using loggers and sensors

Hachem et al. (2014)	Subarctic	Montre al, Canada	Solar potential and energy performance assessment	Energy performance assessment through building integrated PV assessment in façade and roof	Multifamily residential building	EnergyPlus
Mukhopadhyaya et al. (2014)	Subarctic	Yukon, Canada	Thermal performance assessment of VIP	Laboratory experiment, construction and thermal performance evaluation of VIP in a retrofitted wall	Retrofitting	Thermo-physical behavior of VIP monitored in laboratory
Risberg et al. (2015)	Subarctic	Kiruna, Sweden	CFD simulation and evaluation of different heating systems	CFD simulations to evaluate indoor temperature in different zones of the studied building	Low energy building	ANSYS CFX (Computational Fluid Dynamics Software)
Banister et al. (2018)	Subarctic	Nunavut, Canada	Evaluate heating energy use	Assessment of different energy efficient strategies	Energy efficient house	Metered data for heating energy use
Shadram & Mukkavaara (2018)	Subarctic	Kiruna, Sweden	Develop and test a multiobjective optimization approach to solve embodied/operational energy trade-off problems	Energy simulation engine with optimization algorithm	Low energy building	Energy simulation engine Energy plus with optimizati n algorithm
Lidberg et al. (2018)	Subarctic	Borlän e, Sweden	Assess the impact of retrofitting strategies using different ventilation systems	Energy and indoor climate analysis		Building Energy simulation using Transys

Dehlin et al. (2019)	Subarc tic	Kiruna, Sweden	Energy performan ce assessment of	Evaluation of different existing design strategies	Multifamily residential building	Measured heating energy use
Nydahl et al. (2019)	Subrct ic	Ålidhem, Umeå	Environme -ntal impact of different retrofitting strategies	Comparison of refurbishmen t investments based on a life cycle approach.	Multifamily residential building	IDA ICE and ROI (return on investment) for LCA (life cycle assessment)
Ramirez-Villegas et al. (2019)	Subarc tic	Borlänge, Sweden	Environme -ntal impact of different retrofitting strategies	Life Cycle Assessment from materials and energy perspective for different retrofitting strategies	Multifamily residential building	IDA ICE for dynamic building energy simulation and LCA analysis using EPD
Kenzhekhan ov et al. (2020)	Subarc -tic	8 subarctic cities in USA, Canada, Finland, Sweden and Russia	Evaluate the thermal and energy performan ce of PCM (phase change material)	Thermal and energy performance of PCM using building energy simulation	Multifamily residential building	Design Builder
Lundqvist et al. (2020)	Subarc -tic	Kiruna, Sweden	Evaluation of an air heating system	Indoor thermal climate assessment through an air heating system using a computation - al fluid dynamics model	Passive house	ANSYS CFX (Computati onal Fluid Dynamics Software)
Hamburg et al. (2020)	Subarc tic	Tallinn, Estonia	Retrofittin g solutions for achieving NZEB level	Energy performance and indoor climate assessment for different retrofitting strategies	Multifa mily residenti al building	IDA ICE

Lundqvist et al. (2022)	Subarctic	Kiruna, Sweden	Energy use and indoor thermal climate assess-ent	Assessment of energy use and indoor thermal climate through measured data and simulation	Two multifamily residential buildings, one of them is considered retrofitted	ANSYS CFX (Computati onal Fluid Dynamics Software)

From the reviewed literature, it was found that applying high-performance insulation materials such as PIR and VIP, heat recovery ventilation, air-heating systems and energy-efficient windows can be good strategies for achieving thermal comfort and reducing the operational energy use of buildings in a subarctic climate. However, the literature also highlights that even though upgrading to energy-efficient windows and heat recovery ventilation are efficient renovation strategies for operational energy use reduction, it results in higher embodied energy use. Therefore, previous research also motivates the importance of taking embodied energy use into account when considering energy efficient strategies for residential buildings in a subarctic climate.

To assess the energy performance of buildings, energy simulation is regarded as one of the most acknowledged methods in building energy practices. Building performance simulation is the representation of a real building using a computer-based, mathematical model that uses fundamental building physics techniques. The building performance simulation is the quantification of building performance assessment evaluation that takes into consideration design, construction, location, climate and advanced building control system.

3. Methods

3.1. Research design

An overview of the methods and studies used to answer the research questions is presented in Table 2.

Table 2: Overview of the methods and studies used to answer the research questions.

Research question	Methods	Applied cases	Studies
RQ1: What is the impact of evaluated energy-efficiency strategies on the operational energy use?	Literature study, building energy simulation and parametric analysis	Case study building 1, 2 and 3	Papers 1, 2 and 3
RQ2: What is the impact of evaluated energy-efficiency strategies on the life-cycle energy use?	Literature study, building energy simulation and multiobjective optimization	Case study building 2	Paper 2
RQ3: What is the impact of evaluated energy-efficiency strategies on the thermal indoor climate?	Literature study, building thermal indoor climate simulation and parametric analysis	Case study building 1 and 3	Papers 1 and 3

Building energy simulations using IDA ICE or EnergyPlus were performed for case study building 1 and 2, and parametric analyses in IDA ICE were performed for case study building 3. Initially, existing building design strategies were studied to understand the current energy performance of the building. The energy analysis performed was based on the analysis of the building envelope (e.g. construction details) and static metered data. A comparative analysis was performed for case study building 1 to understand the discrepancy between measured and simulated operational stage energy use. Indoor climate analysis was also performed to assess the temperature variations throughout the year. Outdoor temperature data was collected from Swedish Meteorological Institute (SMHI) and indoor temperature was collected through sensors placed in different zones of the building. For case study building 2, a life cycle energy analysis was conducted through multiobjective optimization. The building phases considered in the life cycle energy analysis included the manufacturing and use phases and therefore accounted for both embodied energy and operational stage energy use. In the study, the embodied energy use represented the energy required to produce different insulation materials, windows and the ventilation system, while the operational stage energy use considered the heating energy use. Operational energy use and indoor climate analysis using building energy simulation were conducted for case study building 3. The impact of design strategies with and without glazed balconies, window-to-wall ratio, type of balcony glazing and building location were evaluated from energy and indoor climate perspective. The methods are described in the appended papers (Papers 1, 2 and 3).

3.2. Case study buildings

Figure 1 shows the three residential buildings used in papers 1, 2 and 3 to evaluate the energy use and indoor thermal climate.

Figure 1: Case study building 1, 2 and 3.

3.1.1. Case study Building 1

Case study building 1 was used to evaluate the impact of passive house strategies on the operational stage energy use (RQ1) and the indoor thermal climate (RQ3) through measured data and building energy and indoor climate simulation. The study is presented in Paper 1.

The building is a semi-detached two-story house located in Kiruna, the northernmost subarctic town of Sweden. The building is divided into two apartments with a heated floor area of 140 m2 each. The house was developed from the construction company NCC's concept house, "Kuben", which was upgraded into a passive house. Paper 1 evaluates discrepancies between measured and simulated heating energy use based on measured heating energy use during one year of operation collected from Tekniska Verken in Kiruna AB (the company responsible for the district heating plants in Kiruna). The building envelope of Sjunde Huset is very airtight and well insulated. The house is also equipped with a mechanical ventilation system with heat recovery. There is a vestibule which prevents unnecessary heat loss and protects the indoor climate (NCC, 2017). Photovoltaic panels are placed on the façade for electricity production and roofs are designed green with herbs and plants to see their impact on energy performance. Other energy-efficiency measures inside the passive house are the Nasa shower and energy-efficient appliances connected to district heating.

3.1.2. Case study building 2

Case study building 2 was used to evaluate the impact of a range of retrofitting strategies on the operational energy use (RQ1) and the life cycle energy use (RQ2). To find the optimal retrofitting solutions for case study building 2 that minimize the life cycle energy use, the tradeoff between operational and embodied energy use was evaluated using multiobjective optimization. The trade-off optimization results contain a set of Pareto solutions where each solution can be chosen as an optimal one, i.e., the optimal solution in terms of life cycle energy use can be identified from the Pareto solutions. The study is presented in Paper 2.

The case study building is a three-story multifamily residential building with a heated floor area of 1257 m2 in Piteå, Sweden. It is one of four similar buildings in a small residential area representative of the building technique typical of the 1980s in northern Swedish low-rise housing. The building is divided into two blocks with six apartments on each floor. The intermediate wall between the two blocks is made of 150 mm thick concrete that works as a noise barrier and fire protection. Space and hot water heating are provided through the city's district heating system and the apartments are equipped with hydronic radiators. The building is equipped with a fan-controlled exhaust air ventilation system and the air is extracted from the kitchen and toilets. The building has a concrete ground floor slab. The external facade is mostly rendered with brick. The construction is made of vertical concrete framed load-bearing walls with insulation placed in between and timber framed wooden stud partition walls with rock wool insulation. At the balconies, the walls consist of comparatively thinner timber framed walls with insulation.

3.1.3. Case study building 3

Case study building 3 was used to evaluate the impact of four design parameters (with and without glazed balconies, window-to-wall ratio, balcony glazing, building location) on the operational energy use (RQ1) and indoor thermal climate (RQ2) through building energy and indoor climate simulation. The study is presented in Paper 3.

The building is a newly built (2017) high-rise multi-family residential building with glazed balconies located in Piteå, Sweden. The building has sixteen floors with a total heated area of about 6600 m2. The main active heating system comprises hydronic radiators connected to the city's district heating grid through heat distribution units. The building is equipped with a mechanical ventilation system with a heat exchanger to ensure good energy efficiency and indoor air quality. The structure is a prefabricated sandwich construction consisting of concrete and mineral wool insulation. The building contains 60 apartments with between 46 m^2 and 148 m^2 living space. Each apartment has a curved-shaped glazed balcony with a single clear glass (6 mm) situated up to two meters from the thermal envelope. The glazed balconies are positioned on all floors and in all cardinal directions and cover about 70 % of the façade. The glazing gives the building an oval shape that creates an iconic feature and provides sound insulation from external noise.

4. Summary of the appended papers

This chapter presents a summary of the appended papers

4.1. Paper 1. Performance evaluation of a passive house in subarctic climate

The aim of Paper 1 was to make a comparative analysis of operational energy use and indoor temperatures in a non-occupied and occupied zone for the case study building Sjunde huset. Table 3 shows measured and simulated energy use for Sjunde huset.

Table 3: Simulated and measured energy use in apartment 2 of the "Sjunde Huset".

	Energy use (kWh/m^2. year)		
	Simulated occupied	**Simulated non-occupied**	**Measured non-occupied**
Heating	40	45	32
Domestic hot water	10	0	-
Other (ventilation losses through windows, auxiliary energy for fans and pumps, etc.)	11.2	5.5	-
Total energy use	61	51	32

The zone was unoccupied at the time of measurement; therefore, simulations were used to predict the energy use and indoor thermal climate for both occupied and non-occupied conditions. As shown in Table 3, there is a discrepancy between the measured and the simulated operational energy use. The main reason behind this difference is that the simulated values were predicted in the design stage, whereas the measured values represent the operational-stage conditions. It was found that the heating energy use was higher for the non-occupied zone than the occupied zone. Heat gains do not occur from electrical appliances and occupants in a non-occupied zone, which puts pressure on the heating system to maintain an optimum temperature indoors. Although the building envelope is made well insulated and very airtight, heat gains from the occupants and electrical appliances can positively affect the heating energy use, especially during winter when solar gains are minimal in a subarctic climate.

To assess the temperature variations during summer and winter, the months of July and December were selected for indoor thermal climate analysis. Figure 2 shows the measured daily average temperature collected during July and December 2016.

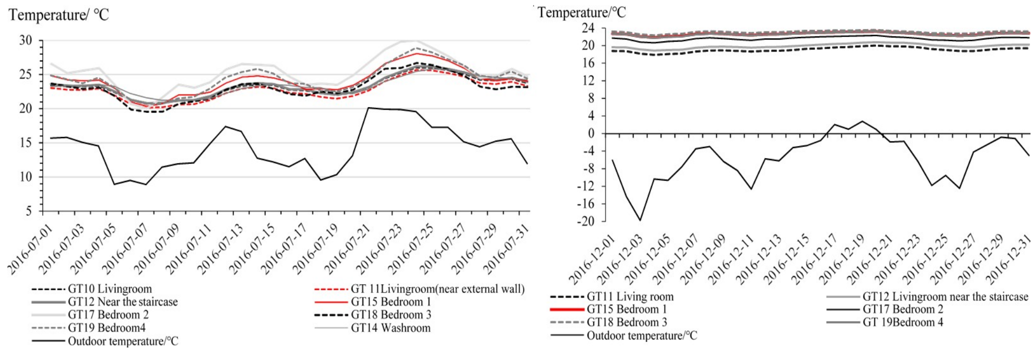

Figure 2: Measured daily average indoor and outdoor temperatures during July and December 2016.

As shown in Figure 2, the measured indoor temperature in the unoccupied zone during winter (December) stayed between 18 °C and 23 °C, whereas the outdoor temperature was low and varied between 0.9 °C and -19 °C. It seems that the heating and ventilation system worked at a satisfactory level.

During summer (July), the indoor temperature peaked at 30 °C in a bedroom situated at the first floor level while the outdoor temperature was only 20 °C. The airtight and well insulated building was unoccupied for a longer time, which seemed to have caused overheating indoors. The building was not equipped with any active cooling system as the climate during summer is very mild and short in the subarctic town of Kiruna. The higher temperature during summer could have been reduced by window airing or shading devices, which was not possible due to the house being unoccupied.

4.2. Paper 2. Exploring the trade-off in life cycle energy of building retrofit through optimization

The aim of Paper 2 was to explore the impact of different retrofitting solutions on the operational/embodied energy trade off for a building located in a subarctic climate in Sweden by using multiobjective optimization. Optimal retrofitting solutions for minimizing the case study building's life-cycle energy use were identified for three Swedish energy-efficient building standards (FEBY, 2018):

The new build energy standard (bronze class) allows a maximum heat loss factor of 24 W/m^2 during the coldest winter day for buildings situated in a subarctic climate.

Mini energy standard (silver class), which can be regarded as a near zero criterion for new and retrofitted buildings, allows a maximum heat loss factor of 21 W/m^2 during the coldest winter day for buildings located in a subarctic climate.

Passive house standard (gold class) is the strictest energy criterion and allows a maximum heat loss factor of 16 W/m^2 during the coldest winter day for buildings located in Swedish subarctic climate.

Table 4 shows the 12 energy-efficiency strategies taken into consideration for performing the multiobjective optimization and the identified optimal combinations of strategies to achieve the bronze, silver and gold classes, respectively.

Table 4: Simulated retrofitting strategies (referred to as retrofitting measures, RM) and corresponding changes in life cycle energy (LCE) use for all identified optimal solutions.

Component and material type							Material thickness (m)										Δ LCE (GJ)	
RM1. Window type	RM2. Ventilation system	RM3. Additional insulation in floor	RM4. Additional insulation in EW 1	RM5. Additional insulation in EW 2	RM6. Additional insulation in EW 3	RM7. Additional insulation in roof	RM8. Additional insulation in floor		RM9. Additional insulation in EW 1		RM10. Additional insulation in EW 2		RM11. Additional insulation in EW 3		RM12. Additional insulation on roof			
							Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Bronze class																		
Triple-glazed window	heat recovery ventilation	PIR	Mineral wool	Mineral wool	Mineral wool	Cellulose	0	0.03	0	0.09	0.02	0.18	0.02	0.04	0.51		-13021	-12867
				PIR			0	0.03	0	0.08	0.02	0.18	0.03	0.04			-	-
		VIP					0.01	0.02	0	0.09	0.18		0.03	0.04			-	-
		PIR			VIP		0.02	0.03	0	0.05	0.18		0.03	0.065			-	-
			VIP		Mineral wool		0.02	0.03	0.04	0.11	0.17	0.18	0.03	0.06			-12323	-11265
					VIP		0.02	0.03	0.08	0.118	0.18		0.06	0.065			-	-
		VIP					0.02	0.03	0.1	0.118	0.18		0.06	0.065			-	-
		PIR		VIP	Mineral wool		0.03		0.08	0.110	0.09	0.11	0.03	0.065			-10309	-9570
					VIP		0.03		0.09	0.118	0.09	0.14	0.06	0.065			-9558	-8282
		VIP					0.02	0.03	0.11	0.118	0.1	0.18	0.06	0.065			-8702	-6870
Silver class																		
Triple-glazed window	heat recovery ventilation	PIR	Mineral wool	Mineral wool	Mineral wool	Cellulose	0.03		0.04	0.118	0.06	0.18	0.03	0.06	0.51		-12979	-12879
				PIR			0.03		0.03	0.08	0.06	0.18	0.03	0.06			-	-
					VIP		0.03		0.03	0.11	0.18		0.03	0.06			-	-
			VIP		Mineral wool		0.03		0.03	0.118	0.18		0.03	0.06			-12362	-11185
					VIP		0.03		0.08	0.118	0.18		0.05	0.06			-	-
		VIP					0.03		0.09	0.11	0.18		0.05	0.06			-	-
		PIR		VIP	Mineral wool		0.03		0.07	0.11	0.06	0.1	0.03	0.06			-10519	-9747
					VIP		0.03		0.09	0.118	0.08	0.14	0.05	0.06			-9710	-8335
		VIP					0.03		0.1	0.118	0.08	0.18	0.05	0.06			-8940	-6940
Gold class																		
Triple-glazed window	heat recovery ventilation	VIP	VIP	PIR	Mineral wool	Cellulose	0.03		0.09	0.1	0.18		0.065		0.51		-11120	-11027
					VIP		0.02	0.03	0.07	0.118	0.03	0.06	0.03	0.06			-	-
				VIP	Mineral wool		0.02		0.07	0.1	0.08	0.1	0.03	0.065			-9985	-9437

According to the results shown in Table 4, four retrofitting strategies (installation of triple pane windows, heat recovery ventilation, additional cellulose insulation in roof and additional cellulose insulation of 0.51m on roof) were found in all the Pareto solutions aiming to achieve the energy standards. The retrofitting strategies that provided the highest LCE savings were obtained from the solutions aiming to achieve the bronze class and these included: (1) addition of (0–0.03 m) PIR insulation on the floor, (2) addition of (0–0.09 m) mineral wool in the external wall 1, (3) addition of (0.02–0.18 m) mineral wool in external wall 2, and (4) addition of (0.02–0.04 m) mineral wool in external wall 3. To obtain the gold class, addition of 0.03 m VIP insulation on the floor, 0.09-0.1 m VIP insulation in external wall 1, 0.18 m insulation in external wall 2, and addition of 0.065 m insulation in external wall 3 was required to obtain the highest LCE savings.

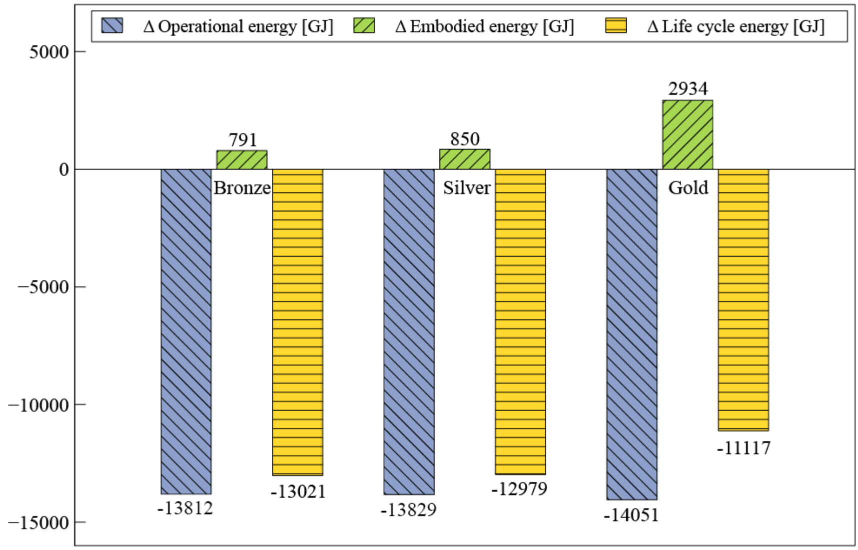

Figure 3: Differences in operational, embodied and life cycle energy values of the optimal solutions for the bronze, silver and gold classes, respectively. A minus sign indicates life cycle energy savings.

Figure 3 shows the simulated life cycle energy savings obtained for the optimal solutions for each of the three energy efficiency standards. As shown in Figure 3, the optimal solution that fulfilled the new build energy standard (bronze class) provided higher life cycle energy (LCE) savings than the optimal solutions of the mini energy standard (silver class) and the passive house standard (gold class). The highest operational energy saving (-14051 GJ) and the lowest embodied energy increase (791 GJ) were attained for the gold class. However, the highest life cycle energy savings (-13021 GJ) was achieved for the bronze class.

4.3. Paper 3. Energy and indoor thermal performance analysis of a glazed façade high-rise building under various Nordic climatic conditions

The aim of paper 3 was to evaluate the energy and indoor thermal performance of a glazed high-rise residential building through a parametric whole-year simulation-based study under various Nordic climate conditions. Four design parameters (with and without glazed balconies, type of balcony glazing, window-to-wall ratio, and building location) were varied to evaluate their influence on the case study building's heating energy use and indoor thermal climate.

According to the simulation results, the as-built condition with glazed balconies resulted in 16 % higher energy use than a simulated case without any glazed balconies. The recommendation issued by the Swedish HVAC Association (Ekberg 2013) and The Public Health Agency of Sweden (FoHMFS 2014:17) for maintaining a comfortable indoor temperature in dwellings is 20-24 ºC during winter and 23-26 ºC during summer. Therefore, temperatures exceeding 26 °C were considered as overheating hours. This criterion was developed based on the International standard ISO 7730 (International Organization for Standardization [ISO] 2005). During winter, the simulated operative temperature showed an optimum range of 20-23 ℃ in both scenarios. However, findings show that during summer, the operative temperature reached 30 ℃ in the case of glazed balconies when the incoming solar irradiation penetrated the glazing and heated the indoor space. On the contrary, the operative temperature during summer never exceeded the recommended maximum 26 °C or the case without glazed balconies, i.e., no overheating occurred.

From the energy perspective, double-pane balcony glazing provided better thermal insulation which led to lower heating energy use than single-pane balcony glazing did. It also resulted in fewer overheating hours. Lowering the window-to-wall ratio (WWR) from 70 % (base case) to 50 % resulted in around 6 % energy saving and a considerable reduction in the overheating hours due to limiting solar irradiation admission.

The simulated locations included six Nordic cities representing different climatic conditions (ranging from oceanic to subarctic): Copenhagen, Reykjavik, Stockholm, Helsinki, Piteå (base case) and Tromsø. The results show that the highest heating energy use was obtained for the most northerly location Tromsø gave and the lowest heating energy use was obtained for the most southerly location Copenhagen. The heating energy saving for the location Copenhagen was around 43% compared to the base case location Piteå. During winter, the operative indoor temperature was moderate and remained within the recommended range of 20-24 °C for all studied locations. However, during summer, the operative indoor temperature exceeded the recommended maximum of 26 °C in all studied locations except Reykjavik. The highest operative temperature (up to 33°C) were obtained for the southwest and southeast oriented apartments at the 15th floor and the south and west oriented apartments situated at the 9th floor level for the location Helsinki.

The simulation results revealed that the overheating hours do not depend on the location only; other factors influencing the higher temperature indoor include heat from direct and diffuse solar irradiation, and heat generated from walls and floors and heat from circulated air flow.

5. Discussion and Conclusion

5.1. Impact on operational energy use

Both physical and human influenced factors influence the operational energy performance of buildings in a cold climate (Nord 2009). The physical factors include climate, building envelope and equipment used in the building and human influenced factors include occupant behavior, indoor environment, operation, and maintenance. This thesis considered the impact of all these factors except occupant behavior.

Energy efficiency strategies applied in case study building 1 include an airtight and highly insulated building envelope which constitutes an uninterrupted thermal barrier, a vestibule to minimize infiltration losses, a mechanical ventilation system with heat recovery to minimize the ventilation heat losses and energy-efficient lighting and appliances. The results show that the strategies significantly reduce the operational energy use of the building. Due to this, the heating energy use is lower than traditional single-family buildings in the subarctic. Nord (2009) mentioned occupancy as an influential factor for operational energy use, which reflects the findings from Paper 1. Due to the absence of occupants, more active heating was required to maintain a comfortable indoor temperature increasing the operational energy use. In addition, it was found that the battery of the heat exchanger was not working properly, which created a disruption in the supply of heating and eventually affected the building's energy performance, which is in line with conclusions derived from investigations of a low-energy house in an arctic climate (Rode et al. 2009, Rode et al. 2010, Vladykova et al. 2012). This indicates the importance of having a well-functioning heating and ventilation system along with an insulated and airtight building envelope for a passive house in a subarctic climate.

Moreover, an airtight and highly insulated building envelope equipped with a mechanical ventilation system with heat recovery can be favorable for not only a passive house but also for existing multifamily residential buildings. In Paper 2, different energy efficiency strategies for retrofitting were evaluated to upgrade the energy performance of a multifamily residential building (case study building 2) which is around 40 years old. The results show that combinations of energy efficiency strategies such as addition of thick insulation material on the exterior wall and roof, upgradation of existing windows to triple pane windows and change of the traditional mechanical extract ventilation to heat recovery performed well in terms of reducing the operational energy use. These results support recommendations by Boverket

(2016) and La Fleur et al. (2019) to improve the building envelope as well as technical installations such as ventilation system in order to reduce the operational energy use.

For case study building 3, the impact of three different energy efficiency strategies – adding glazed balconies, changing from single to double pane balcony glazing and lowering the window to wall ratio – was evaluated. According to the simulation results, the building's operational energy use was lower when there were no glazed balconies present. Previous studies have mentioned that glazed balconies can yield up to 20 % (Asdrubali et al. 2012) and 15-32 % (Suárez et al. 2011) of reduction in heating energy demand during winter in southern European climates, which contradict to our findings. When glazed balconies were applied, double pane balcony glazing resulted in lower heating energy use compared to single pane glazing which matches with the study by Hilliaho et al. (2015b) where energy savings of 14.8 -16 % was achieved after replacing the balcony glazing by double pane glazing. Double pane glazing has a higher thermal resistance, so it provides better insulation and therefore reduces the heat loss more than single pane glazing. Reduction in window to wall ratio compared to the base case setting proved to be better from the energy perspective. Generally, increasing the window to wall ratio can help increase the passive solar gains which contribute to heating. However, during winter in a subarctic climate the passive solar heat gains are limited as the amount of incoming solar irradiation is small. Furthermore, finding an optimal window-to-wall ratio while designing buildings is crucial and requires considering the orientation, climate, type of the building, etc. In addition, the results indicated that single-glazed balconies are not ideal choice for lowering the operational energy use of residential buildings under subarctic and Nordic climate conditions and suggested double-pane balcony glazing as a better option. Upon reviewing the existing literature, it was found that previous studies have not explicitly investigated the energy performance of a glazed residential building in Nordic climate conditions. The findings add value to the existing knowledge base.

5.2. Impact on life cycle energy use

In paper 2, the impact of various energy efficiency strategies – addition of insulation on the exterior wall, floor and roof, upgradation of existing windows to triple pane windows and changing the traditional mechanical extract ventilation to heat recovery – on the life cycle energy use was explored. The findings show that aforementioned retrofitting strategies are the optimal ones that yield highest LCE savings. As previously discussed, while adopting energy efficient strategies it is important to consider the influence on life cycle energy, which were investigated in the studies by Nydahl et al. (2019) and Ramirez-Villegas et al. (2019). The results from Nydahl et al's (2019) study show that installing energy-efficient windows can reduce the operational energy moderately but contributes highly to the embodied energy. However, in Paper 2 the "trade-off" was considered to illustrate possible combinations of strategies that result in not only operational energy reduction but do not generate too high embodied energy as well.

According to findings of Paper 2, the optimal retrofitting strategies that brought significant life cycle energy savings are: addition of thermal insulation such as cellulose and mineral wool on roof and external wall, replacing the existing double pane to more efficient triple pane windows and replacing the traditional mechanical extract ventilation to heat recovery. Ramirez-Villegas et al. (2019) also discuss the combination of different energy efficient strategies and the influence on life cycle from a trade off perspective, which aligns to Paper 2. However, the life cycle analyses performed was broader and also took building materials and construction process into consideration which could be of interest as a further step from the study presented in Paper 2.

Mukhopadhya et al. (2014) proposed using high-performance insulation material (VIP) in a retrofitted building located in a subarctic climate for a better reduction in operational energy use. Another study by Kenzhekhanov et al. (2020) tested the performance of PCM in a multifamily building in eight subarctic cities in various countries, including Sweden and Finland, and found that PCM can contribute to significant annual operational energy savings. In Paper 2, it was tested how the application of advanced insulation materials such as PIR and VIP to the multifamily building envelope for retrofitting can affect the operational/embodied energy tradeoff. These materials are considered as "high performance" as they provide high thermal efficiency with minimum thicknesses and are of alternatives for retrofitting buildings when there exist space constraints. However, they materials generate higher embodied energy use than traditional materials such as mineral wool and EPS. According to the findings of Paper 2, the application of PIR and VIP can bring significant reduction to the operational energy use of the studied building, but since the embodied energy use increased considerably there were little LCE savings. From the tradeoff perspective, the use of PIR and VIP were therefore not recommended in Paper 2. PCM was not tested in any of the case study buildings. However, as it can be considered an interesting option for a multifamily residential building located in a subarctic climate, the impact of PCM could be evaluated from a life cycle energy perspective in future studies.

On a different note, in case study building 1, space and hot-water heating are provided through district heating which is converted to air heating via a heating coil. Since the heating is not supplied through radiators but through air heating, the embodied energy saving might be significant here. Therefore, air heating may act as a sustainable option from a life-cycle energy perspective for passive houses in a subarctic, although this requires further investigation.

5.3. Impact on thermal indoor climate

When constructing passive or low energy buildings the building envelope is generally made very airtight and well insulated to limit heat losses. Due to this and excessive solar gains, the risk of overheating is described as a common problem in passive or low energy buildings situated in southern European or Mediterranean climates (Mlakar & Štrancar, 2011; Figueiredo et al., 2016). Strategies such as the installation of triple pane windows and external shadings were suggested to reduce the risk of high indoor temperatures in the aforementioned literature. Even in a cold, subarctic and arctic climate, overheating has been detected as a potential problem for residential buildings (Fleur et al., 2018; Lundqvist et al., 2020; Vladykova & Bjarløv, 2012), which aligns with the findings from Paper 1 regarding overheating during summer. Results of Paper 1 shows that as the building was unoccupied for a longer time, a substantial increase in indoor temperature was noticed during summer in the airtight and highly insulated building envelope although the outdoor temperature was moderate. To reduce the high indoor temperatures during summer manual airing or ventilating the space as well as shading were suggested in Paper 1. It means that occupancy can have a profound influence as occupants can detect, intervene and take action against any indoor environment discomfort. In addition, Lundqvist et al's (2020) study provided insights into how the air heating system in case study building 1 could be redesigned to create a satisfactory indoor thermal environment. It means that solutions such as inspection and adjustment of the heating system can be important to mitigate the risk of overheating in passive houses. It can be concluded that not all adopted energy efficiency strategies applied to the studied building can guarantee a good indoor thermal environment. Therefore, while adopting such strategies, priorities should not only be given towards energy efficiency instead, consideration must be given towards both energy savings and a comfortable indoor environment because energy efficiency strategies that contribute to energy reduction will not sustain if they cannot also ensure a good thermal indoor environment.

Adding glazed facades, balconies or sunspaces to an existing building has been considered an energy efficient strategy in the existing literature (Bataneh & Fayez 2011; Fotopoulou et al. 2018; Hilliaho et al. 2016; Mihalakakou 2002, Oliveti et al. 2012); however, the influence of such a strategy on the indoor thermal climate is not always satisfactory. Overheating has previously been portrayed as a potential problem during summer in buildings with glazed balconies or attached sunspaces located in Middle eastern, southern European and humid subtropical climates (Saleh, 2015, Ribeiro et al., 2020; Mihalakakou, 2002, Oliveti et al., 2012, Fernández-González, 2007). Greenhouse effects of glazed balconies during summer under cold climate conditions were also detected in earlier studies where the balcony temperature was around 5°C higher than the outdoor temperature (Hilliaho et al., 2015a, 2016; Fernández-González, 2007). Similar to Hilliaho et al. (2015a, 2016), the findings obtained from Paper 3 strengthen the case for the occurrence of overheating in residential buildings with glazed facades and balconies under subarctic conditions. It adds evidence through simulation that applying glazed balconies is not favorable from an indoor thermal climate perspective in subarctic conditions unless appropriate shading or cooling is designed for the affected space. Furthermore, the study's results suggest that double-pane balcony glazing helps to decrease the overheating hours during summer, as does lowering the window-to-wall ratio due to less admission of solar irradiation.

5.4. Method discussion

While performing energy and indoor climate analysis for case study building 1, it was unoccupied during the entire analysis period. However, the energy performance and indoor climate may vary if the building is occupied. Therefore, a detailed comparative energy and indoor climate analysis with occupied and unoccupied zone could have strengthened the study. Another limitation of the study is that the impact of energy-efficient strategies such as minimizing thermal bridges, applying renewable onsite energy production and using advanced building control systems was not investigated.

The studies of case study building 2 and 3 suggest energy-efficient strategies that have been considered from a theoretical perspective but have never been tested on the actual building. Monitoring and analyzing the real case study buildings for a few years could help to determine whether the suggested combinations of energy-efficient strategies are suitable or not for residential buildings in a subarctic climate.

The strategies for improving energy efficiency have been evaluated for three case study residential buildings in the subarctic region of northern Sweden. The results might only be generalized for some residential buildings in this region since other buildings might have different designs and characteristics. Moreover, the solutions addressed in this study for improving energy efficiency might not apply to other types of buildings (e.g. office buildings) in the region, the performance of which could be the subject for future studies.

6. Future Research

The results provide guidance towards establishing a set of energy-efficient strategies helpful for building owners to apply to residential buildings in a subarctic climate. For further research, the following could be considered:

- Life cycle cost analysis can add value to the existing research, as it can help building owners make economically viable choices for adopting energy efficiency. Such analysis can also benefit researchers exploring scenarios and associated costs for buildings in a subarctic climate.
- Natural ventilation and shading can both contribute to minimizing the indoor temperature, which can be considered as a future step for case study building 1 and 3.
- It would be interesting to get measurement data regarding heating energy use and indoor temperature in a fully occupied passive house (case study building 1). A comparative analysis can be performed between occupied and non-occupied zone which can further add value to the topic.
- The impact of solar irradiation during summer in a passive house could be interesting to investigate. Since case study building 1 is equipped with solar panels it could be of interest to explore the possibility of implementing renewable energy sources into more passive houses in subarctic climates.

References

Annunziata, E., Frey, M., & Rizzi, F. (2013). Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe. Energy, 57, 125–133. https://doi.org/10.1016/j.energy.2012.11.049

Antipova, E., Boer, D., Guillén-Gosálbez, G., Cabeza, L. F., & Jiménez, L. (2014). Multi-objective optimization coupled with life cycle assessment for retrofitting buildings. Energy and Buildings, 82, 92–99. https://doi.org/10.1016/j.enbuild.2014.07.001

Ascione, F., Bianco, N., De Stasio, C., Mauro, G. M., & Vanoli, G. P. (2015). A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. Energy and Buildings, 88, 78–90.

Ascione, F., Bianco, N., De Stasio, C., Mauro, G. M., & Vanoli, G. P. (2016). Simulation-based model predictive control by the multi-objective optimization of building energy performance and thermal comfort. Energy and Buildings, 111, 131–144.

Ascione, F., Bianco, N., De Masi, R. F., Mauro, G. M., & Vanoli, G. P. (2017). Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance. Energy and Buildings, 144, 303–319.

Asdrubali, F., Cotana, F., & Messineo, A. (2012). On the evaluation of solar greenhouse efficiency in building simulation during the heating period. Energies, 5(6), 1864-1880.

Banister, C., Swinton, M., Moore, T., Krys, D., & Macdonald, I. (2018). Energy Consumption of an Energy Efficient Building Envelope in the Canadian Arctic. Cold Climate HVAC.

Bataineh, K.M., & Fayez, N. (2011). Analysis of thermal performance of building attached sunspace. Energy and Buildings, 43(8), 1863-1868.

Berge, A., & Johansson, P. (2012). Literature review of high performance thermal insulation.

Boverket. (2016). Underlag till den andra nationella strategin för energieffektiviserande renovering. https://www.boverket.se/globalassets/publikationer/dokument/2016/forslag-pa-uppdaterad-strategi-for-energieffektiv-renovering_slutversion.pdf

Brun, A., Spitz, C., Wurtz, E., & Mora, L. (2009). Behavioural comparison of some predictive tools used in alow-energy building. IBPSA 2009 - International Building Performance Simulation Association 2009.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews, 29, 394–416.

Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment, 105, 267–282.

Dehlin, S., Heincke, C., & Koskinen, P. (2019). Passive House Construction Above the Arctic Circle. Cold Climate HVAC Conference.

Diakaki, C., Grigoroudis, E., & Kolokotsa, D. (2008). Towards a multi-objective optimization approach for improving energy efficiency in buildings. Energy and Buildings, 40(9), 1747–1754.

Ekberg, L. (2013). R1 – Riktlinjer för specifikation av inneklimatkrav. EMTF Förlag AB.

Fan, Y., & Xia, X. (2015). A Multi-objective Optimization Model for Building Envelope Retrofit Planning. Energy Procedia.

Figueiredo, A., Kämpf, J., & Vicente, R. (2016). Passive house optimization for Portugal: Overheating evaluation and energy performance. Energy and Buildings, 118, 181-196.

Fotopoulou, A., Semprini, G., Cattani, E., Schihin, Y., Weyer, J., Gulli, R., & Ferrante, A. (2018). Deep renovation in existing residential buildings through façade additions: A case study in a typical residential building of the 70s. Energy and Buildings, 166, 258-270.

FoHMFS 2014:17. Folkhälsomyndighetens allmänna råd om temperatur inomhus. https://www.folkhalsomyndigheten.se/contentassets/da13aa23b84446d3913c4ec32a6a276d/fohmfs-2014-17.pdf

Fumo, N., Mago, P., & Luck, R. (2010). Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. Energy and Buildings, 42(12), 2331–2337.

Hachem, C., Athienitis, A., & Fazio, P. (2014). Energy performance enhancement in multistory residential buildings. Applied Energy, 116, 9–19.

Hamburg, A., Kuusk, K., Mikola, A., & Kalamees, T. (2020). Realisation of energy performance targets of an old apartment building renovated to nZEB. Energy, 194.

Hilliaho, K., Lahdensivu, J., & Vinha, J. (2015). Glazed space thermal simulation with IDA-ICE 4.61 software - Suitability analysis with case study. Energy and Buildings, 89, 132–141.

Hilliaho, K., Köliö, A., Pakkala, T., Lahdensivu, J., & Vinha, J. (2016). Effects of added glazing on Balcony indoor temperatures: Field measurements. Energy and Buildings, 128, 458-472.

Janson, U. (2010). Passive houses in Sweden. From design to evaluation of four demonstration.

Kalamees, T. (2004). IDA ICE: the simulation tool for making the whole building energy- and HAM analysis. In IEA Annex 41 MOIST-ENG, Working meeting May 12-14,.

Karlsen, L. (2015). Integrated design of daylight, thermal comfort and energy use with use of IDA ICE. 7. Passivhus Norden Conference.

Kenzhekhanov, S., Memon, S. A., & Adilkhanova, I. (2020). Quantitative evaluation of thermal performance and energy saving potential of the building integrated with PCM in a subarctic climate. Energy.

Kurnitski, J., Allard, F., Braham, D., Goeders, G., Heiselberg, P., Jagemar, L., Kosonen, R., Lebrun, J., Mazzarella, L., Railio, J., Seppanen, O., Schmidt, M., & Virta, M. (2012). How to define nearly net zero energy buildings nZEB. REHVA Journal, 48(3), 6–12.

Kurnitski, J. (2013). Technical definition for nearly zero energy buildings. Journal of the REHVA Federation of European Heating, Ventilation and Air Conditioning Associations, 50(3).

La Fleur, L., Rohdin, P., & Moshfegh, B. (2018). Energy use and perceived indoor environment in a Swedish multifamily building before and after major renovation. Sustainability, 10(3), 766.

Lidberg, T., Gustafsson, M., Myhren, J. A., Olofsson, T., & Ödlund (former Trygg), L. (2018). Environmental impact of energy refurbishment of buildings within different district heating systems. Applied Energy, 227, 231–238.

Lin, B., Wang, Z., Liu, Y., Zhu, Y., & Ouyang, Q. (2016). Investigation of winter indoor thermal environment and heating demand of urban residential buildings in China's hot summer–Cold winter climate region. Building and Environment, 101, 9-18.

Lundqvist, P., Risberg, M., & Westerlund, L. (2020). The importance of adjusting the heating system after an energy-retrofit of buildings in a sub-Arctic climate. Energy and Buildings, 217, 109969.

Lundqvist, P., Risberg, M., & Westerlund, L. (2022). Indoor thermal climate after energy efficiency measures of a residential building in a sub-Arctic region: Comparing ANSYS CFX and IDA ICE methods. Indoor and Built Environment, 31(3), 732-744.

Magrini, A., Lentini, G., Cuman, S., Bodrato, A., & Marenco, L. (2020). From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example. Developments in the Built Environment.

Mlakar, J., & Štrancar, J. (2011). Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations. Energy and Buildings, 43(6), 1443-1451.

Mihalakakou, G. (2002). On the use of sunspace for space heating/cooling in Europe. Renewable Energy, 26(3), 415-429. doi:10.1016/S0960-1481(01)00138-0

Mukhopadhyaya, P., MacLean, D., Korn, J., Van Reenen, D., & Molleti, S. (2014). Building application and thermal performance of vacuum insulation panels (VIPs) in Canadian subarctic climate. Energy and Buildings, 85, 672–680.

NCC. (2017). Sjunde huset -ett lågenergiparhus i Kiruna, Slutrapport 38548-1.

Nord, N. (2017). Building energy efficiency in cold climates. Encyclopedia of Sustainable Technologies, 149.

Nydahl, H., Andersson, S., Åstrand, A. P., & Olofsson, T. (2019). Environmental performance measures to assess building refurbishment from a life cycle perspective. Energies, 12(2).

Oliveti, G., Arcuri, N., De Simone, M., & Bruno, R. (2012). Solar heat gains and operative temperature in attached sunspaces. Renewable Energy, 39(1), 241-249.

Paiho, S., Seppä, I. P., & Jimenez, C. (2015). An energetic analysis of a multifunctional façade system for energy efficient retrofitting of residential buildings in cold climates of Finland and Russia. Sustainable Cities and Society, 15(75–85).

PHI. (2016). Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard. In Passive House Institute.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. Energy and Buildings, 42(10), 1592–1600.

Ramírez-Villegas, R., Eriksson, O., & Olofsson, T. (2016). Assessment of renovation measures for a dwelling area - Impacts on energy efficiency and building certification. Building and Environment, 97, 26–33.

Ramírez-Villegas, R., Eriksson, O., & Olofsson, T. (2019). Life cycle assessment of building renovation measures–trade-off between building materials and energy. Energies, 12(3).

Ribeiro, C., Ramos, N.M.M., & Flores-Colen, I. (2020). A review of balcony impacts on the indoor environmental quality of dwellings. Sustainability, 12(16), 6453.

Risberg, D., Vesterlund, M., Westerlund, L., & Dahl, J. (2015). CFD simulation and evaluation of different heating systems installed in low energy building located in sub-arctic climate. Building and Environment, 89, 160–169.

Rode, C., Kragh, J., Borchersen, E., Vladykova, P., Furbo, S., & Dragsted, J. (2009). Performance of the Low-energy House in Sisimiut. Cold Climate HVAC.

Rode, C., Vladykova, P., & Kotol, M. (2010). Air tightness and energy performance of an Arctic Low-Energy House. Proceedings of the 5th International Symposium on Building and Ductwork Air-Tightness.

Rohdin, P., Molin, A., & Moshfegh, B. (2014). Experiences from nine passive houses in Sweden–Indoor thermal environment and energy use. Building and Environment, 71, 176-185.

Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive building energy savings: A review of building envelope components. Renewable and Sustainable Energy Reviews, 15(8), 3617–3631.

Saleh, P.H. (2015). Thermal performance of glazed balconies within heavy weight/thermal mass buildings in Beirut, Lebanon's hot climate. Energy and Buildings, Shadram, F., & Mukkavaara, J. (2018). An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy. Energy and Buildings, 158, 1189–1205.

Suárez, M.J., Gutiérrez, A.J., Pistono, J., & Blanco, E. (2011). CFD analysis of heat collection in a glazed gallery. Energy and Buildings, 43(1), 108-116.

Swedish energy-efficient building standards FEBY 18, Sweden's center for zero energy houses." should be "Swedish Forum for Energy Efficient Buildings, FEBY (2018).

Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Building and environment, 37(4), 429-435.

Vladykova, P., Rode, C., Kragh, J., & Kotol, M. (2012). Low-Energy House in Arctic Climate: Five Years of Experience. Journal of Cold Regions Engineering, 26(3), 79–100.

Vladykova, P., & Bjarløv, S. P. (2012). Prospective future introduction of reduction of energy use in buildings in the Arctic regions - How might it affect the indoor climate? 10th International Conference on Healthy Buildings 2012.

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