DOCTORAL THESIS

Realisation of Energy Renovation Targets of Estonian Apartment Buildings

Anti Hamburg

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

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Eesti korterelamute renoveerimisel energiatõhususe eesmärkide saavutamine

ANTI HAMBURG

TALTECH KIRJASTUS

Abstract

Realisation of energy renovation targets of Estonian apartment buildings

Renovation of apartment buildings has been relevant in Estonia, and more widely in Eastern Europe, for the last 25 years due to the Energy Efficiency Directive as well as the motivation to save energy costs. The Energy Efficiency Directive sets targets for the decarbonisation of building stock. It is often the case that targets for energy savings after renovation are not reached.

This research focused on the analysis of the energy performance of renovated apartment buildings and clarification of the factors influencing the realisation of savings targets. Heat consumption is significantly affected by the indoor air temperature, the performance of ventilation and use of domestic hot water (DHW). The study included these aspects in the analysis of why energy performance targets have not been achieved. The study assessed how much the energy consumption of renovated buildings differs, compared with energy consumption before renovation. Human influence on energy usage after deep energy renovation was examined, and also whether there is a need to make changes to the Energy Performance Classification (EPC) calculation standard use of apartment buildings.

The research showed that in all buildings, the average indoor air temperature was, on average, more than 1 °C higher after renovation than before renovation. According to questionnaires, this was due to a change in the heating system where, after the renovation, adjustment with thermostatic valves is possible, and is also related to the need for people to feel comfortable. Measured ventilation airflows are lower than calculated values in most apartments, which is largely due to the technical capabilities of installed ventilation systems. The analysis of electricity consumption showed that the losses are comparable to standard use, and there is no significant change compared to the pre–renovation situation. In contrast, the larger change is related to the change of the building's domestic hot water system from local domestic hot water heaters to a central system, where the loss of circulating hot water is added to the heat losses. For this reason, this study recommends calculating and measuring the heating energy for domestic hot water and for circulation separately.

The most serious problem in achieving heating energy goals is related to the quality of energy performance calculations, as well as the capability of the calculation program. There was also a clear link with the desire to reach the maximum limit set for financial support, which has motivated those making calculations to show the heating energy losses more optimistically than can be measured after reconstruction. Calculations made on the basis of implementation projects resulted in significantly higher calculated heating energy consumption in most buildings, which would have made the energy efficiency class of buildings one class higher.

In the current situation, domestic hot water circulation is not calculated as a part of energy efficiency calculations. This research showed that domestic hot water system heat losses can affect energy performance values significantly, and in this study a method was developed that allows calculation of these heat losses at an early design stage, when limited data about service systems is available.

Keywords: indoor climate, energy audit, energy renovation, heat consumption, performance gap, domestic hot water system heat losses.

Lühikokkuvõte

Eesti korterelamute renoveerimisel energiatõhususe eesmärkide saavutamine

Korterelamute renoveerimine on olnud Eestis, Ida–Euroopas kui ka laiemalt aktuaalne viimased 25 aastat tulenevalt energiatõhususe direktiiviga kui ka motivatsiooniga energiakulusid kokku hoida. Energiatõhususe direktiiviga on pandud paika ka oluliselt rekonstrueeritavate hoonete energiatõhususe saavutamise eesmärgid.

Oma uuringutes olen keskendunud renoveeritud korterelamute renoveerimisjärgse energiatõhususe analüüsile ja energiatõhusust mõjutavate tegurite selgitamisele. Peamiselt olen analüüsinud seda, kas hoonetes on saavutatud eesmärgiks seatud kütteenergia kulu. Kütteenergia kulu omakorda mõjutavad oluliselt ka ruumiõhu temperatuur ning ventileeritav õhuvooluhulk. Seepärast olen ka oma uuringutes hinnanud nende seoseid kütteenergia kulule. Kui hoonete energiatõhususarvutused teostatakse nn. standardkasutusel olen hinnanud ka hoonete mõõdetud soojatarbevee energia kui ka kulutatud elektrienergia kaudu, palju on renoveeritud hoonete energia kulu sellega võrreldes erinev ning kas oleks vajalik muuta renoveeritud hoonete standardkasutust või mitte.

Minu uuringutes selgus, et renoveerimisjärgses olukorras on keskmine siseõhutempteratuur kõigi hoonete keskmisena rohkem kui 1 °C võrreldes renoveerimiseelse olukorraga kõrgem. Küsitluste põhjal on see tingitud süsteemi muutusest, kus reguleerimine renoveerimisjärgselt on võimalik ja ka on see seotud inimese mugavustunde vajadusest. See omakorda tähendab ka seda, et hoonete kütteenergia saavutamine eesmärgiks seotud tasemel on raskendatud. Seevastu mõõdetud ventilatsiooni õhuvooluhulgad on enamikes elamutes võrreldes arvutusliku olukorraga väiksemad, mis on tuleneb paljuski selle tehnilisest lahendusest. Kütteenergia kulu saavutamise kõige tõsisem probleem on seotud ebakompetentselt sooritatud arvutustega ning ka arvutusprogrammiga. Selge seos on olemas ka sooviga saavutata toetuseks ette antud maksimumpiir, mis on motiveerinud arvutajaid projektlahenduse kütteenergia kulu näitama optimistlikumalt kui see realiseeruks. Teostusprojektide alusel tehtud arvutused andsid enamikus hoonetes oluliselt suurema arvutusliku kütteenergia kulu, millega oleks hoonetete energiatõhusussklass olnud ühe klassi võrra kõrgem. Elektrienergiakulu analüüs näitas, et kulu on standardkasutusega võrreldav ning olulist muutust võrreldes renoveerimiseelse olukorra pole. Seevastu suurem muutus on seotud hoone tarbevee süsteemi muutmisel lokaalsete veesoojendusseadmetelt tsentraalsele süsteemile, kus kulule lisandub soojavee ringluse soojuskadu. Mille tõttu on soovitav tulevikus tarbevee tsirkulatsioonile kulunud soojushulka eraldi arvutada ning ka mõõta.

Tänases olukorras soojavee tsirkulatsiooni eraldi hoone energiatõhususe kavandamise staadiumis ei arvutata, vaid kulu baseerub ainult tarbitud vee soojendamise kulule. Oma doktoritöös pakun välja meetodi kuidas võiks tulevikus soojatarbevee süsteemi kadu eraldi arvesse võtta.

Märksõnad: siseõhu temperatuur, energiatõhus renoveerimine, kütteenergia kulu, mõõdetud energia kulu, arvutatud energia kulu, sooja tarbevee soojuskadude arvutamine

Contents

List of publications

The thesis is predominantly based on the publications in the following peer–reviewed journals:

I Hamburg, A. and Kalamees, T. (2019). 'How well are energy performance objectives being achieved in renovated apartment buildings in Estonia?' Energy Build. 2019, 199, 332–341, doi:10.1016/j.enbuild.2019.07.006.

II Hamburg, A.; Kuusk, K.; Mikola, A.; Kalamees, T. (2019). Realisation of energy performance targets of an old apartment building renovated to nZEB. Energy, 194, 116874. DOI: 10.1016/j.energy.2019.116874.

III Hamburg, A. and Kalamees, T. (2018). 'The Influence of Energy Renovation on the Change of Indoor Temperature and Energy Use', Energies. Multidisciplinary Digital Publishing Institute, 11(11), p. 3179. doi: 10.3390/en11113179.

IV Hamburg, A.; Mikola, A.; Parts, T. M.; Kalamees, T. (2021). Heat Loss Due to Domestic Hot Water Pipes. Energies, 14 (20), #6446. DOI: 10.3390/en14206446.

and on publication in the following peer–reviewed conference proceeding:

V Hamburg, A. and Kalamees, T. (2018). 'Improving the indoor climate and energy saving in renovated apartment buildings in Estonia', The 9th International Cold Climate Conference Sustainable new and renovated buildings in cold climates. Kiruna Sweden 12-15 March.

Author's contribution to the publications

Contribution to the papers in this thesis are:

I In publication I, the analysed data was collected by the author of the thesis in 2016−2017. Data analysis was performed by the author and guided by the supervisor. The research principles of the study were developed together with the supervisor, T. Kalamees.

II Publication II was written together with K. Kuusk. All analyses were made A. Mikola, K. Kuusk and the author. T. Kalamees designed the scientific research in the building and revised the paper.

III In publication III, analyses of the measured data were carried out by the author of the thesis. The research principles of the study were developed together with the supervisor, T. Kalamees.

IV In publication IV analyses of the measured data were carried out by the author of the thesis. The research principles of the study were developed together with the supervisor, T. Kalamees. A. Mikola helped build up the calibration of the indoor climate and energy simulation model of the nZEB case building and T–M. Parts helped with statistical analysis.

V In publication V, calculations and analyses of the collected and measured data were carried out by the author of the thesis. The research principles of the study were developed together with the supervisor, T. Kalamees.

Introduction

Currently, about 35% of buildings in Europe are over fifty years old, and are responsible for 40% of energy consumption (EPBD recast, 2010) and 36% of CO_2 emissions in the EU. In Estonia, the proportion of buildings as a percentage of total energy consumption is significantly higher than the EU average – around 50%.

The residential sector represented 25% of final energy consumption in the EU (Eurostat, 2019). At 35%, Estonia holds third position after Romania and Latvia (Raudjärv & Kuskova, 2013). Space heating is the main use of energy by the residential sector in the EU (65% of final energy consumption in the residential sector) (Eurostat, 2019). In Estonia 88% of dwellings are connected to a district heating (DH) system (Statistics Estonia, 2013).

Although the requirements for energy use of new buildings have been tightened since the energy crisis in the 1970s, the energy use of existing buildings is still high (Csoknyai et al., 2016) compared to what we expect from nearly–Zero Energy Buildings. Because the replacement rate of the existing building stock is only some percentages per year, the renovation and improvement of the energy performance of existing building stock plays an important role in reaching national energy efficiency targets. A large number of buildings in Europe are old and in need of refurbishment, which would improve their functionality, living standards, and energy performance and decrease CO_2 emissions (Cetiner & Edis, 2014; Corrado & Ballarini, 2016; Dascalaki et al., 2011; Hrabovszky–Horváth et al., 2013; Matic et al., 2015; Niemelä et al., 2017a; Sandberg et al., 2016; Shahrokni et al., 2014).

Many studies have discussed the energy saving potential in existing buildings. One of the first analyses of the energy saving potential in Post–Soviet countries was done by Cooper and Schipper (1992). Energy saving potential in Hellenic buildings has been shown by Balaras et al. (2000). Heating energy consumption analyses in five countries by Balaras et al. (2005) showed that about 38% of the buildings have averaged more than 174 $kWh/m^2{\cdot}a$ of heating energy consumption which is similar to existing buildings in Estonia (Martinot, 1997).

Many studies have underlined the importance of energy renovation to improve indoor climates, especially the performance of ventilation (Földváry et al., 2017; Meijer et al., 2009).

The Energy Performance of Buildings Directive (EPBD) (EPBD, 2018), the Energy Efficiency Directive (EED) (EED, 2012), and the Renewable Energy Directive (RED) (RED, 2009) defines a framework for long–term improvements in the energy performance of Europe's building stock. Uihlein and Eder (2010) have shown that energy–renovation forced by EU policy improved new building, and also renovated building, energy efficiency.

The problem is that the replacement rate of the existing building stock is only some percentages per year. This means it is important to renovate apartment buildings more and improve energy efficiency, as much as this is cost–effective. By doing this it becomes possible to reach national energy efficiency targets. Analyses in 2016 (2016/0381 (COD), 2016) showed that, depending on the Member State, only 0.4% – 1.2% of the building stock is renovated each year. In 2009 Meijer et al. showed that higher energy savings can be achieved in the large stock of existing dwellings than in the relatively small proportion of newly built dwellings. Baek and Park (2012) showed that lack of awareness, information, regulatory systems and economic reasons, are the major barriers to improving the energy performance of existing residential buildings. Indoor climate and energy modelling have estimated the savings potential to be in the range of 40% – 80% of energy use (Kuusk & Kalamees, 2015b; Paiho, Pinto, et al., 2015; Pombo et al., 2016; Thomsen et al., 2015).

Based on the 2011 Population and Housing Census (Statistics Estonia, 2011), 64% of the population in Estonia lives in apartment buildings. In Estonia, there are approximately 27 000 apartment buildings. Approximately 80% of these buildings were built between 1945 and 1990, using similar mass production technology. The majority of these buildings have the same typical problems: high energy consumption levels, insufficient ventilation, uneven indoor temperatures, and insufficient thermal comfort levels (Ilomets, Kalamees, et al., 2017; Ilomets, Kuusk, et al., 2017; Mikola et al., 2017). Previous studies (Arumägi & Kalamees, 2014; Kuusk et al., 2014; Kuusk & Kalamees, 2015) have shown that average heating–related energy consumption levels for apartment buildings falls between 136–150 kWh/(m^2·a), while, when heating domestic hot water, the figures are 27–39 kWh/(m^2·a), and for electricity, they are 32–35 kWh/(m^2·a) (Kuusk & Kalamees, 2015). Based on calculations, energy reductions of approximately 70% in delivered energy need and 60% in primary energy need are possible with nZEB renovation. The targeted energy saving is not always realised. Therefore, it is important to find the extent and reasons for this performance gap.

The first steps to evaluating buildings energy consumption started in the 1990s after Estonian independence from the Soviet Union. The starting point was collaboration with specialists from Finland, Sweden, and Denmark. The moving force for renovation for energy saving reasons starts at the beginning of the 2000s. Energy prices were already an issue and there was also a desire to follow the EPBD directive on the energy performance of buildings (EPBD recast, 2002) in Estonia. The first government requirement for energy efficiency was established in Estonia in December 2007 (RT I 2007, 72, 2007). At that time a training program for energy efficiency specialists was started in Estonia. The training was based on different subjects and the trainees came from different backgrounds in electricity, HVAC, heat supply and construction engineering. These courses lasted only some months. Before study courses began in 2008 some specialists had already gained some knowledge from an earlier course in the late 1990s.

2008 and 2011 was the period over which many energy audits were done in apartment buildings. The goal was to see how much and where the energy losses were and what solutions could be employed to negate these losses. Unfortunately, the quality level of these was not as good as it should have been (Kõiv et al., 2011).

In addition to building properties, the user also influences the energy use, by influencing the indoor climate (thermal comfort, indoor air quality), the use of domestic hot water (DHW), appliances and lighting. Ideally, the standard use of the building, defined by user profiles, should be as close as possible to the average use and equalise the variation between apartments. How the renovation of the building changes the user energy consumption profile (temperature, ventilation, DHW, household electricity etc.) has not been well studied. We also have very little knowledge of DHW circulation losses. This is assumed from measured DHW consumption (litres) and from calculated heating energy use which is compared with measured DHW heating energy. There is also a lack of knowledge of how much of these losses can be utilised as internal gain and how these losses affect the entire renovated apartment building energy consumption. A method for introducing DHW system losses into EPC calculations is needed.

Objective and content of the study

The main objective of this PhD research was to determine the realisation of energy renovation targets of Estonian apartment buildings. For this target, an analysis was made of the performance gap in energy consumption of apartment buildings – energy use before and after renovations – and comparing these values with targeted ones.

The following research questions have been raised:

- How big is performance gap between calculated and measured energy consumption?
- Why is there a performance gap between calculated and measured energy saving and energy performance levels?
- How much does user related energy use change after renovation and is there a need to change the standard use for apartment buildings?
- How to calculate DHW system losses in early–stage designs in EPC calculations?

The approach to the research questions in the thesis is based on five peer–reviewed publications (see list of publications, page 11).

Performance gap between calculated and measured energy consumption were analysed in articles V (energy save target), I (EPC target) and II (nZEB renovation) together in 36 renovated apartment buildings. Calculated and measured energy consumptions were compared in all buildings. The reasons why there exist performance gap were analysed in those buildings. Indoor temperature and energy consumptions before and after renovation were analysed and energy consumption was calculated according to the design in all buildings.

User related energy consumption were analysed in article III. The aim was to analyse how the renovation affect thermal comfort, is there a gap between measured indoor temperature before and after renovation and how DHW and electricity consumption changes. The aim was to see how measured consumptions differ from calculated values.

Earlier studies showed that DHW system losses are in buildings where is DHW circulation, that one reason why there exists performance gap. There was analysed in article V how performance gap can be minimized, when DHW system heat losses are involved in EPC calculations. It also was studied how much these losses can be utilised as internal heat gain.

New knowledge

This thesis gained new knowledge from renovated apartment buildings:

- The research showed that a financial grant target to save energy or to reach an EPC class could motivate auditors to show energy performance calculations more optimistically then could be achieved in reality. In most cases, heating energy consumption was calculated to a lower figure than subsequent recalculations with the same renovation solutions resulted in.
- Many systematic inaccuracies were found in heating energy calculations (with envelopes, thermal bridges, thermal transmissions and infiltration heat losses), which could be avoided with better inspection after design. Unfortunately, these inaccuracies seriously affect the heating energy need calculations.
- Research in 35 apartment buildings showed that the indoor temperature after renovation is more than one degree higher compared to the situation before renovation. This is primarily caused by the added possibility to regulate thermostat valves (TRV). This potential for occupants to regulate the heating levels is also one reason why measured heating energy is larger than calculated.

- This analysis showed that DHW circulation heat losses should be calculated separately from volume based DHW heating use. With local boilers in apartments DHW system pipe losses are non–existent but, with centralised DHW systems, DHW circulation pipe losses in basements and shafts start to appear. In this study, an alternative calculation method for DHW system heat loss for use early in the design process was developed.

Practical applications

After researches:

- A guide has been compiled based on experience and practice from field research (Hamburg & Jõesaar, 2015). It describes in more detail how to avoid the serious calculation and analysis mistakes that were discovered in examined audits. Recommendations as to how energy audits should be done, and which calculation and energy analysis methods should be used, are also presented.
- After this research in which heating energy savings target realisation was analysed, new government financial grant rules were developed (RT I, 31.12.2015 2016). From year 2015, the renovation grant is based only on the targeted EPC class.

Limitations

In this research only renovated, prefabricated concrete element, brick and lightweight concrete apartment building types, which were constructed between 1950 and the 1990s in Estonia were analysed.

Abbreviations

AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air–Conditioning Engineers
AVG	Average
COP	Coefficient of performance
CO_2	Carbon dioxide
DE	Delivered energy
DH	District heating
DHW	Domestic hot water
EED	Energy Efficiency Directive
EN	European standard
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Classification
EPV	Energy Performance Value
EPS	Expanded Polystyrene
EU	European Union
ETICS	External thermal insulation composite system
EXHP	Exhaust air heat pump
IDA–ICE	IDA Indoor Climate and Energy
ISO	International Organization for Standardization
LED	Light–Emitting Diode
MW	Mineral Wool
NAT	Natural ventilation as it was before renovation
NAT+FAI	Natural ventilation plus added extra outdoor air inlets
PE	Primary energy
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfaction
PV	Photovoltaic
RED	Renewable Energy Directive
SERU	Supply and exhaust air room based ventilation unit
SD	Standard Deviation
TRV	Thermostat valves
TRY	Test reference year
nZEB	Nearly zero–energy building
VHR	Ventilation heat recovery

Terms

Deep renovation	Improvement of energy performance to level of EPC “C” or low–energy buildings (EPC “B”). Generally, this means a minimum of 70% energy savings.
Delivered energy, DE	Energy, expressed per energy carrier, supplied to the technical building systems through the system boundary, the uses of energy are taken into account (e.g. heating, cooling, ventilation, domestic hot water, lighting, appliances etc.) or to produce electricity.
Energy audit	Energy audit is documents which show the energy consumption of a building for different energy sources and how to improve the energy performance of building.
Energy performance of a building, EP	The calculated or measured amount of energy needed to meet the energy demand associated with the typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water, and electricity (for lighting and depending on national regulations, also for appliances).
Rebound effect	This situation where the calculated energy savings are not being achieved due to behavioural responses.
Energy renovation package	A set of energy performance measures and/or measures based on renewable energy sources applied to a renovation of a building.
Performance gap	The performance gap in energy saving presents deviations of buildings’ overall energy efficiency target compared to its actual operating performance. It is associated with a number of contributing factors in the design and construction of the building envelope and systems or in the management procedures affecting the operational phase of the building.
Primary energy, PE	Energy forms found in nature from renewable and non–renewable sources that has not undergone any conversion or transformation process. Can be presented as measured (real use on TRY) or simulated (standard use on TRY) amount. PE takes into account the use of primary energy (for space heating, ventilation, domestic hot water, all electricity loads (including lighting and appliances (plug loads)) and environmental impact according to the energy source, with the weighting factors.
Energy carrier factor	The Estonian regulation (RT I, 13.12.2018 2018) uses the following multiplayer factors to calculate PE from delivered energy (DE). Wood, wood–based fuels, and other biofuels: 0.75 (until 2019), 0.65 (from 2019); district heating: 0.9 efficient district heating: 0.65; fossil fuels (gas, coal etc.): 1.0; electricity: 2.0; district cooling: 0.4; efficient district cooling: 0.2.

Symbols

A	area, m^2
c	specific heat capacity, J/(kg·K)
d	thickness, m
H	specific heat loss coefficient, W/K
l	length, m
M	mass, kg
n	air change rate, h^{-1}
O	occupancy, m^2/person
Q	thermal energy, J
RH	relative humidity, %
R	thermal resistance, $m^2 \cdot K/W$
R^2	coefficient of determination, –
t	temperature, °C
U	thermal transmittance, $W/(m^2 \cdot K)$
V	volume, m^3
v	velocity, m/s

1 Renovation of housing stock

1.1 Overview of renovation of the housing stock in Estonia

The final energy use in Estonia is 33 TWh/a (Statistics Estonia, 2019), of which half (50%) is used by buildings (Kurnitski et al., 2014). The majority of Estonian apartment buildings were constructed between 1960–1990. These buildings are mostly concrete large–panel and brick apartment buildings, built mostly according to typical design solutions. Buildings were designed mainly by local designers, Soviet Union–wide typical designs were adopted to Estonian local conditions or Soviet Union–wide designs were used directly. All major towns have larger or smaller districts with typical buildings. In Tallinn the largest apartment building districts are Mustamäe, Õismäe, and Lasnamäe and in Tartu, Annelinn. Without renovation, heating energy consumption of these buildings is 136–150 kWh/(m^2·a). Domestic hot water energy consumption is 27–39 kWh/(m^2·a), and electricity consumption is 32–35 kWh/(m^2·a) (Arumägi & Kalamees, 2014; Kuusk et al., 2014; Kuusk & Kalamees, 2015a).

The systematic research and renovation of apartment buildings started at the beginning of the 1990s, after Estonian independence from the Soviet Union. With the involvement of experts from several foreign countries (Sweden, Finland, Denmark, etc.), priority measures for energy savings in residential buildings were quickly identified (Hääl et al., 2000). The main driver for this was increased energy prices and indoor climate problems. Martinot, Schipper and Khrushch (1995) showed that, at the beginning of the 1990s, Estonia had some barriers to improving energy efficiency in buildings, such as: lack of ownership, lack of capital, also low electricity prices and lack of energy meters, especially in the residential sector. That is why it was so hard to motivate people to start thinking about energy–renovation. In 1993 one of the first pilot projects was done by Finnish company AIR–IX OY and Estonian consulting company Ehituskonstruktsioonide ja katsetamise OÜ (EKK). Studies were carried out in the Õismäe district (Tallinn, 5 and 16 storey buildings), which ended with the renovation of the first concrete large panel building (Õismäe tee 5, a 5 storey apartment building constructed in 1975, Figure 1.1 left) in Estonia. Roof, end–facades and upper part (between roof and upper storey's windows, to avoid a serious thermal bridge between the external wall and roof) of the side walls were insulated, side facades were cleaned and painted, the heating system was renovated, natural ventilation was cleaned, and, in every staircase, extraction fans were installed. In 1994 another concrete large-panel building (Sütiste tee 16, a 9 storey apartment building constructed in 1970) was studied by the company Stockholm Konsult, who made proposals for renovation (Roèn et al., 1994).

In 1994 EKK studied typical 5 and 9 storey concrete large–panel apartment buildings and designed example renovation solutions for 14 buildings (EKK, 1994). In 1996 the design company EstKONSULT studied apartment buildings in Tallinn, Mustamäe district and designed example renovation solutions for 16 buildings (EstKONSULT, 1996).

With the support of the INTERREG IIIB project, Baltic Energy Efficiency Network for the Building Stock (BEEN,) a concrete large-panel apartment building was renovated in 2006–2007 (Paldiski mnt. 171, a 5 storey apartment building constructed in 1977, Figure 1.1 right) (KredEx, 2008). The main idea of this pilot project was to have as great as possible energy efficiency to lower, mainly, the heating energy bills (the target was ≈50% energy saving in heating energy consumption). All external walls and roof were insulated, all windows were replaced and the heating system was reconstructed. The weak point of this pilot was ventilation which was not renovated (mechanical ventilation) because of a lack of funding. Based on the first measurements, heating consumption decreased ≈70% and the indoor temperature equalised on all storeys after the renovation. This project showed that all reconstruction works must be done together, as a complete project. The authors of this study came to the same conclusion during previous research into partly renovated apartment buildings, in which the typical apartment building indoor climate, external walls and energy efficiency were analysed (Hamburg et al., 2010). In all buildings external walls have been insulated but ventilation was poor and CO_2 levels in those buildings were high.

Figure 1.1 Development of renovation of apartment building over 15 years. In the beginning (left, 1993) only end–walls and roof were insulated, and the heating system was balanced. Later (right, 2008) the whole building envelope was insulated, windows were replaced, heating system was rebuilt. Mechanical ventilation with heat recovery is still missing today.

During 2008 and 2012, the Tallinn University of Technology conducted several cross–sectional research projects around the technical condition and renovation solutions of apartment buildings (Kalamees et al., 2009, 2011; Kalamees, Kõiv, et al., 2010). These research projects have shown that the main saving from reconstruction solutions and renovation packages came from heating energy consumption. Heating energy need, together with ventilation heat, in prefabricated concrete element buildings could fall after renovation (depending on the building) by 48 to 65 kWh/(m^2·a) and in brick apartment buildings by 51 to 54 kWh/(m^2·a). From the first cross–sectional research project on concrete large-panel apartment buildings a pilot renovation followed in 2010 (Kuusk et al., 2017). The building envelope (roof, external walls and basement walls) was completely insulated, windows were changed, new 2–pipe system with thermostats and a central exhaust system with heat recovery with exhaust air heat pump were installed in a large panel apartment building (Sõpruse 244, 5 storeys, constructed in 1966, Figure 1.2 left). The renovation project was generally successful, with delivered energy need decreasing by 40% and heating energy need decreasing by 50%.

The Horizon2020 project 'MORE–CONNECT' has been launched to develop energy performance, hygrothermal performance and aesthetics of buildings, and demonstrate technologies of prefabricated modular renovation elements, including the prefab integration of multifunctional components, e.g. for climate control (Veld, 2015). In Estonia, a pilot renovation was conducted in 2017 on a large panel apartment building (Akadeemia 5a, 5 storeys, constructed in 1991, Figure 1.2 right). The building envelope above ground (walls and roof) was insulated with prefabricated modular insulation elements where the window was installed under factory conditions. Basement walls were insulated with an external thermal insulation composite (ETICS) system. Completely new service systems were installed: hydronic radiators with thermostats, mechanical ventilation with heat recovery (VHR) (for parallel comparison of two different solutions: apartment based balanced VHR and centralised balanced VHR), new DHW system (for parallel comparison of heating of DHW by solar collectors and sewage heat recovery), PV panels for electricity production (Pihelo et al., 2017). Based on preliminary results, substantial energy reductions were achieved. Nevertheless, based on measured energy consumption, the nZEB target was not achieved, mainly because of a higher (compared to standard use values) use of DHW and electricity.

Figure 1.2 Complete energy renovation of apartment building with onsite renovation (left 2012) and offsite prefabricated renovation (right 2018).

During the period between 2010 and 2014, a total of 663 apartment buildings have undergone refurbishment work, and the average energy savings for each apartment building were 43% (Kuusk & Kalamees, 2015). Based on the knowledge obtained over many years, a guide for renovation of ventilation and building envelopes of typical post WWII apartment buildings was developed in Estonia (Kalamees et al., 2016) and is well used by designers and consultants. In 2015 a new grant scheme started, supporting more intensive energy efficiency–related refurbishment work with a total of 102 million euros for existing apartment buildings in Estonia. The grant was closed at the end of 2017 due to a lack of funding. A new grant was established in 2019. Financial support in 2019 was planned at 17.7 million euros which should be enough for 50 apartment building renovations (MKM, 2019).

1.2 Overview of renovation of the housing stock in Estonia's neighbouring countries

Martinot (1998) gave, in his study, an overview of apartment renovation projects at the beginning of the 1990s in Post–Soviet countries. In his study he showed that during the 1990s, which is analysed in cross–sectional studies by himself, the Danish Building Research Institute, BCEOM French Engineering Consultants, SWECO Ab, Finnish Energy Conservation Group, World Bank etc. that in 27 houses investigated in Lithuania there were potential energy savings of 17% to 65% and, in 5 Russian studied houses, between 28% to 33%.

1.2.1 Sweden

There are close to 5 million dwellings in Sweden, 51% are located in apartment buildings (Statistics Sweden, 2017). A lot of residential buildings were constructed between 1965 and 1974, as part of a state–subsidised program known as Million Homes Program (Hall & Vidén, 2005). These buildings have a great need, and potential, for energy saving, shown by many studies. Lind et al., (2016) searched for a sustainable renovation strategy for the Million Homes Programme and showed that a sustainable renovation is possible, but a number of conflicts exist between the different dimensions of sustainability. In 44% of apartment buildings some energy efficiency measures have been implemented (Boverket, 2013). Mata, Sasic Kalagasidis and Johnsson (2013) analysed the technical potential for energy savings and showed that there is a potential to reduce the final energy demand of the Swedish residential sector by 53%. The greatest savings were provided by heat recovery systems (22%) and those that involve a reduction of the indoor temperature (14%). Liu et al. (2014) showed that energy saving measures such as external wall insulation, window replacement, installation of VHR, adjusting heating systems and utilising solar thermal or PV panels would reduce energy use of apartment buildings in the Gävleborg region by 50% by 2050. Gustafsson et al. (2016) showed that exhaust air heat pumps in combination with flow–reducing water taps and improvements of the building envelope reduced the primary energy consumption by up to 58%, CO_2 emissions by up to 65% and non–renewable energy consumption by up to 56%, compared to apartment buildings with only district heating and no energy saving measures. Lina La Fleur, Moshfegh, and Rohdin (2017) studied apartment buildings with district heating (constructed in 1961 and renovated in 2014) and showed a 44% reduced energy demand after renovation because of significantly reduced transmission and ventilation losses.

Dodoo, Gustavsson, and Le Truong (2018) showed that by using improved insulation for attic floor, basement walls and exterior walls, improved windows and doors, resource–efficient taps, heat recovery of exhaust ventilation air, energy–efficient household appliances and lighting, the cost–effective final heat savings are between 34% and 53% while the cost–effective electricity savings are between 34% and 46% for the analysed buildings under different contexts including locations.

1.2.2 Finland

There are 3 million dwellings in Finland, 46% are located in apartment buildings (Statistics Finland – Housing, 2019). The amount of new buildings built in a typical year is about 1.4% compared to existing buildings (Tuominen et al., 2013), and the cumulative energy consumption of the whole building stock of Finland could have been reduced by 2% by the year 2020 (Tuominen et al., 2014).

Holopainen, Hekkanen, and Norvasuo (2007) have shown in their research on Finnish buildings energy saving potential, that in three apartment buildings, specific heat consumption varied before renovation between 188–255 kWh/(m^2·a) and after renovation 82–138 kWh/(m^2·a). Holopainen et al., (2016) have shown in their case studies of nearly–Zero Energy Building renovation that the renovation potential in a reference building done in the traditional way was 42% and using nZEB concepts was up to 71.5%. Niemelä et al., (2017) showed in their study of the cost–effectiveness of energy performance renovation measures in Finnish brick apartment buildings, that the cost–optimal level for the renovation was close to the minimum energy performance requirements of new apartment buildings (130 kWh/(m^2·a)).

Niemelä, Kosonen, and Jokisalo (2017) demonstrated that by renovating large-panel apartment buildings to nZEB level, up to 90–98 €/m^2 net savings, 850–930 kWh/m^2 over the studied 30–year life–cycle period can be achieved, when the cost–optimal renovation concepts are selected.

Lahdensivu and Uotila (2013) analysed energy consumption of 119 apartment buildings, where various renovations of the building envelope and service systems had been made and showed a 14% average saving with facade renovation, 5% with renewing the windows and 4% by adjustment of heating system. In some cases, heat consumption did not change or even increased after repair actions.

1.2.3 Lithuania

In Lithuania the biggest share (81%) of housing stock in cities goes to apartment buildings and 69% of them were built between 1961 and 1991 (M. Staniūnas et al., 2013). In 1998 Kazakevičius showed that in Post–Soviet countries it is hard to find finances to renovate existing housing stock and there can also be other problems (Kazakevicius et al., 1998). In 1999 Vine showed that while the potential for saving energy in this sector is large, significant barriers to energy efficiency remain (Vine & Kazakevicius, 1999). Lithuania's technical monitoring of the implemented residential projects have shown a 50% heating energy saving potential (Kazakevičius et al., 2002). In the 1960s, the quality of construction works was not as good as in the 1970s and that is why energy consumption in earlier buildings is greater with a more variable heating energy use (Juodis et al., 2009).

In 2011 Biekša et al. showed that in Lithuania, the residential building sector has not utilised the energy saving potential, and one reason for this is the lack of transparency in the building modernisation process and because the building certification method for energy saving estimation in use at the time was far from accurate. The conclusion was that energy auditing methods should be more accurate.

Prasauskas et al. (2016) showed that RH levels in some Lithuanian apartments can be associated with more airtight building envelopes and lack of ventilation and this can be improved by installing mechanical ventilation units.

1.2.4 Latvia

Augustins *et al.*, (2018) showed in analysis of ESCO experiences in Latvia, that the normalised specific heating energy needs on a yearly basis in buildings after deep renovation consumes from 70 kWh/m^2 to 100 kWh/m^2 year, which correspond to the designed energy performance before renovations. The main renovation solutions in this region are similar to those in Estonia and Lithuania. Upitis et al., (2020) showed even better results from the Latvian DME programme (renovation financial support in the form of grants, loans, guarantees and advice). The grant goal was that heating energy consumption cannot be more that 90 kWh/m^2 year.

1.2.5 Russia

The existing housing stock of the Russian Federation is 3.6 billion m^2. In Russia, about 60% of the country's apartment buildings need extensive capital repair and reconstruction to improve the energy efficiency and the comfort of the accommodation therein (IFC & EBRD, 2012). The average heating energy consumption of typical old apartment buildings in Moscow is 217 kWh/(m^2·a) and the average electricity consumption 42 kWh/(m^2·a). A 60% reduction from total energy consumption is possible by using advanced renovation concepts (Paiho et al., 2013). Korniyenko (2018) showed that for non–modernised buildings with a specific heat consumption for heating and ventilation of 150–200 kWh/(m^2·a), that, after thermal modernisation of buildings, the heat consumption decreases twofold. At the same time (Korppoo & Korobova, 2012) showed in their study that, in Russia, heating consumption levels in apartment buildings are not measured. That is why it is hard to analyse the renovation packages energy savings and cost–efficiency (Satu Paiho, Abdurafikov, et al., 2015). In 2015 it was shown (Satu Paiho, Seppä, and Jimenez, 2015) that since the climate in Finland is rather similar to that in Moscow, then tested renovation solutions from Finland could also be utilised in Russia and would be even more energy–efficient. Later investigations have shown that, due to a lack of housing space, it is common to reconstruct buildings not only for more energy efficiency but to add extra floors (Project Russia, 2018).

1.2.6 Summary of renovation of the housing stock in Estonia's neighbouring countries

An overview shows that in the countries neighbouring Estonia, the same kind of situation occurs with non-renovated apartment buildings as it does in Estonia. The main issue is high heating energy consumption before renovation, and following reconstruction, this can be reduced by more than two times. Renovation practices are common across the whole region but have been more thoroughly analysed in Sweden and Finland where there is more knowledge of how much deep energy renovations can reduce energy consumption and which practices give greater benefits.

1.3 Performance gap in energy saving and user behaviour related energy usage

The performance gap in energy saving presents deviations of a buildings' overall energy efficiency target compared to its actual operating performance. It is associated with a number of contributing factors in the design and construction of the building envelope and systems, or in the management procedures affecting the operational phase of the building (Kampelis et al., 2017). The occupants' behaviour has also been identified as one of the reasons for the energy performance gap (Calì et al., 2016; Mohareb et al., 2017). The systematic review of the literature on occupant behaviour and building energy performance by Zhang et al. (2018) estimated that the occupant behaviour related energy–saving potential could be in the range of 10% − 25% for residential buildings. Desideri et al. (2012) highlighted the need for a better understanding of occupancy behaviour patterns and the use of more realistic input parameters in energy models; needed to bring the predicted figures closer to reality.

It is important from the point of view of quality, finances and energy use that the actual energy consumption of buildings does not differ significantly from the predicted, calculated consumption. Nevertheless, there is often a significant difference between the predicted energy performance for buildings and the actual, measured, energy use levels once buildings become operational (Aydin & Kok, 2013; de Wilde, 2014; O Guerra Santin, 2013). Other studies have also shown that the energy saving gap can be caused by incorrect assumptions of building characteristics in older buildings (Lucchi, 2018; Rasooli et al., 2016; Visscher et al., 2016). Laurent et al. (2013) also showed that energy saving policies are based on the use of theoretical normative calculations and there is a risk that evaluation of energy saving potential, and the speed of its achievement, could be overestimated, and that this risk requires investigation.

Santin, Itard, and Visscher (2009) showed that building characteristics determine a large part of the energy use in a dwelling. Marshall et al. (2017) showed that the calibration of building energy models using accurate measurements for the building's fabric properties reduces the observed performance gap.

Modelling has usually been done on the standard use of buildings (Jarek Kurnitski et al., 2018). In reality, the use of user–related energy can be different compared with the standard use because of the density of occupants or the number of apartments in a building (Ahmed et al., 2015). The use of standardised user profiles for modelling is good for comparing similar buildings and to work out the building stock level. To work out cost–effective energy renovation measures for specific buildings, this peculiarity has to be taken into account. Gram–Hanssen (2013) showed that user behaviour is at least as important as building physics when it comes to energy consumption related to heating, though the user behaviour can only to a very limited degree be explained by objective characteristics of the inhabitants. Van den Brom, Meijer, and Visscher (2019) indicate that occupants on higher incomes save, on average, more energy than occupants on lower incomes. Fransson et al., (2020) showed that the user profile of the apartments in the building can also be assessed by analysing the use of domestic water. Their work in Sweden showed an increase in the number of occupants absent during national holidays by about 300%, and by about 100% over weekends.

Current thesis analyses performance gap in apartment buildings in Estonian cold climate. There is lack of knowledge of where and why there are reasons for performance gap and also how to minimize the performance gap.

1.4 The indoor climate and rebound effect

The rebound effect has been investigated by Sorrell (2014). He has found that most governments are seeking for solutions to improve energy efficiency to fulfil their energy policy goals. But measured energy savings generally turn out to be appreciably lower. He postulates that one explanation could be that improvements in energy efficiency encourage a higher use of those services which are provided by the energy supply. This situation where the calculated energy savings are not being achieved due to behavioural responses has come to be known as the energy efficiency 'rebound effect'. In some cases this rebound effect is high enough to lead to an overall increase in energy consumption, an outcome termed as 'backfire' (Sorrell, 2007). In general the rebound effect is not taken into account in energy efficiency calculations which may lead to an overestimation of the future energy savings (Sorrell, 2014).

Karlsson, Rohdin, and Persson (2007) have shown in their study that the calculated indoor temperature was lower than measured and that is why calculated heating energy consumptions were not achieved. WHO Regional Office for Europe (1987) recommends indoor temperatures between 18 °C and 21 °C. Measured indoor temperature in bedrooms and living rooms can also be lower than is comfortable in existing residential buildings (+18 °C) for inhabitants as is shown by Magalhães, Leal, and Horta (2016) in Northern Portugal. The same kind of problem is analysed by Santamouris et al. (2014) in Greece. One reason could be due to the heating system. In 1982 it was shown (Hunt & Gidman, 1982) that buildings with central heating have an approximately 3 °C higher temperature then buildings without it. Firth, Lomas, and Wright (2010) showed in the UK that changing thermostat settings from 20 °C to 22 °C increased heating energy consumption by 15%. Lindén, Carlsson–Kanyama, and Eriksson (2006) showed in 2006, in a study which was based on 600 Swedish households, that in apartment buildings the indoor temperature was 2 °C higher than in single–family houses. In 1998 Reinhard Haas, Auer, and Biermayr (1998) it was shown that after renovation there was a rebound–effect in about 15% to 30% of buildings. Higher indoor temperatures after renovation have also been shown by Lina La Fleur, Moshfegh, and Rohdin (2017).

In a review of ventilation in dwellings, it was pointed out that ventilation of residential spaces is often poor (Dimitroulopoulou, 2012; Mikola et al., 2017). After an energy renovation, the air tightness of the building envelope increases, and as many buildings have natural ventilation, the air exchange rate is reduced. Sometimes energy saving targets motivate the occupants to decrease ventilation speed or close fresh air valves, if they have been installed, thereby furthermore reducing air change indoors. Park and Kim (2012) showed that among 200 apartments, where a heating allocation system was installed, 68% did not use installed fans and the most common reason for that was elevated heating costs.

This thesis analyses so–called rebound effect and user related changes in energy use after renovations.

1.5 DHW system heat losses

Nearly–Zero Energy Buildings (nZEB) have a relatively higher share of energy use for domestic hot water (DHW) because of reduced heat loss from the well–insulated building envelope, the use of ventilation heat recovery and LED lighting systems that use relatively less energy. DHW energy consumption can be divided between energy used to heat the water and energy consumed by system losses. Bøhm and Danig (2004) showed that the heat loss from the hot water system corresponds to approximately 65% of the energy consumption for domestic hot water and the cause of these heat losses should be further investigated. Later, it was specified (Bøhm, 2013) that most of the energy demand for DHW is lost in the circulation system. As the system's apartment building's DHW heat loss was 23% – 70%, its efficiency was 0.30 – 0.77. Andreas Gassel (1999) showed that if the DHW circulation is constantly in operation, this equates to 15 $kWh/m^{2}\cdot a$ energy consumption, the circulation share being 19% of total DHW heating demand. Horvath, Hrabovszky–Horvath, and Csoknyai (2015) showed that when the specific DHW annual heat demand is between 23 and 32 $kWh/(m^2\cdot a)$, distribution and circulation losses are between 5.7 and 9.9 $kWh/(m^2\cdot a)$. Zhang et al. (2012) indicated that recirculation loops pipe heat loss represented about one third of system fuel energy consumption and the average overall system efficiency was only about 34%. Similar results have been found in their study by Marszal–Pomianowska et al. (2019), where DHW accounts from 16% to 50% of total DHW heating consumption. Huhn and Davids (2008) showed that the energy losses from hot water circulation are in the range of 25% to 75% of the energy used for DHW supply. In buildings with low DHW consumption, the efficiency is particularly poor. When DHW use is small, then DHW circulation heat loss is more or less the same as in buildings with a bigger DHW consumption, but the relative share of DHW system losses in those buildings is bigger.

Minimising DHW distribution and circulation losses improves the efficiency of the system and the energy performance of the whole building. (Kitzberger et al., 2019) showed that minimising the runtime of the circulation pumps and decreasing hot water flow and storage capacities reduces the annual energy consumption for DHW by 15% – 25%. Mühlbacher and Carter (2002) deduced a dependency between the energy loss and the operating time of the circulation pump in buildings with DHW circulation energy use from 21% – 65%. Without a reduction in the operating time of the circulation pump, energy loss from circulation was more than 60%. Cholewa, Siuta–Olcha, and Anasiewicz (2019) showed in their long term field measurements on performance of DHW, that a significant part (57% – 71%) of the heat loss is allocated to the circulation of hot water. Using temperature control valves in risers of the circulation installation to limit the circulation flow during periods of time when it is not required generated average energy savings of 19%. Adam et al. (2016) proposed shortening circulation runtime (a minimum of 16 hours per day) to decrease DHW circulation heat loss. Bøhm (2013) suggested that replacing the bypass function with an in–line supply pipe and a heat pump can help to reduce the return temperature of the decentralised substation system. As a result, the annual distribution heat loss decreased by 12%.

Lowering circulation time is one possibility but it depends on how people use DHW. Ahmed, Pylsy, and Kurnitski (2016) studied hourly DHW consumption in 86 apartments with 191 occupants over the course of one year and found that almost 90% of hourly consumption was between 0 and 20 l/(person·h). Two sharp peak consumption periods were present on week–days. Morning peak consumption was between 7:00 and 9:00 whereas evening peak consumption was between 20:00 and 22:00. The average consumption was 4.1 and 1.1 l/(person·h) for peak and non–peak hours respectively. Overnight DHW consumption was almost zero.

Another possibility to decrease DHW energy consumption is to lower DHW temperature. Navalón (2015) showed that by reducing the return temperature to 52 °C (limit temperature to avoid Legionella), the theoretical saving is 15% – 18%. The growth of Legionella bacteria is high risk and that is why water temperatures between 25 °C and 45 °C should be avoided, ideally maintaining hot water above 50 °C. To improve energy efficiency and avoid the risk of Legionella, Brand (2013) suggested stopping the use of DHW circulation.

In old apartment buildings, heat from DHW distribution and circulation heat losses are distributed mainly in unheated basements and through shaft walls into apartments. Grasmanis, Talcis, and Greķis (2015) showed that DHW circulation heat losses in an unheated basement vary between 10% – 12% during the non–heating season and 12% – 15% during the heating season. Depending on the season, the rate of circulation heat losses from vertical distribution circulation loop pipes varies from 55% – 60% for 5 storey buildings and 62% – 67% for 9 or 12 storey buildings. Rocheron (2012) showed that the insulation of storage and distribution systems is an essential parameter in the process of energy savings, especially in the case of the DHW circulation.

The earlier studies showed the gap between calculated and measured DHW consumptions and showed DHW circulation losses but there is a lack of knowledge how these losses can be involved in EPC calculations. This thesis firstly finds out how much energy could be utilised from DHW system pipe losses in the basement and in shafts per calculated pipe length, and how large non–utilised losses per calculated length would be and secondly, what the EPC class would be with and without pipe losses in the different cases.

1.6 Summary of renovation of housing stock overview

In the geographic region of this study, renovation of housing stock is important to primarily lower heating energy consumption. There is a significant potential for energy savings. Most studies have shown that heating energy consumption can be reduced by more than 50%. However, despite calculated and measured energy consumption showing reductions, there still exists a performance gap. Earlier research in this region has shown that this can be caused by occupancy or quality of construction work. There are also problems in the design phase with calculation tools and simplification of user profiles for residential buildings. These aspects of housing stock renovation were important lines of investigation for this study. Earlier studies have failed to come up with definitive recommendations as to whether there is a need to develop or fix calculation methodologies or should construction work be subjected to more detailed inspections during renovations to minimise any potential shortfalls in performance targets.

Earlier studies have also shown problems with high DHW circulation losses in residential buildings. Based on analyses of Estonian apartment buildings, similar losses are apparent in the geographic region of this study but there is lack of knowledge of how to introduce DHW system losses into EPC calculations at the design phase and so minimise the performance gap between calculated and measured losses after renovation.

2 Methods

2.1 Studied buildings and renovation measures

2.1.1 Minor and major renovation

The energy use and indoor climate were investigated in 35 typical apartment buildings (Table 2.1). Studied apartment buildings were selected from the time period of the highest apartment building construction activity 1950 – 1990, the median construction year being 1975. The average number of apartments in one building was 27 (varied between 12 and 72, standard deviation was 17), average heated area was 1757 m^2 (varied between 550 m^2 and 5030 m^2, standard deviation was 1046 m^2). Average occupancy in one apartment was 2.2 persons (standard deviation was 0.5) and the average living density – area per person was 31 m^2/person (varied between 16 m^2/person and 55 m^2/person, standard deviation was 7.7 m^2/person).

The first selection of buildings to study was done by Fund Kredex, who were responsible for overseeing the distribution of financial support from the government to apartment buildings for renovation projects, and who supported investigation into those renovated apartment buildings. Buildings were selected from the main cities such as Tallinn (in the north of Estonia) and Tartu (south Estonia), and from other smaller towns like Haapsalu (west Estonia) and Põlva, Elva (small cities in the south of Estonia). Buildings in the outer suburbs of Tallinn were also chosen (Viimsi, Saue, Jüri).

Figure 2.1 shows an example of an apartment building before (left) and after (right) the deep energy renovation.

Figure 2.1 Studied apartment building before (left) and after (right) the deep energy renovation.

All 35 apartment buildings had district heating that was always used for space heating and mostly (24 buildings) for DHW.

Table 2.1 The main properties of studied apartment buildings (Publication III Table 1).

Code	No. of apartments	Heated net area, m^2	No. of inhabitants in building	Renovation measures				
				Ventilation	DHW circulation before/after	Additional insulation, cm / (U, W/(m^2·K))		
						Walls	Roof	Windows
Target: Energy Performance Classification (EPC) “D”, PE ≤ 180 kWh/(m^2·a). 25% renovation grant.								
1.1	25	1665	47	Exhaust fan	−/+	+20/0.16	+30/0.10	≤1.1
1.2	18	1673	45	Exhaust fan	−/+	+15/0.18	+45/0.10	≤1.6
1.3	18	1592	44	Exhaust fan	+/+	+15/0.18	+30/0.12	≤1.5
Target: EPC “D”, PE ≤ 180 kWh/(m^2·a) (DHW with electrical boilers). 40% renovation grant.								
2.1	12	1029	40	Central AHU	−/−	+15–20/0.21	+23/0.13	≤1.4
2.2	18	1490	27	Central AHU	−/−	+15–20/0.20	+30/0.11	≤1.3
2.3	18	1508	40	Central AHU	−/−	+15/0.24	+21/0.15	≤1.1
2.4	24	1370	41	Central AHU	−/−	+15/0.20	+30/0.12	≤1.3
2.7	18	1180	40	Central AHU	−/−	+15/0.21	+40/0.09	≤1.1
Target: EPC “C” PE ≤ 150 kWh/(m^2·a) (with central Air Handling Unit (AHU)). 40% renovation grant.								
2.5	18	1306	45	Central AHU	−/+	+15/0.20	+28/0.11	≤0.9
2.6	18	1306	35	Central AHU	−/+	+15/0.21	+28/0.12	≤1.1
2.8	18	886	25	Central AHU	−/+	+15/0.21	+35/0.09	≤1.1
2.9	12	903	24	Central AHU	+/+	+15/0.20	+28/0.12	≤1.3
Target: EPC “C” PE ≤ 150 kWh/(m^2·a) (with exhaust air heat pump). 40% renovation grant.								
2.10	55	3378	89	Exhaust fan	+/+	+20/0.16	+25/0.16	≤1.1
2.11	32	1505	96	Exhaust fan	+/+	+15/0.21	+30/0.12	≤0.9
2.12	50	3904	130	Exhaust fan	+/+	+20/0.19	+35/0.15	≤1.1
Target: Heating energy saving 30% (with natural ventilation and extra outdoor air inlets (FAI)). 15% renovation grant.								
15.1	60	3163	150	NAT	−/−	+10/0.38	+15/0.20	≤1.8
15.2	36	1718	61	NAT+FAI	+/+	+15–20/0.21	+0/0.4	≤2.0
15.3	60	2959	150	NAT	+/+	+0–10/0.75	+23/0.15	≤2.0
15.4	24	1737	60	NAT+FAI	+/+	+15/0.21	+20/0.17	≤1.8

Code	No. of apartments	Heated net area, m^2	No. of inhabitants in building	Renovation measures				
				Ventilation	DHW circulation before/after	Additional insulation, cm / (U, W/(m^2·K))		
						Walls	Roof	Windows
15.5	40	3075	100	NAT	+/+	+0–10/0.75	+10/0.25	≤2.0
Target: Heating energy saving 40% (with natural ventilation (NAT) and extra outdoor air inlets (FAI)). 25% grant.								
25.1	12	777	27	NAT+FAI	−/−	+15/0.21	+25/0.13	≤1.6
25.2	40	2623	80	NAT+FAI	+/+	+10–15/0.30	+25/0.13	≤1.4
25.3	60	3519	150	NAT+FAI	+/+	+15/0.21	+20/0.17	≤1.6
25.4	12	550	24	NAT	−/−	+15/0.21	+25/0.13	≤1.6
25.5	16	1903	38	NAT+FAI	−/−	+10–15/0.28	+30/0.11	≤1.6
Target: Heating energy saving 50% (supply–exhaust room units (SERU)). 35% grant.								
35.1	18	1064	40	SERU	−/+	+10–15/0.30	+13/0.20	≤1.4
35.2	18	1285	44	SERU	−/+	+15/0.21	+13/0.20	≤1.6
35.7	18	1026	34	SERU	+/+	+5–15/0.28	+23/0.15	≤1.6
35.9	12	940	30	SERU	−/−	+15–20/0.20	+20/0.17	≤1.6
Target: Heating energy saving 50% (with exhaust air heat pump). 35% grant.								
35.3	21	1527	60	Exhaust fan	−/+	+15/0.21	+25/0.15	≤1.6
35.4	18	1041	40	Exhaust fan	−/+	+15/0.21	+23/0.16	≤1.6
35.5	18	1162	40	Exhaust fan	+/+	+10/0.28	+23/0.16	≤1.6
35.6	15	1151	38	Exhaust fan	+/+	+15/0.21	+23/0.16	≤1.6
35.8	72	5030	200	Exhaust fan	+/+	+15/0.21	+23/0.16	≤1.6
Target: Heating energy saving 50% (with central Air Handling Unit (AHU)). 35% grant.								
35.10	15	561	16	Central AHU	−/−	+15/0.21	+10/0.25	≤1.6

The heating system was renovated in all of the apartment buildings: a hydronic radiator with thermostat valves (TRV) was installed (before renovation, a one pipe system without TRV).

In 10 buildings, the performance of natural ventilation was improved by adding outdoor air inlets (NAT+FAI). In 11 buildings, centralised exhaust ventilation (without ventilation heat recovery) was installed. In eight buildings, the exhaust ventilation was equipped with an exhaust air heat pump (EXHP) for heat recovery. Supply and exhaust ventilation with heat recovery was installed in 14 buildings: four apartment buildings had supply–exhaust room units (SERU) and ten buildings had central air handling units (AHU).

In 11 buildings, DHW was heated by electrical boilers, located in apartments, as before renovation. In nine apartment buildings, the DHW heating by local electric boilers was changed to a central system heated by district heating after renovation (installing DHW and DHW circulation pipes). In all other buildings, district heating for DHW was used before and after the renovation. In all those buildings where DHW is heated by district heating, DHW circulation is also in use. Table 2.1 shows where DHW circulation was in use before renovation and how the situation is after renovation.

In Table 2.1 there are also renovation solutions for additional thermal insulation for external walls and roof. This study also analysed how many existing windows have been replaced and how large is the windows average thermal conductivity. In some buildings the old windows were removed and new windows moved to the additional insulation layer, and in other buildings, the window frame perimeter was insulated.

The target for energy performance was set by renovation grant requirements and targeted Energy Performance Certificate (EPC) classes based on the design's primary energy use (RT I, 05.06.2015, 2015):

- EPC 'A' PE ≤100 kWh/(m^2·a), a nearly–Zero Energy Building (nZEB);
- EPC 'B' PE ≤ 120 kWh/(m^2·a), a low–energy building;
- EPC 'C' PE ≤ 150 kWh/(m^2·a), the minimum requirement for new buildings;
- EPC 'D' PE ≤ 180 kWh/(m^2·a), the minimum requirement for major renovation work;
- EPC 'E' PE ≤ 220 kWh/(m^2·a), minor renovation work.

Table 2.2 Renovation grant rules (RT I 2010, 58, 2010) *used for buildings coded from 15.1 to 35.10.*

Grant's rule (RT I, 31.12.2015, 2016)	Renovation grant's financial support		
	15%	25%	35%
EPC and primary energy needs*	'E' ≤ 250 kWh/(m^2·a)	'D' ≤ 200 kWh/(m^2·a)	'C' ≤ 150 kWh/(m^2·a)
Heating energy saving	30%	40%	50%
ICC (EN 15251, 2007)	II	II	II
Mechanical ventilation	Not required	Not required	Required
Ventilation heat recovery	Not required	Not required	Required
Minimum ventilation air flow (air change rate)	0.35 l/(s· m^2) (0.5 h^{-1})	0.35 l/(s· m^2) (0.5 h^{-1})	0.35 l/(s· m^2) (0.5 h^{-1})
U_{wall}	Not required	≤ 0.25 W/(m²·K)	≤ 0.22 W/(m²·K)
U_{roof}	Not required	≤ 0.15 W/(m²·K)	≤ 0.15 W/(m²·K)
$U_{windows}$ (for new windows)	Not required	≤ 1.1 W/(m²·K)	≤ 1.1 W/(m²·K)

*EPC before 2013 was different (RT I 2007, 72, 2007) also the main focus was heating energy savings.

In buildings coded 15.1 to 35.10 (Table 2.1) the energy saving from earlier total heating energy consumption including heating energy need for space heat, ventilation heating energy use and DHW energy together with circulation losses, has been calculated (renovation grant rules are described in Table 2.2). Heating energy saving targets in those buildings are connected to renovation grant financial support which has been calculated by energy auditors. For buildings 15.1 to 15.5, the financial support was 15% and calculated heating energy savings were 30%. For buildings with code 25.1 to 25.5, the financial support was 25% and calculated heating energy savings were 40% and for buildings with code 35.1 to 35.5, the financial support was 35% and calculated heating energy savings were 50%. Heating energy savings have been calculated with the following equation (1).

$$\text{Heating energy save} = \frac{100 \times (\text{Measured after renovation} - \text{Measured before renovation})}{\text{Measured after renovation}}\,\% \qquad (1)$$

In 2015, a new renovation grant scheme started (Kuusk & Kalamees, 2016; RT I, 31.12.2015, 2016) which was based mainly on the designed energy performance level. In addition, some specific rules for thermal transmittance were introduced, Table 2.3 shows the minimum requirements for energy refurbishment work cofounded by grants:

Table 2.3 Renovation grant rules (RT I, 31.12.2015, 2016) *used for buildings coded from 1.1 to 2.12.*

Grant's rule	Grant's support	
	25%	40%
EPC and primary energy needs	'D' ≤ 180 kWh/(m^2·a)	'C' ≤ 150 kWh/(m^2·a)*
ICC (EN 15251, 2007)	II	II
Mechanical ventilation	Required	Required
Ventilation heat recovery	Not required	Required
Minimum ventilation air flow (air change rate)	0.35 l/(s· m^2) (0.5 h^{-1})	0.35 l/(s· m^2) (0.51/h)
U_{wall}	≤ 0.25 W/(m^2·K)	≤ 0.22 W/(m^2·K)
U_{roof}	≤ 0.15 W/(m^2·K)	≤ 0.12 W/(m^2·K)
$U_{windows}$ (for new windows)	≤ 1.1 W/(m^2·K)	≤ 1.1 W/(m^2·K)

*Some exceptions from the aforementioned targets were accepted, depending upon the location of the building and the particular nature of the specific building's service systems. For example, 40% financial support was accepted for EPC 'D' when buildings were not able to access DHW heating from the district heating system (they had electrical boilers for their supply of DHW).

2.1.2 Renovation to nZEB criteria for new building

A five storey concrete large-panel apartment building with 80 apartments was selected to realise the nZEB renovation pilot (Kuusk & Kalamees, 2015). The building was constructed in 1986 and renovated in 2017. This building type was dominant during the construction industrialisation period between 1970–1990. Approximately two million square meters of apartment buildings were constructed with prefabricated concrete large panels during that period in Estonia. As prefabricated concrete large-panel apartment buildings were also widely used in other countries, results of this pilot are usable in other countries. Figure 2.2 shows the building before and after the renovation.

Figure 2.2 View of the nZEB case building before (2015) (left) and after (right) the renovation (2018).

The thermal transmittances of the building envelope before renovation was: external walls: U_{wall} ~1.1 W/(m^2·K) (70 mm wood–chip + 50 mm phenolic foam for insulation); roof: U_{roof} ~1.0 W/(m^2·K) (100 mm wood–chip insulation); windows: U_{window} ~1.6 W/ (m^2·K)) (some windows were old wooden windows with double panes, some windows were changed to new PVC frame windows) (Rose et al., 2016). The concrete large-panel apartment building type has serious thermal bridges (Ilomets, Kuusk, et al., 2017). One indicator of lower temperatures in the connections of building envelope elements was mould growth on the interior surfaces, especially in the corners of the exterior walls and roof.

The building had a natural passive stack ventilation system with ventilation shafts and one–pipe radiator heating system without thermostats. Room temperature for the whole building was regulated by a heat substation depending on the outdoor temperature. Measured room temperature varied before renovation between 20.1–24.4 °C (Prasauskas et al., 2016).

Total primary energy (PE) use before renovation was 302 kWh/(m^2·a).

nZEB criteria for new buildings (EPC class A, PE ≤100 kWh/(m^2·a)) was set as the energy performance target in designing the renovation solution. The whole building envelope was additionally insulated (Pihelo et al., 2017) and new heating and ventilation systems were installed. To minimise the influence of thermal bridges and to get an additional living area, the existing balconies were changed to indoor spaces. A small attic was constructed to insulate the roof with prefabricated elements and to get space for ventilation pipes. Table 2.4 presents design solutions to achieve nZEB. EPC for design solution was class A (PE=97 kWh/(m^2·a)).

Table 2.4 Design solutions for nZEB renovation.

	Design solution
Building envelope	Additional insulation with prefabricated modular elements with designed thermal transmittance values: $U_{external\ wall}$=0.11 W/(m^2·K), U_{roof}=0.10 W/(m^2·K), $U_{basement\ wall}$=0.10 W/(m^2·K), $U_{basement\ floor}$=0.26 W/(m^2·K)), q_{50}=2 m^3/(h·m^2)
Windows	New triple glazed windows ($U_{windows}$=0.80 – 0.84 W/(m^2·K)) were installed into prefabricated insulation elements in the factory.
Ventilation	Mechanical supply and exhaust ventilation system with heat recovery was installed. Half of the building (40 apartments) have a central ventilation unit (*η*–83%, *SFP*= 1.8 kW/(m^3·s)) in the attic and ventilation ducts are embedded into the wall insulation elements. Half of the building (40 apartments) have apartment–based ventilation units (*η*–89%, *SFP*=0.88 kW/(m^3·s)). Basement, and staircases have separate ventilation units (*η*–80%, *SFP*=1.8 kW/(m^3·s)).
Heating	A new two–pipe heating system with hydronic radiators and room thermostats. District heating remained as heat source.
Domestic hot water	District heating remained as heat source for heating the domestic hot water. Half of the building has an additional heat source from solar collectors (50 collectors with total effective area of 100 m^2, 4x1.5 t storage tanks). Half of the building has an additional heat source to pre–heat the incoming cold water before the heating sub–station from a passive wastewater (grey water from showers and sinks) heat recovery system.
Renewable electricity	PV panels (55 panels, total peak power of 14 kW)

Comparing the renovation solution to the minimum requirements of the renovation grant rules (Table 2.3) where the goal was to reach EPC 'C', the nZEB case building solution was stricter and renewable energy production is also needed.

2.2 Performance gap

Having analysed the performance gap between design and measured energy consumption levels, the author of this study carried out several comparisons as follows (Table 2.5). In calculation steps from D to B, the standard use of buildings was used for simulations, and in calculations step C and M, measured indoor temperature and air flow was used.

Table 2.5: Analysed energy consumption levels and their descriptions.

Calculation step code	Description	Input data parameters for indoor climate, ventilation, DHW, infiltration, internal heat gains
0	Measured energy consumption levels before refurbishment	As measured before renovation
D	Energy consumption levels as designed (using mainly BV^2 software)	Standard use of buildings
A	Re–simulated energy consumption levels (using IDA ICE 4.8 dynamic software) (building envelopes have been taken from preliminary design)	Standard use of buildings
B	Re–simulated energy consumption levels with corrected building envelope properties (building envelopes have been taken from detailed design)	Standard use of buildings
C	Re–simulated energy consumption levels with corrected building envelopes, internal heat gains, and measured indoor temperature and ventilation rates	As measured after renovation
I	Ideally corrected re–simulated energy consumption with changed indoor temperature and ventilation rates (same envelopes and internal heat gains as model C)	Indoor temperature and air flow have been changed to get best correlation with measured heating energy need
M	Measured energy consumption levels after refurbishment work	As measured after renovation
C*	Model calibration: simulation model with measured indoor air parameters, measured internal heat gains and measured thermal transmissions. Without window airing.	From every apartment separately measured indoor temperature, ventilation air flow, electricity use of lighting and appliances, real number of occupants. Measured supply air temperature from every ventilation unit (half of

Calculation step code	Description	Input data parameters for indoor climate, ventilation, DHW, infiltration, internal heat gains
		apartments with apartment based unit used average supply air temperature from 4 units) and building heat loss.
W	The influence of window airing: building as built and used but with window airing (that is not considered in design methodology).	Same as “C*” but with window airing. One window in every apartment is 10% open in total for half an hour a day
DHW 1.2	The influence of 1.2 higher population difference DHW use	1.2 times the standard usage
DHW1.5	The influence of 1.5 higher DHW use	1.5 times the standard usage
S*	Energy consumption with standard use parameters (RT I, 19.01.2018, 2018)	Standard use parameters and measured envelope transmittances from earlier studies in this building

C* is model calibration in nZEB reconstructed building.

S* is standard use of building in nZEB reconstructed building which is more or less same as B in other analysed buildings.

To compare the gap between calculated and measured or designed and re–simulated energy consumption levels, the following equation (2) was used.

$$\text{Gap} = \frac{100 \times (\text{Measured (M)} - \text{Designed (D)})}{\text{Measured (M)}}\% \qquad (2)$$

Primary energy use is calculated by multiplying delivered energy by weighting factors according to the energy carrier: 2.0 for electricity and 0.9 for district heating.

2.3 Measurements

2.3.1 Indoor climate

Indoor temperature and ventilation airflow, as the most important parameters to guaranteeing thermal comfort and indoor air quality, were measured in all buildings in at least 3 or 4 of apartments (altogether 120 apartments) after the renovation. The criteria for the selection of apartments were that they should be located on different floors, and that in the selected apartments there should be more inhabitants than bedrooms. In the nZEB renovated building indoor temperature was measured in all apartments. Measurements conducted during the heating period:

- buildings coded from 15.1 to 35.10 during the period December 2013 until February 2014,

- buildings coded from 1.1 to 2.12 during the period December 2016 until February 2017,
- nZEB renovated building during the period December 2018 until March 2019.

Indoor temperatures and relative humidity were measured at fifteen–minute intervals with portable data loggers (EVIKON E6226, temperature measurement range –10–50 °C with an accuracy of ±0.6 °C, relative humidity measurement range 0–100% with an accuracy of ±4%) (Evikon MCI OÜ, Tartu, Estonia). The data loggers were located mainly in master bedrooms on the separating walls.

Exhaust air outlet airflow was measured in apartments twice, generally at the beginning of December and again at the end of February. Ventilation airflow was measured with a Testo 435 hot wire anemometer sensor (measurement range 0–20 m/s, with an accuracy ±0.03 + 5% m/s) (Testo SE & Co. KGaA, Lenzkirch, Germany) together with a volume flow funnel Testovent 410 (∅ 340 mm).

In every apartment, where indoor temperature and ventilation airflow were measured, data was collected regarding the appropriateness of the indoor temperature via a questionnaire (PMV values from –2 to +2: rather cool, slightly cool, neutral, slightly warm, and rather warm). Questionnaires were completed in 120 apartments in 35 investigated buildings (one questionnaire per apartment) which is 3 or 4 questionnaires per building. The study also asked a question on how occupants feel the temperature is after renovation (5 step scale: warmer, slightly warmer, neutral, slightly cooler, and cooler). In most buildings the ventilation system has been renovated. That is why the study also asked how occupants evaluated ventilation air quality (5 step scale: fresh, rather fresh, neutral, rather stuffy, and stuffy).

2.3.2 Energy consumption

The information about energy consumption (electricity, space heating together with ventilation air heating (heat), and DHW) after renovation was measured, and data was collected from building managers. In apartment buildings with district heating, where heat for space heating and DHW was measured together, the heat for DHW was calculated based on the assumption that 40% of the total water used was hot water (Toode & Kõiv, 2005) and the difference between the temperatures is 50 °C. Circulation heat loss was calculated by using the difference between theoretical (energy consumption from water use and temperature difference) and measured energy use for DHW during the summer months.

In buildings 2.11 and 2.12, the study also measured exhaust air heat pump (EXHP) electricity use and produced heat separately, so that EXHP real efficiency could be analysed and compared to the design values.

In the nZEB renovated building, the energy consumption (electricity consumption of apartments, electricity consumption of ventilation units, space heating, ventilation air heating, DHW heating, cold and hot water consumption) and indoor temperature and ventilation airflow were measured by a building control and automation system.

Energy consumption and indoor temperature before renovation were taken from energy audits, done by professional energy auditors. The audits used energy consumption data from a three–year period prior to the renovations for heat balance calculations, they also used the existing building thermal transmittance values. The majority of energy auditors were educated through special courses and most of auditors used the same audit methodology and form. From year 2015, a new energy audit procedure was developed by Fund Kredex (Hamburg & Jõesaar, 2015).

2.4 Calculations

2.4.1 Thermal comfort

Thermal comfort (PMV and PPD) in all 120 apartments was estimated based on ISO 7730 (2005) standard by using an Excel based tool (da Silva, 2014). Measured air temperature and relative humidity values were used. The surface temperature of the external wall (1/5 of all surface area) was calculated based on its thermal resistance (taken from design documentation) and typical indoor surface resistance (0.13 $m^2 \cdot K/W$). The surface temperature of other room surfaces was taken as equal with indoor air temperature. For other input parameters (clothing = 1.0 clo, activity level = 1.2 met, and air velocity = 0.1 m/s) this study used values recommended in EN 15251 (2007) for indoor climate category indoor climate class (ICC) II.

To investigate how occupants described their thermal comfort after renovation the study used a questionnaire. A 5–point scale (PMV scale –2 to +2: rather cool, lightly cool, comfort, lightly warm, rather warm) was used.

2.4.2 Energy consumption modelling and standard use of buildings

The indoor climate and energy performance of the buildings were re–simulated in all 35 buildings (so that the difference between dynamic, static and semi–dynamic results could be seen) using the energy and indoor climate simulation program, IDA Indoor Climate and Energy (IDA–ICE). The accuracy of the IDA–ICE simulation tool has been examined in a good many validation studies in recent years (Equa Simulation AB, 2010; Kropf & Zweifel, 2001; Travesi et al., 2001) and has been used in many analyses of predicted and actual indoor climate and the energy performance of buildings (Andersen et al., 2016; Bjørneboe et al., 2017; Lina La Fleur et al., 2017).

The energy specialist who made calculations in the design phase, used, in most cases, the program BV^2 (AB, 2007). This tool is a one–zone energy efficiency calculation tool that takes into account air leakage, thermal bridges, temperature variations and solar radiation etc. Earlier studies (Jarek Kurnitski et al., 2016; Voll et al., 2010) have shown that BV^2 underestimates heating energy use by between 15% to 30%. This program is a more static, or so called semi–dynamic, calculation program where there is no possibility to see heat flow through building internal walls and floors. Also, heat gain from the sun is calculated from outdoor temperatures which can be another reason why this program underestimates heating energy use.

In buildings which used an EXHP after renovation, the heat pump electricity required was calculated from general electricity usage (the same is true for lighting for common areas), according to the earlier electricity requirements (building 2.10). The Estonian Test Reference Year for the outdoor climate (annual heating degree days at t_i +17 °C: 4 160 °Ch) (T. Kalamees & Kurnitski, 2006) was used for simulation purposes and a reduction of measured heating energy under the same climate conditions.

Energy use was simulated under standard use conditions using input parameters from the Estonian regulations for energy performance calculations (RT I, 19.01.2018, 2018):

- Indoor temperature heating set point: 21 °C;
- Ventilation air flow: 0.42 $l/(s \cdot m^2)$;
- Apartments with central AHU 0.5 $l/(s \cdot m^2)$;
- Supply air temperature with AHU: 18 °C;
- The standard use for DHW is in apartment buildings: 520 $l/(m^2 \cdot a)$ (30 $kWh/(m^2 \cdot a)$);
- Air leakage rate of the building envelope: q_{50}= 3 $m^3/(h \cdot m^2)$;

- Internal heat gains were as follows:
- Inhabitants: ~10.5 kWh/(m^2·a). Heat generated by inhabitants was calculated using 2 W/m^2 and 85 W per person (1.2 met, 1.0 clo);
- Appliances, equipment: 12.6 kWh/(m^2·a). Heat generated by appliances and equipment was calculated using 2.4 W/m^2 and the use rate was 0.6. The use of electricity for appliances and equipment was 30% higher (some of that energy leaves the building via the sewerage);
- Lighting: 7 kWh/(m^2·a). Heat generated by lighting was calculated using 8 W/m^2 and the use rate was 0.1.

Primary energy use (PE) is calculated by multiplying delivered energy by weighting factors (RT I, 05.06.2015, 2015) according to the energy supplier (2.0 for electricity, 1.0 for fossil fuels, 0.9 for district heating).

2.4.3 DHW system's heat losses

The indoor climate and energy performance model was built in the simulation program IDA ICE 4.8 (Björsell et al., 1999; Shalin, 1996). This software allows the modelling of a multi–zone building, internal heat gains and external solar loads, outdoor climate, heating and ventilation systems and dynamic simulation of heat transfer and air flows. It was also possible to model heat losses to the zones in which they occurred, and represent uninsulated valves by using a 2–meter uninsulated pipe length, which is more or less an average from calculated values (ISO 12241, 2021).

To create and to calibrate the DHW heat loss model, a complex model was built up using detailed DHW and DHW circulation drawings for the reference building and then simplified to create the calculation model (Figure 2.3).

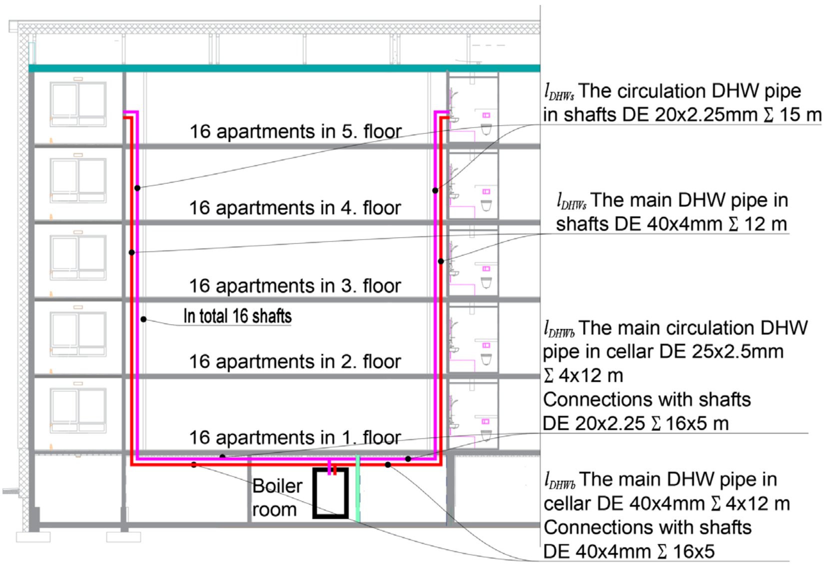


Figure 2.3. The principle of DHW and DHW circulation piping in basement and shafts.

Building a simulation model that matched all losses with the zones where those losses were occurring was very complicated. Therefore the basement was simplified to a one zone model (originally this was a multizone basement with 14 rooms, as the study wanted to see how heat losses affected indoor temperatures in the basement in different thermal insulation cases (no insulation, 20 mm, 40 mm with and without valve insulation)) but calculated with the different EPC classes that were used in earlier studies of the same building (Hamburg & Kalamees, 2020).

The calculations can be repeated when the design of DHW and DHW circulation have been simplified by using a standard length for all main pipes' lengths between shafts, and all pipe lengths and thermal insulation thicknesses have been described. The pipe model used is important, as is showing where pipes are located (in which zone). All pipes in the model were hydraulically balanced, and inlet and outlet water temperature from the plant were accurately represented.

Using measured pipe lengths in basement and shafts, a dynamic simulation model with previously calibrated building heat losses was built up. Indoor temperatures in the basement were measured and used for calibrating measured heat losses against calculated heat losses.

The dependence of DHW heat loss on energy performance of the building was analysed by using IDA ICE 4.8 dynamic simulation software. That is why the annual loss in the nZEB case building (Figure 1.2b) was analysed with different thicknesses of pipe thermal insulation and with the different building envelope thermal insulations which are typically used in renovation scenarios in Estonia. The nZEB case building was selected because it is an average Estonian apartment building and detailed information about DHW consumptions and heat losses was available. Inputs for the simulation model are presented in Table 2.6. Simulations were done in two different cases, with a heated basement and with an unheated basement. For this reason, two different heated areas 3562 m^2 (without basement) and 4324 m^2 (with basement) were used. In the figures, EPC classes are designated by class symbols (A, C, D, E and F).

Table 2.6: Different building envelope thermal transmittances and ventilation strategy used to calculate nZEB building's EPC classes.

		Energy performance of building – primary energy (PE) use and energy performance certificate (EPC) class				
		EPC "A*" & "B" PE ≤125 kWh/(m^2·a)	EPC "C" PE ≤150 kWh/(m^2·a)	EPC "D" PE ≤180 kWh/(m^2·a)	EPC "E" PE ≤220 kWh/(m^2·a)	EPC "F" PE ≤280 kWh/(m^2·a)
Thermal transmittance of building envelope *U*, W/(m^2·K)	External wall	0.13	0.17	0.22	0.22	1.0
	Basement wall	0.10	0.21	0.61	0.61	0.61
	Basement floor	0.23	0.38	0.39	0.39	0.39
	Roof	0.11	0.17	0.17	0.22	0.76
	Window	0.82	1.0	1.2	1.4	1.7
Ventilation strategy	Apartments	Mechanical ventilation 0.5 l/(s·m^2), ventilation heat recovery (VHR) 0.8.	Mechanical ventilation 0.5 l/(s·m^2), ventilation heat recovery (VHR) 0.8.	Mechanical ventilation 0.5 l/(s·m^2), ventilation heat recovery (VHR) 0.8.	0.5 l/(s·m^2) no VHR	0.35 l/(s·m^2) no VHR
	Common rooms and heated basement	Mechanical ventilation 0.5 l/(s·m^2), VHR 0.8.	Mechanical ventilation 0.5 l/(s·m^2), VHR 0.8.	No VHR 0.5 l/(s·m^2)	0.5 l/(s·m^2) no VHR	0.35 l/(s·m^2) no VHR
	In unheated room	0.15 l/(s·m^2) without heat recovery	0.15 l/(s·m^2) without heat recovery	0.15 l/(s·m^2) without heat recovery	0.15 l/(s·m^2) without heat recovery	0.15 l/(s·m^2) without heat recovery

*A is together with solar collectors and locally used PV panel electricity production (PE ≤105 kWh/(m^2·a).

2.4.4 Determining DHW pipe length

To come up with an appropriate method for determining DHW pipe length, 15 buildings with basic data available were selected (these are presented in article V in Table 2). The data (buildings volume, heating area, net area, floor gross area, total number of apartments etc.) from the 15 test buildings was analysed to find out what data could be used and how to formulate an equation to generate length and energy used of the DHW systems. The building's perimeter and the number of DHW shafts are calculated and counted from the design drawings of these buildings.

R square was used to find the best one parameter model with intercept. The average difference between measured and calculated, Mean Bias Error and Root Mean Square Error was also included in the analysis. For the two parameter model, a bootstrapping method (Davison & Hinkley, 1997) was used to find best frequency by randomly sampling 2 parameters 10 000 times. The goal was to find a minimum pipe length difference from measured values. All measured pipe lengths in the buildings are presented in article IV table 2. Measured DHW pipes and DHW circulation pipes are more or less the same (measured pipe length in test and reference buildings), which is why a decision was made to present, for measured pipe length, an average DHW and DHW circulation pipe length in each building.

3 Results

3.1 Performance gap in energy saving targeted renovated buildings

The renovation grant, which was calculated from energy saving targets, was based on energy audit calculations (Equation 1) before renovation and the design solution's target after renovation. Therefore, the renovation grant scheme for buildings depended directly on achieved heat savings (room heating, ventilation, DHW). As energy saving was calculated based on energy use before renovation, determined by energy audits, it was important to re–check and verify all energy audits.

Various methodological errors were found in energy audits that presented energy use for the studied buildings. The larger mistakes in energy audits were:

In 30% of energy audits, energy use for room heating, ventilation heat and also the consumption of DHW was multiplied by a factor of degree–hour. But for DHW heating this is not correct because DHW does not depend on outdoor temperature.

In some 15% of energy audits, the electricity consumption for heating, DHW, lighting and appliances was wrongly allocated. District heating energy was measured at one point for room heat and DHW, but in some audits this energy is taken into account only as room heat energy, whereas in reality it also consists of DHW heating energy. DHW use was calculated as double the volume of DHW use.

In 20% of energy audits the real electricity consumption was not taken into account at all, and the auditor just estimated the consumption of electricity.

To eliminate mistakes with energy use before renovation, a new analysis was made with the same methodology in all buildings. Figure 3.1 (left) shows the checked and verified energy consumption before renovation situation. The graph shows heat consumption for room heating, DHW, DHW circulation and electricity consumption lighting and appliances. Energy use before renovation of 9 buildings (15.2; 15.3; 15.5; 25.2; 25.4; 35.8; 35.3; 35.6, and 35.9) were calculated correctly by energy auditors. In buildings 15.4, 25.5 and 35.1 the total energy use calculated by the energy auditor was similar to the new analysis but there were methodological mistakes. A comparison of energy consumption with the auditor's figures for other buildings shows that the re–verified results were lower in 50% of cases.

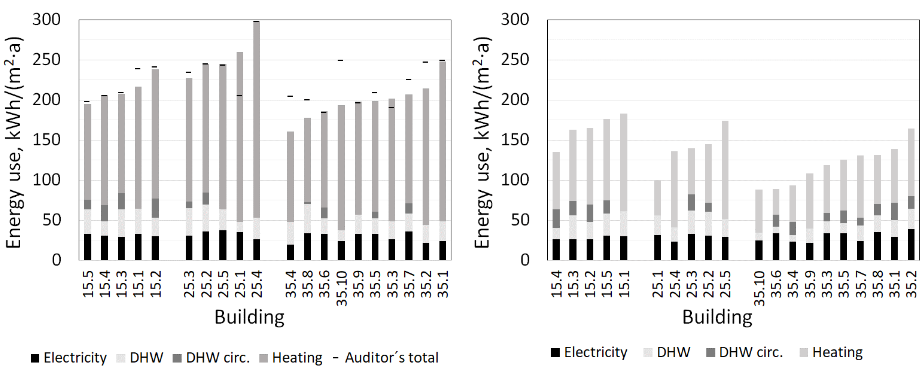


Figure 3.1 Measured energy use before (left) and after (right) the renovation.

Higher energy consumption before renovation (as calculated by the auditor) also showed larger predicted energy savings (Figure 3.2).

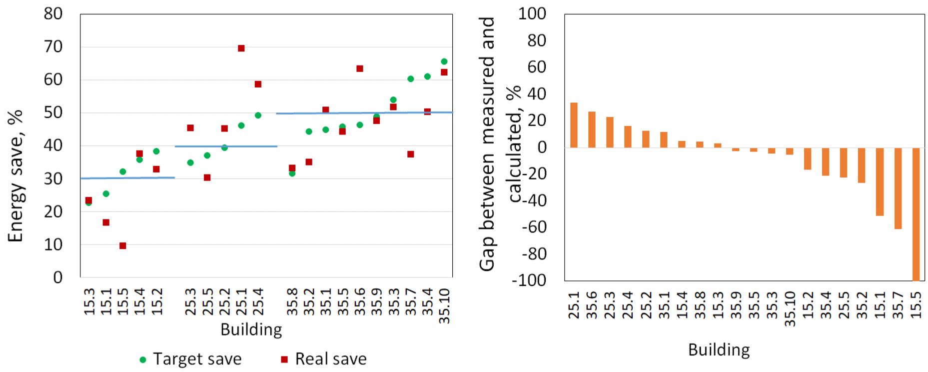


Figure 3.2 Target and measured energy savings compared with financial support target level (line) (left) and gap between measured and calculated energy savings, positive values are buildings where the measured save was greater than calculated (right).

When comparing the energy consumption before and after renovation (Figure 3.1), it can be seen that the real average total energy (room heating, ventilation heat and DHW heating energy) saving achieved in renovated buildings was 37%.

For buildings with an energy saving target (for heating up rooms, ventilation air and DHW) of 30% (KredEx renovation grant 15%) the total energy consumption after renovation was on average 22% lower than before renovation. For buildings with an energy saving target of 40% (KredEx renovation grant 25%) the total energy consumption after renovation was on average 44%, and for buildings with an energy saving target of 50% (KredEx renovation grant 35%) the total energy consumption after renovation was on average 40%. When comparing the total energy consumption after renovation then the best energy savings were shown by buildings with 35% financial support. In these buildings the average delivered energy consumption was 119 kWh/(m^2·a). After renovation, in the buildings with 15% financial support, energy consumption is on average 165 kWh/(m^2·a) which is more than 25% higher than in the 35% financed buildings. The reason why energy savings were greater with 40% targeted energy saving buildings compared with 50% targeted energy saving buildings was the lower ventilation rate and better thermal insulation of those buildings.

The comparison of energy saving for room heating, DHW, and DHW circulation show that only half of the buildings fulfil the targeted energy saving (Figure 3.2). The reason why many buildings fail to meet the criterion was due to the differences in the calculation of energy saving before renovation.

For buildings where heat consumption was calculated solely on the basis of thermal energy required for heating and ventilation air heating without DHW, the achievable energy savings (round dots in Figure 3.2) was below the level of thermal energy required under the financing requirements of the grant. In Figure 3.2, the round dots indicate the energy saving projected by the auditor and square dots indicate real savings.

The indoor air temperature and ventilated airflow after renovation did not correlate with achievable energy savings (Figure 3.3). Most buildings have higher temperatures than in the calculations used, and ventilation airflow is on average two times lower than the required level (0.35 l/(s·m^2)). Only some buildings (35.2, 35.3 and 35.4) where indoor air temperatures are near 22 °C degrees and airflow per heated area is 0.2 l/s·m^2 can reach the target energy saving with energy efficiency by the fifth energy saving criterion. When comparisons are made between the target and real energy savings of various buildings with air temperature and airflow, then in buildings 15.1, 15.5, 25.5, and 35.7 there is no explicit correlation between the measured values. Therefore, it can be said that the calculation of the thermal energy savings made by the auditor of these buildings was too optimistic. Looking at the energy savings achieved and comparing them with the measured airflow and indoor temperatures, it can be said that in buildings 25.2, 25.4, 35.3, 35.5, 35.6, 35.7, 35.9, and 35.10 (40%) the heat savings were achieved at the expense of indoor climate. If the airflow of these buildings was at the required level, achieving energy efficiency would be difficult (Figure 3.3 right, Figure 3.2). In buildings 35.3 and 35.5 the achievement of energy saving may be related to the low efficiency of the exhaust air heat pump and in buildings 35.7 and 35.9 with the low efficiency of space–based ventilation equipment.

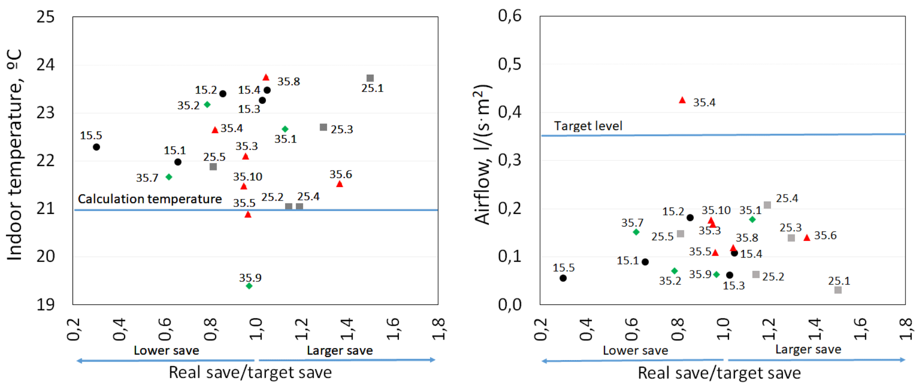


Figure 3.3 The comparison of indoor temperature (left) and ventilation airflow with target energy saving for space heating (right).

Even if comparisons between measured indoor temperature or airflow and energy savings seem to be random, we can conclude that buildings with the target level airflow don't have larger heating savings and those buildings energy savings compared to the calculations would be lower, except buildings 25.1 and 35.6 where measured savings were over 20%.

3.2 Performance gap in energy performance level targeted renovated buildings

3.2.1 Total energy use after renovation

The average use of electricity in 15 renovated buildings was on average 32 kWh/(m^2·a) (this varied between 22 and 43 kWh/(m^2·a) in different apartment buildings). This was close to the standard value (RT I, 19.01.2018, 2018) for energy simulations at 36 kWh/(m^2·a) (±3 kWh/(m^2·a) and depended upon the type of ventilation being used (see Figure 3.5, left). In the nZEB case building, measured electricity consumption after renovation was 39.2 kWh/(m^2·a) which is 5.5 kWh/(m^2·a) higher than in standard use.

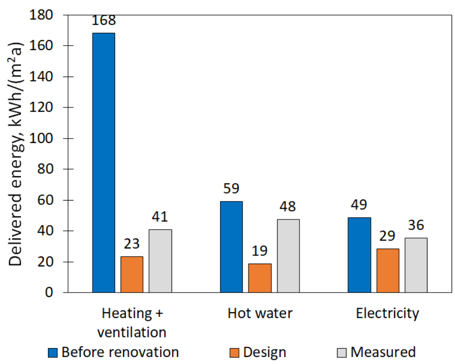
Measured and designed PE was analysed in more detail in the apartment building renovated to nZEB energy performance level as a typical case for future renovations.

The aim of the renovation was to achieve the energy performance requirement for a new build nZEB (EPC class A).

Measured annual delivered energy (DE) use after renovation was 124 kWh/(m^2·a) (Figure 3.4 left) and primary energy (PE) 147 kWh/(m^2·a) (Figure 3.4 right), fulfilling minimum requirements for energy performance of new buildings (EPC class "C"). The performance gap between measured and designed primary energy was 35%. The most important parameter causing the difference between the designed and the measured energy use after renovation was energy use for DHW. Although energy use for DHW decreased 19% (from 59 kWh/(m^2·a) to 48 kWh/(m^2·a)) it stayed higher than predicted by the design solution (19 kWh/(m^2·a) to 8 kWh/(m^2·a) delivered from district heat), given the standard use of building with designed efficiency of service systems. This showed that the prediction was a little bit too optimistic, or there is some calculation error, or the DHW system does not perform as it is designed.

The heat use for space heating and heating of ventilation air after nZEB renovation decreased 76% (from 168 kWh/(m^2·a) to 41 kWh/(m^2·a)) but remained 1.8 times higher than predicted by the design EPC solution (23 kWh/(m^2·a) (space heating 18 kWh/(m^2·a) + heating of ventilation air (5 kWh/(m^2·a)) (Figure 3.4 left).

Also, the electricity use (appliances, lighting, ventilators, and pumps) after nZEB renovation decreased 27% (without heating circulation pump energy use) (from 49 kWh/(m^2·a) to 36 kWh/(m^2·a)) but it stayed 20% higher (29 kWh/(m^2·a)) than predicted by design (standard use).



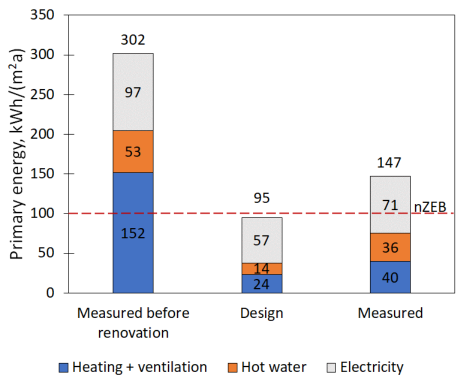


Figure 3.4 nZEB case building delivered energy need (left) and primary energy need (right) measured before the nZEB renovation, calculated by design, and measured after the renovation.

3.2.2 Energy for DHW

The average use of energy for DHW heating in 15 analysed buildings was, on average, 32 kWh/(m^2·a) (this varied between 14 and 61 kWh/(m^2·a) in different apartment buildings). This was also close to the standard value (RT I, 19.01.2018, 2018) for energy simulations (30 kWh/(m^2·a)) but depended significantly upon the circulation or otherwise of DHW (Figure 3.5, right).

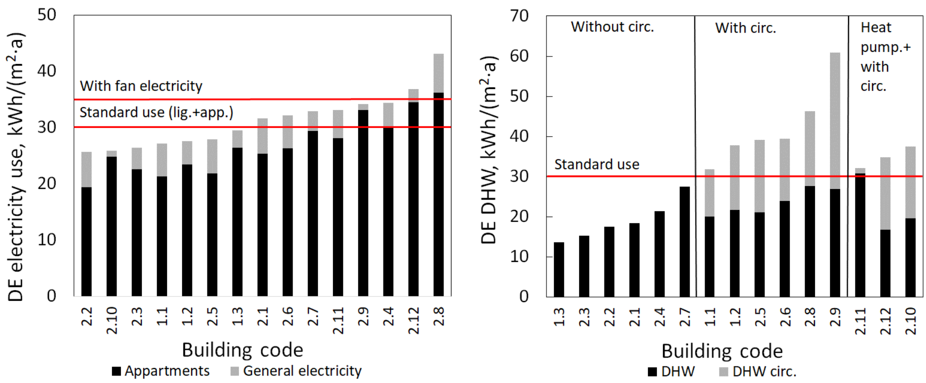


Figure 3.5 Delivered electricity for lighting, appliances, ventilators, and pumps (left) and DHW heat (right).

The DHW energy consumption in the apartment building renovated to nZEB level was analysed in more detail. The designed DHW heating energy need was 19 kWh/(m^2·a) and the actual measured heating energy need was 48 kWh/(m^2·a). Figure 3.6 shows that the designed delivered energy need for DHW from district heating was only 7.5 kWh/(m^2·a) but the measured value was 30.6 kWh/(m^2·a).

One part of the problem was that circulation losses were not taken into account in the energy calculation methodology. Measured energy use for DHW circulation was 9.4 kWh/(m^2·a) which accounts for 30% of the energy needed for DHW in the standard use profile (30 kWh/(m^2·a)).

Measured DHW need was 775 l/(m^2·a) and the calculated standard value is 516 l/(m^2·a) (1.5 times difference). The standard value for population density is 28.3 m^2/pers. Population density in the pilot building was 1.2 times higher: 23.6 m^2/pers. DHW use per one person was 49 l/(d·pers.). In standard use, the DHW use per one person is 40 l/(d·pers). This caused an additional increase of water use compared with designed values.

Another reason for the large difference is the performance of renewable energy systems which did not produce the amount of energy expected in the building design. Measured energy production from wastewater and solar collectors is significantly lower than was expected in the energy calculations. Most of the energy need for DHW was designed to be covered by a waste–water heat pump (50%) and solar collectors (25%). During the construction, the wastewater heat pump system was replaced with a passive heat recovery system from wastewater. Measurements conducted after the renovations showed that heat recovery from wastewater was only 2.6 kWh/(m^2·a) which is significantly lower than the designed value: 15 kWh/(m^2·a). Designed electricity use for the wastewater heat pump was 3.8 kWh/(m^2·a). The originally designed heat production of the solar collectors was 7.5 kWh/(m^2·a) while the standard use value was 10.7 kWh/(m^2·a), which was similar to the measured value: 10.1 kWh/(m^2·a). Nevertheless, only half of the produced heat (5.0 kWh/(m^2·a)) was transferred to the DHW system. The unexpected poor performance of the solar collector system was caused by large heat losses from the DHW tanks and pipes (uninsulated valves and heat exchangers) and a complicated and inefficient functional scheme of the system (three heat exchangers, mistakes in control system).

For the standard use of DHW energy requirements, measured wastewater preheating was used, as the wastewater heat exchanger efficiency is unknown, and the solar collector energy production was calculated. From this, DHW energy from district heating is 18.6 kWh/(m^2·a) (in Figure 3.6 as "S"). Using the same assumptions as used for calculating standard use energy requirements, energy requirements were calculated with a population difference of 1.2 times greater (Figure 3.6 as DHW 1.2) and DHW usage of 1.5 times greater (larger population + larger water use per person) (Figure 3.6 as DHV 1.5). Figure 3.6 shows that DHW district heating energy use is 25.3 kWh/(m^2·a) (DHW 1.2) and 35.3 kWh/(m^2·a) (DHW 1.5). The performance gap between measured district heating DHW use with a larger population is 17% and with the larger consumption is plus 15%. Taken together with measured DHW circulation, the gaps are 37% and 12%.

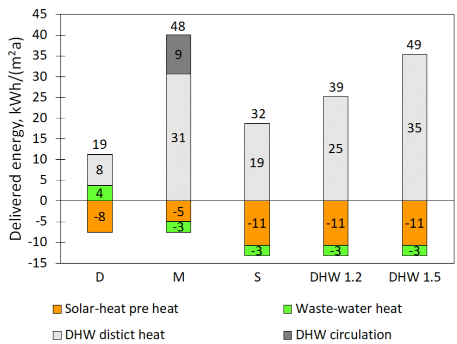


Figure 3.6 Delivered DHW heating energy consumption in nZEB case building.

3.2.3 Achieving energy performance targets

The target EPC class after renovation work in 15 analysed building had been achieved in only 26% of buildings (four of fifteen). None of the buildings that had lower energy performance targets (EPC 'C') reached their targets. The largest energy performance gap between designed energy use – which was calculated before refurbishment work – and actual energy use – which was measured after refurbishment work – was in the energy use for room heating and ventilation (Figure 3.7). While the average calculated PE use for heating in the design phase was at 51 kWh/(m^2·a), the measured heat use after refurbishment work was at 83 kWh/(m^2·a). This is approximately 40% higher.

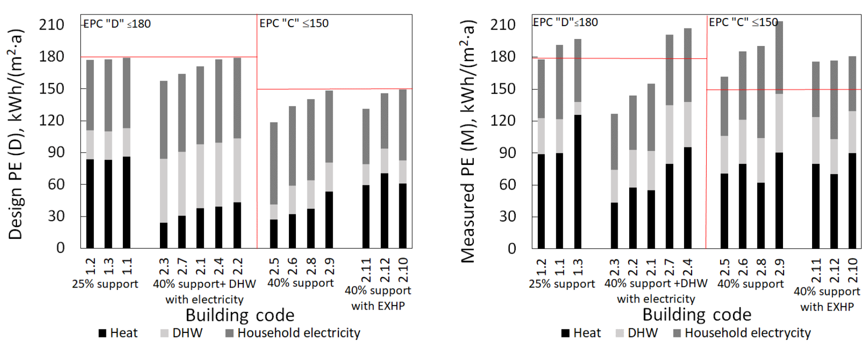


Figure 3.7 Designed PE under standard building use prior to refurbishment work (left) and for measured PE values after the refurbishment work has been completed (right).

The average use of room heating in EXHP buildings (which also includes heating for ventilation air) was at 91 kWh/(m²·a) (this varied in different apartments between 48 and 140 kWh/(m²·a)). The decrease for room heating in EXHP buildings after refurbishment work had been completed was, on average, 48% (this varied between 0% and 73%).

According to standard use figures, the delivered energy use in buildings for room and ventilation heat (buildings which have access to district heating) should be less than 56 kWh/(m²·a) (a PE value that is less than 51 kWh/(m²·a)) on average to reach EPC 'C' targets. Nevertheless, the measured delivered heating energy was higher in almost all cases, averaging 91 kWh/(m²·a). This is more than 35% greater (see Figure 3.8, right).

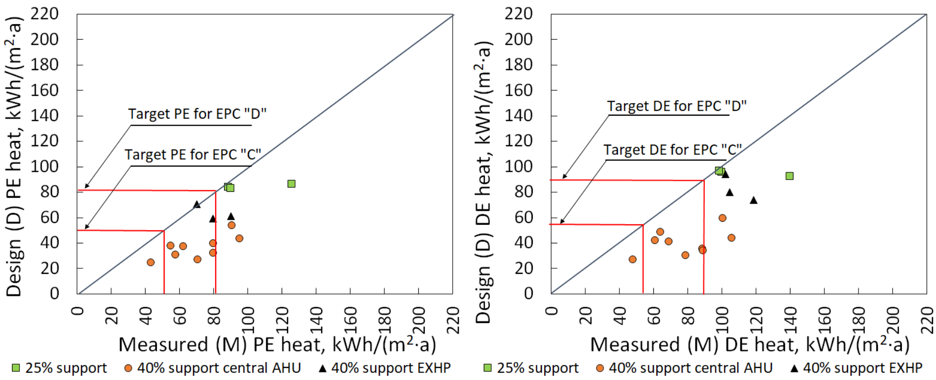


Figure 3.8 Designed PE heating energy compared to measured PE heating energy (left), with designed delivered heating compared to measured delivered heating energy and designed and measured heating energy use (space heat + ventilation heat).

3.2.4 Energy performance gap

There is a big gap between the calculations for delivered heat consumption in the design phase and the measured heat consumption (see Figure 3.8, right). The following deeper analysis shows that there were various methodological errors present on the existing energy labels. All energy efficiency calculations have been made after the preliminary design phase and these also have lots of simplification for heating energy calculations.

The first check on the energy efficiency calculations showed that the calculation of heat flow through the basement ceiling may be wrong. A recalculated thermal transmittance for the basement ceiling showed that, in fourteen out of fifteen buildings, it had been incorrectly calculated. The main mistake was that air change in the basement was not taken into account, as is required in European standard EN 13370 (2017). Minor mistakes also existed in the calculations for other thermal transmitters. Also, there were mistakes with envelope areas and mistakes which over–simplified the one–zone BV² model.

Table 3.1 shows energy calculation results in different phases before any refurbishment work has been carried out. In models D (design) to B, standard usages were used and, in models 0 (before renovation), C (calibration) and M (measured), measured consumption levels were used.

Table 3.1 Energy consumption levels in the buildings being studied in different calculation phases.

		Energy use Average (min–max) kWh/(m²·a)					
Calculation step code (Table 2.5)		0	D	A	B	C	M
EPC 'C'	Heat (space + vent)	183 (145–219)	59 (30–94)	87 (60–119)	92 (58–135)	92 (68–107)	95 (69–119)
	DHW	42 (28–72)	30 (30–30)	30 (30–30)	30 (30–30)	41 (32–61)	41 (32–61)
	Household electricity+ fans	34 (25–46)	36 (33–39)	36 (33–39)	36 (33–39)	32 (26–43)	32 (26–43)
	PE	271 (222–326)	138 (119–149)	159 (146–167)	164 (149–174)	181 (160–216)	184 (162–214)
EPC 'D'	Heat (space + vent)	157 (130–195)	60 (27–97)	90 (49–156)	93 (47–143)	86 (49–129)	88 (48–140)
	DHW	20 (16–26)	30 (30–30)	30 (30–30)	30 (30–30)	23 (14–38)	23 (14–38)
	Household electricity + fans	27 (22–32)	36 (33–39)	36 (33–39)	36 (33–39)	29 (26–34)	29 (26–34)
	PE	237 (215–296)	173 (158–179)	201 (177–234)	203 (175–223)	173 (127–207)	175 (127–207)

Firstly an energy performance multi–zone model in IDA ICE (calculation step A, see Figure 3.8) was built up with the same input data as in existing calculations (phase D) but with unheated basement air flow as in ISO 13370 (2017) and existing basement ceiling as in original design documents. Recalculations with the dynamic simulation tool have been done in all 35 investigated buildings. Energy simulations have been done to review the heating energy need of all apartment buildings

Comparing these calculated heating energy needs with measured heating, it can be seen that there is a gap of between –58% to 45%, see Figure 3.9. Re–simulated values are very different for the designed heating energy consumption, but these are still far from the measured heating energy consumption.

In the second phase (calculation step B, see Figure 3.9) the influence of detail design was examined. In this phase all changes in the design phase were taken into account, and all re–calculated thermal transmittances and thermal bridges' transmittances were included in the calculations. In most buildings the changes are small but, in several buildings, there are big differences between windows and thermal bridges' thermal transmittances. After simulation, differences between measured and detail design heating energy from –37% to 20% can be seen.

In the third step (calculation step C, see Figure 3.9) calculations were made with detailed design thermal transmittances and with measured temperatures and air flows. After calculations it can be seen that differences between measured and calculated heating energy are averaged in all buildings at 2.4% (between –2% and 9.3%). The assumption of this study was that, in the third step, there would have been more or less the same results as measured, but in 2 buildings there was a difference of more than 5%. In all buildings air temperature and airflow were only measured in three apartments, and it is possible that more measuring points are needed.

When heating energy consumption in building 1.2 was calculated using air temperatures as measured and changing airflow from 0.13 to 0.17 l/(s·m^2) the results gave the same heating energy consumption as actually measured, while in building 2.11 the airflow had to be changed from 0.34 to 0.4 l/(s·m^2) to get the same result. In these buildings it can be seen just how much effect changing air flow has on heating energy needed. However, the heating energy difference between the measured and corrected indoor climate models (C) can be caused by different indoor air temperatures.

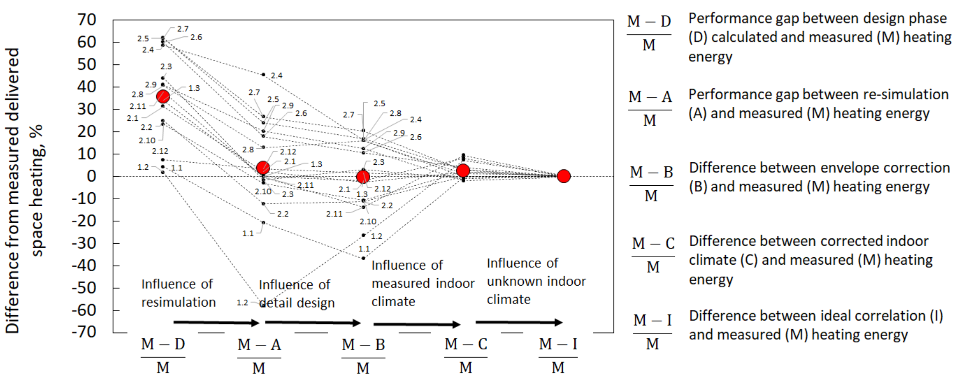


Figure 3.9 Heating energy differences from the measured (M) values when compared to the design (D), re–simulation (A), corrected envelopes (B), measured temperatures and air flows (C), Indoor climate correction (I).

To provide a more in–depth analysis of the heat consumption in the apartment building renovated to nZEB level and to find the main factors contributing to the performance gap, several simulations were done.

From measured heating energy, 5.5 kWh/(m^2·a) is the heating system´s pipe heat losses. The main pipe losses come from the 50 meters of main district heating pipe in the basement and from central AHU heating coil pipes in the service shaft running from the basement to the attic floor. District heating pipes losses provide heat to the basement area but from spring until autumn these losses are not utilised and not needed. The same situation occurs with pipe losses in the service shaft. In the current study there was no investigation into how much this heat gain is utilised.

Without window airing, the calculated (W) energy consumption for room heating was 30.6 kWh/(m^2·a). Of the entire consumption, 26 kWh/(m^2·a) is for room heating, 2.3 kWh/(m^2·a) is for central AHU heating and 2.3 kWh/(m^2·a) for apartments AHUs heating (Figure 3.10). Using standard use values in the same calculation simulation model, re–calculated heating energy consumption for room heating is 16.3 kWh/(m^2·a) which together with ventilation air heating comes to 19.7 kWh/(m^2·a) (Figure 3.10 as S). Compared with designed consumption this is 15% lower (D). The differences from designed use come from differences between the air flow rate in apartments. In standard use, airflow in apartments should be 0.42 l/(s·m^2) but the designed figure was 0.5 l/(s·m^2).

The biggest difference between standard use and the calibrated model without window airing room heating energy consumption (Figure 3.10 as C) is caused by the indoor temperature which is on average 3.6 °C higher than the standard use temperature. Changing the calculation model to use indoor temperature as measured gives a calculated room heating energy use (Figure 3.10 as S+M temp) that is 70% higher but, together with ventilation heat, is 52% higher. This means that a 1 °C raise in temperature caused a 15% heating energy consumption growth. In Figure 3.10 it can be seen that the difference from standard use consumption, where a measured indoor temperature and without window airing model has been used, heating energy consumption is small (2%), which is caused mainly by differences in the supply airflow rate and supply air temperature. A 3 °C higher supply air temperature increased ventilation heating energy use but at the same time decreased room heating energy consumption. From this it can be seen that heating energy consumption differences are caused mainly by air flow rate differences which increase heating energy consumption and also heat gains from a higher density of people and higher electricity use decreasing heating energy consumption.

When window airing is not taken into account, energy consumption is 15% lower than the measured energy consumption.

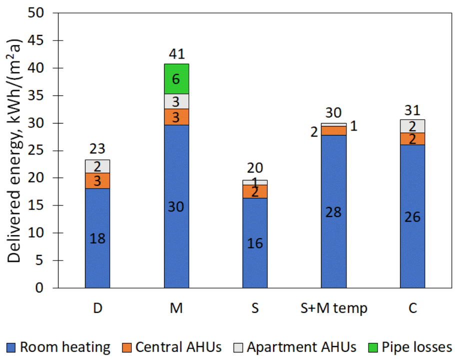


Figure 3.10 Measured energy need for space heating and ventilation air heating in the building renovated to nZEB as design (D), measured (M), standard use (S), standard use and measured temperature (S+M temp), model calibration (C).

The performance gap components and the electricity and DHW energy consumption gap was analysed in more detail in the apartment building renovated to nZEB level. In total the delivered energy gap between measured (124.0 kWh/(m^2·a)) and standard use (81.5 kWh/(m^2·a)) was 42.5 kWh/(m^2·a) (39%). A breakdown of the various reasons for higher energy consumption in Figure 3.11 shows that 39% of the difference is caused by higher heating energy consumption where: 25% is higher energy needs for room heating, 4% higher ventilation heating needs and 10% is caused by heating pipe losses. The total DHW heating gap between measured is 50% and in detail: 22% from higher district heating use, 17% caused by DHW circulation and 10 % caused by lower energy from the solar collector system. The gap between electricity use is 11%. The main reason is an 8% higher energy consumption in common area appliances and lighting. Other differences are lower than 4%.

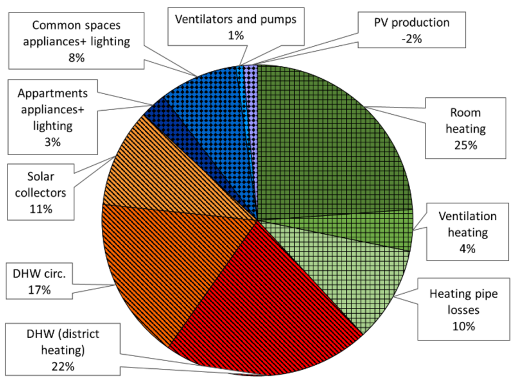


Figure 3.11 Building delivered energy need gap between measured and standard use in nZEB case building.

When taking into account (in 15 analysed buildings) all influences, it was possible to calculate new PE values. The recalculated primary energy level is more than 10% larger than the design values (with one exception) (see Figure 3.12 (left)). The performance gap between recalculated PE and measured energy averages 5% (see Figure 3.12). There are two buildings (Figure 3.12 in circle) where the difference between measured and re–simulated values is more than 20% and, in these buildings, measured DHW energy was more than 10 kWh/(m²·a) lower than in standard use (building code 2.2 and 2.3 – see Figure 3.5, right). Measured PE is mainly greater in buildings in which DHW energy use is greater than calculated. In buildings in which measured DHW consumption is lower than calculated, the measured PE levels are also lower. When using these in calculations which measured electricity, DHW, indoor temperatures and ventilation airflow (Figure 3.12 (C)), the measured and calculated PE energy difference can be up to 10%.

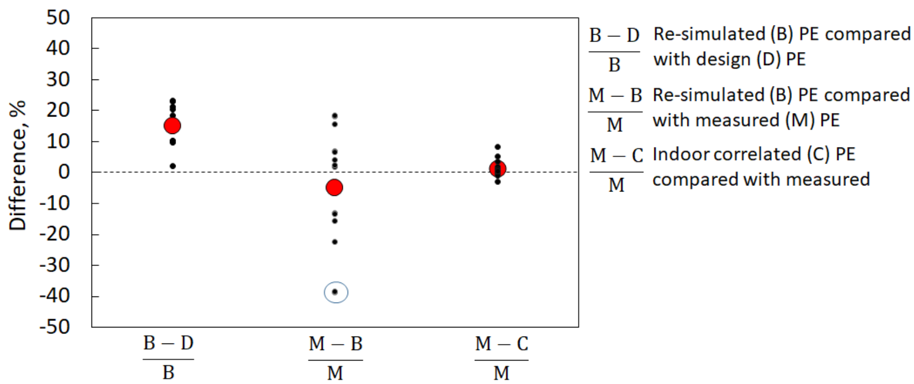


Figure 3.12 The difference between re–simulated (B) and designed (D) PE, between measured (M) and re–simulated (B) PE, and between measured (M) and indoor climate corrected heat (C)PE (and also between measured DHW and electricity).

In Figure 3.13 (left), there is a comparison between measured PE and calculated PE with the measured indoor temperature, ventilation airflow, DHW and household electricity levels. If primary energy is calculated using the calibrated simulation model, it can be seen that the average difference between designed and recalculated PE averages is 30 kWh/(m²·a) with one exception (building 2.12, which was at 3 kWh/(m²·a)) – see Figure 3.13 (right).

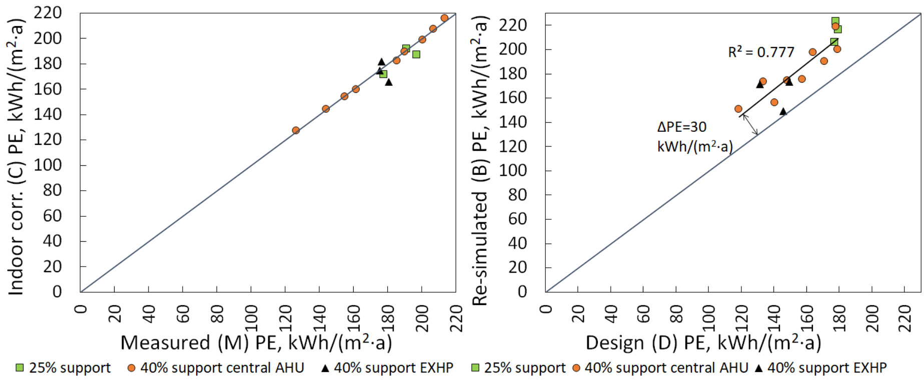


Figure 3.13 Indoor climate corrected primary energy needs when compared to measured primary energy needs (left), plus recalculated EPC when compared to designed EPC (right).

3.3 Use of the building

3.3.1 Indoor temperature and thermal comfort

Before renovation, the indoor temperature in 35 researched apartment buildings during the heating period was 20.8 °C on average, which is slightly lower than the value for standard use (RT I, 19.01.2018, 2018) for indoor climate and energy simulations (21 °C). After renovation, the indoor temperature was on average 22.4 °C (varied between 19.4 °C and 24.5 °C), Figure 3.14 (left), i.e. 1.6 °C higher than before renovation. In Figure 3.14, on the right, it can be seen that, after renovation, the room temperature is on average 1.4 °C (relative difference 6%) higher than the value for standard use (21 °C).

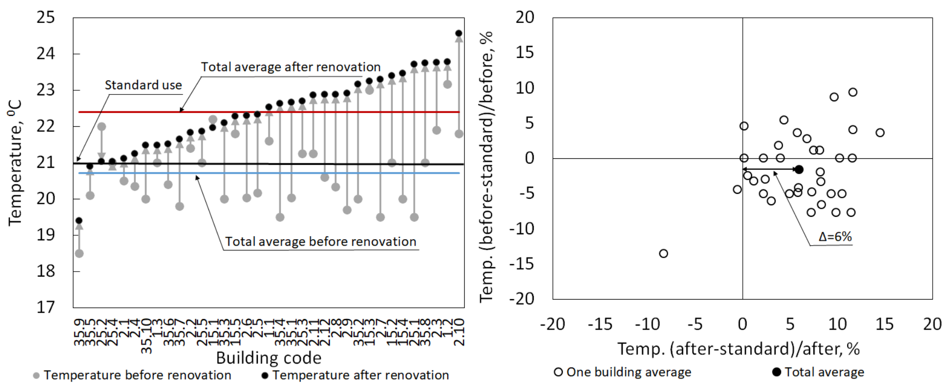


Figure 3.14 Indoor temperature before and after renovation (left); Indoor temperature performance gap from standard (right).

In the more detailed analysis of the nZEB case building, measured average indoor temperature in 80 apartments during winter months (from December to March) was 23.6 °C (Figure 3.15), which is on average 2.6 °C higher than the value for standard use.

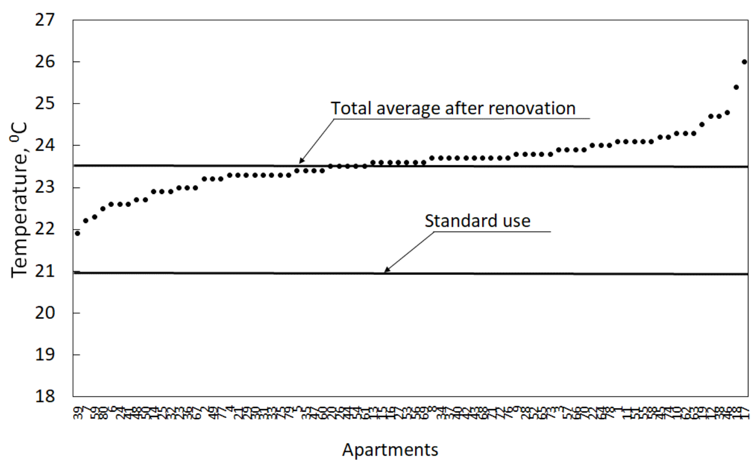


Figure 3.15 Average indoor temperature in apartments during winter – between December and March.

Based on the questionnaire (in 35 apartment buildings), in general, occupants were satisfied with the indoor temperature after renovation. 78% of 120 occupants answered that indoor temperature was comfortable (Figure 3.16). Only 11% of the occupants said that the temperature is lightly or rather warm.

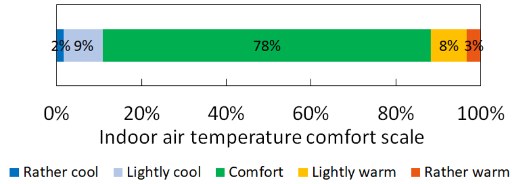


Figure 3.16 Occupant perceptions of the room temperature in apartments after renovation.

The lower and higher calculated PMV values were –0.66 and 0.67 and maximum PPD value was 14.4%. From 120 apartments, 10 are outside of the neutral thermal comfort (–0.5 < PMV < 0.5) zone. Based on calculations, 90% of apartments inside the comfort zone are satisfied. Differences between the reported satisfaction are very different from calculated (Figure 3.17); this can be caused mainly by the fixed initial parameters (human based input: clothing, activity) in calculations of PMV.

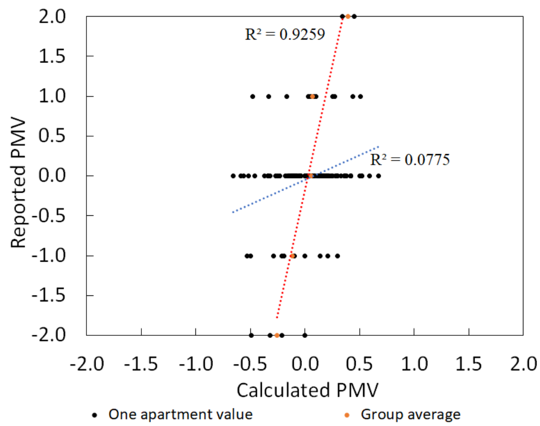


Figure 3.17 Calculated PMV index and PMV index by questionnaire.

Figure 3.18 shows that 68% of occupants reported an increase of the indoor temperature after renovation. Only 8% of occupants said that the temperature has decreased. In apartments where occupants said that the indoor temperature had decreased, the average temperature was 21 °C to 22 °C, but in the same apartments people complained about draughts.

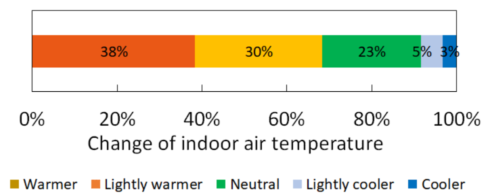


Figure 3.18 Occupant evaluation on the perspective change of room air temperature after renovation.

3.3.2 Performance of ventilation

The average ventilation air change rate of old Estonian apartments with natural ventilation before renovation is reported at 0.24 h^{-1} and 0.17 l/(s·m^2) (Mikola et al., 2017). The ventilation airflow after renovation, 0.36 h^{-1}, 0.25 l/(s·m^2) (varied between 0.05 h^{-1} and 0.86 h^{-1}, 0.03 l/(s·m^2) and 0.60 l/(s·m^2)), was much less than the value of standard use (RT I, 19.01.2018, 2018) for indoor climate and energy simulations 0.5–0.6 h^{-1}; 0.35–0.42 l/(s·m^2), Figure 3.19. The best correspondence and higher ventilation rate 0.48 l/(s·m^2) to indoor climate value was ventilation in buildings with central AHU. The lowest ventilation rate was in buildings with natural ventilation with new air inlets 0.11 l/(s·m^2) and room based units (SERU) 0.18 l/(s·m^2).

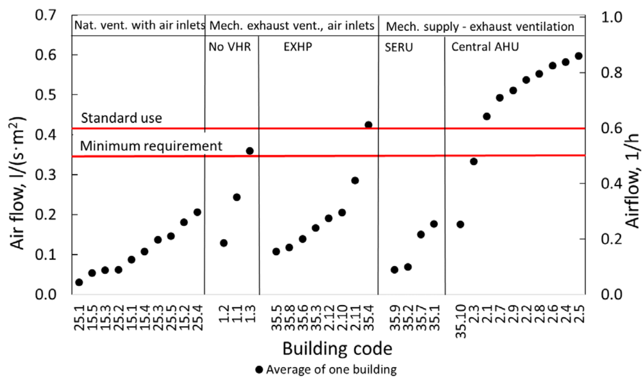


Figure 3.19 Ventilation air flow after renovation in studied apartments.

Based on the questionnaire (Figure 3.20), just 56% of occupants feel that the air in indoor apartments was fresh or rather fresh after renovation.

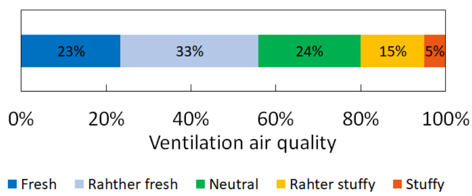


Figure 3.20 Occupant evaluation of ventilation air quality after renovation.

In the nZEB case building, the ventilation airflow rate with central AHU was similar to the standard use profile (0.47 l/(s·m^2)) but in apartments with apartment based AHU–s, the average airflow rate was 0.69 l/(s·m^2) which is a 60% higher airflow rate than the value used in the standard use profile (0.42 l/(s·m^2)). Ventilation supply air temperature on average was 21 °C, which is 3 °C higher than the supply air temperature in standard use. Higher supply airflow rate, supply air temperature and indoor temperature increased the heating energy need.

3.3.3 Domestic hot water use

The average DHW use in studied buildings was, on average, 31 l/(pers.·d) before renovation and 28 l/(pers.·d) after renovation (in buildings without circulation losses 24 l/(pers.·d) and 22 kWh/(m^2·a) correspondingly). DHW use in buildings with circulation losses was, on average, 31 kWh/(m^2·a) before renovation and 33 kWh/(m^2·a) after renovation. Buildings were divided into three groups depending on DHW circulation. Table 3.2 features DHW energy use before and after renovation. Buildings with DHW circulation have an average DHW use of 38 kWh/(m^2·a) after renovation, and without circulation of 21 kWh/(m^2·a). In buildings where circulation was installed during the renovation, the average increase of energy consumption for DHW was 13.4 kWh/(m^2·a) (Figure 3.21, left).

Table 3.2 The influence of DHW energy consumption on circulation and renovation.

	Energy use for DHW, kWh/(m^2·a)	
	DHW circulation after renovation	No DHW circulation after renovation
DHW circulation before renovation	42	
DHW circulation after renovation	39	
No DHW circulation before renovation	24	21
No DHW circulation after renovation	37	21

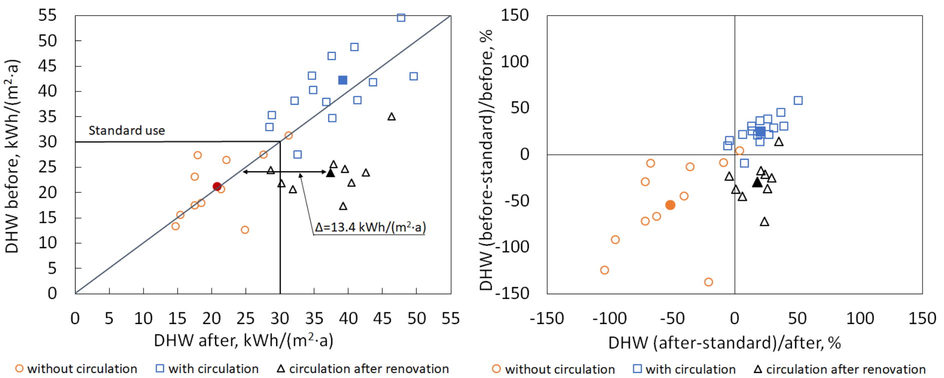


Figure 3.21 DHW use before and after renovation (left) and DHW performance gap from standard (one building parameter is with hole and group average is filled) (right).

Figure 3.21, right, shows the gap between the measured and standard use of DHW. Almost all buildings where there was no DHW circulation before and after the renovation used less DHW energy compared to the standard use. The relative difference between the measured energy and standard use was 54% before renovation and 52% after renovation. On the other hand, buildings with DHW circulation had a higher DHW energy use compared with standard use: before renovation 26% and after renovation 20%. Hence, independently from the availability of DHW, the energy for DHW decreased a little. The main difference in the change in DHW use was apparent in buildings where DHW circulation was installed during renovation. In these buildings the energy use for DHW increased 56%. For example, if before renovation the DHW consumption was 24.0 kWh/(m^2·a) than after renovation with installation of DHW circulation systems, the energy consumption increased to 37.4 kWh/(m^2·a).

In the regulations, DHW use is defined as water use per heated area. In reality, an area does not use the water; it is the occupants in the building who do. To analyse which is the better DHW use presenting unit – l/(pers.·d) or kWh/(m²·a), energy use was calculated with an average DHW use per person (28 l/(pers.·d)) and with standard usage of (30 kWh/(m²·a)), with and without DHW circulation (Figure 3.21, left). It can be seen that in most cases, DHW use without circulation compared with standard use per heated area is lower; the average gap from the standard use in all buildings is –48% (Figure 3.22, left). The gap between the standard use (kWh/(m²·a)) is –140% to 4%; from DHW use per person (l/(pers.·d)) it is between –61% and 40%. When we take into account DHW circulation, then it can be seen that the average difference from standard use per heated area moves to the positive side and when hot water circulation is considered, then the average difference with standard use after renovation is +19%, which is between –5% and 50% (Figure 3.22, right). In those figures it is apparent that volume–based consumption is more or less the same before and after renovation. Differences were caused mostly by DHW circulation losses.

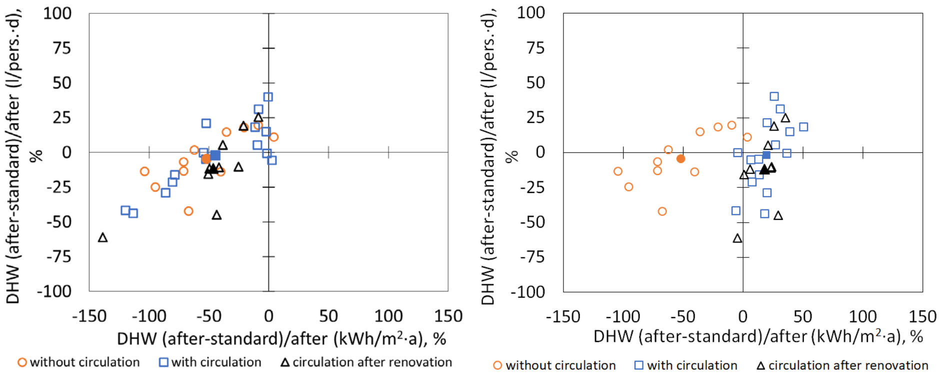


Figure 3.22 DHW use gap from average usage per person (l/(pers.·d)) and use gap from standard use per heated area (kWh/(m²·a)) without DHW circulation (left) and with DHW circulation (right).

3.3.4 Household electricity use

The renovation did not influence the average use of household electricity (apartments + common spaces): before renovation, it was 30.1 kWh/(m²·a), and after renovation, approximately the same, 29.5 kWh/(m²·a) (Figure 3.23, left). In general, the renovation did not change the use of electricity that much. The gap between the standard use, which has been taken without electricity use for ventilation (30 kWh/(m²·a)), is, on average, –3% before renovation (between –54% and 35%) and after renovation –4% (between –29% and 30%) (Figure 3.23, right).

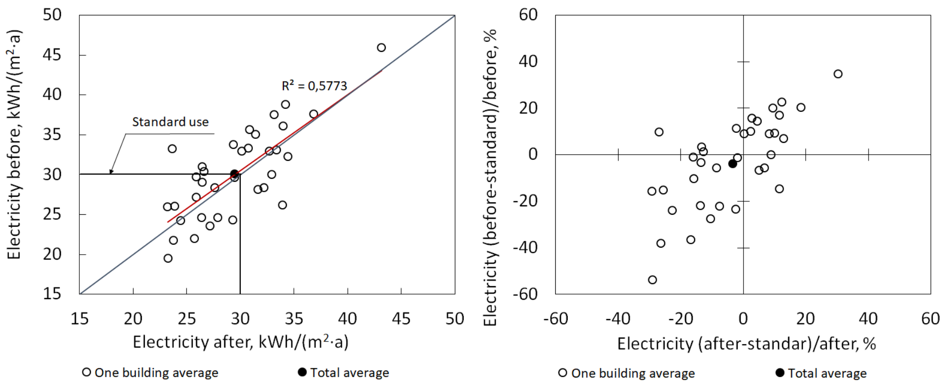


Figure 3.23 Electricity use before and after renovation (left) and electricity performance gap from standard use (right).

The use of electricity in common spaces (includes circulation pumps for DHW and heating and electricity for central ventilation units) in all buildings was, after renovation, 0.9 kWh/(m^2·a) higher (Figure 3.24, left) than before renovation. The increase of the use of electricity in common spaces was significantly higher ($P = 0.001$) in buildings with central AHU compared with buildings with other ventilation types. Figure 3.24, left, shows that in buildings with a central AHU, the average electricity use increased from 1.6 kWh/(m^2·a) before renovation to 4.9 kWh/(m^2·a) after renovation. Figure 3.24, right, shows that after the renovation, air flow in these buildings was also higher than in other buildings (average 0.5 l/(s·m^2)). An increase in the use of electricity in general spaces after the renovation was very small in buildings with other ventilation systems. Higher electricity consumption in buildings with central AHU doesn't mean that the entire energy consumption in those buildings was higher compared to others. A positive effect is that in those buildings the indoor air quality improved.

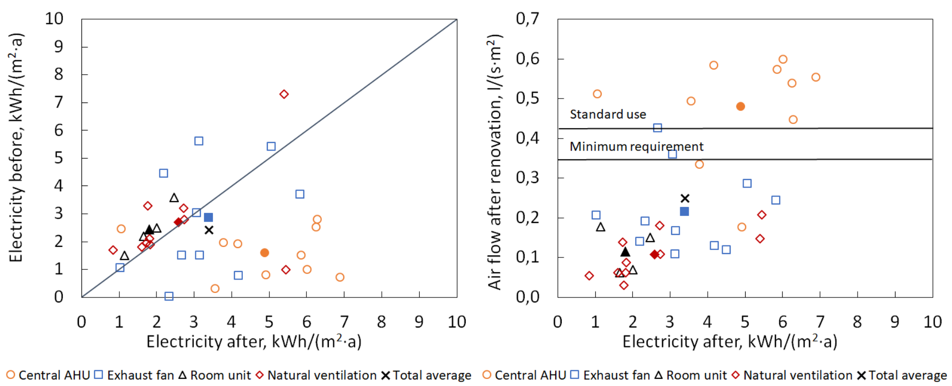


Figure 3.24 Electricity use in common spaces (including pumps and ventilators) before and after renovation (left) and electricity use in common spaces (including pumps and fans) after renovation compared with air flow (right).

3.4 DHW system’s heat loss calculations

Analysing DHW energy use in the analysed apartment buildings it was found that DHW system heat losses were 14 kWh/(m^2·a) but the problem is that the Estonian energy efficiency calculation method doesn’t include these losses in calculations. Measured results shows these losses, and the expected PE, can be larger by this unincluded figure. In Figure 3.21, a, it is clear that in 8 analysed buildings where, before renovation, local boilers were used for DHW, and after renovation a central DHW system was used, the DHW energy use is 13.4 kWh/(m^2·a) greater. These losses are mainly circulation losses and should be considered in energy performance calculations. For early stage design, a simplified tool is needed.

3.4.1 Pipe length calculation

To go about finding an equation for DHW pipe length in basements and shafts both one and two parameter equations were generated.

Table 3.3 presents the best results using the studied buildings basic data. The best results (the smallest difference in pipe length difference) gained with the one parameter model equation for basement pipe length using building gross area, was a length difference between measured and calculated in test buildings of 17% and in reference buildings of 8%, which gives an average of 14%. Using a building perimeter calculated from the building design drawings gave slightly better results (16% with test buildings), but with reference buildings the average is the same.

Pipe lengths in shafts is best fit with the building’s heating area equation (pipe length difference from measured lengths is on average 28%).

For the two parameter equation a bootstrapping method was used. Best results for pipe lengths in basements when combining building gross area and number of DHW shafts (frequency from 1000 samples was 182) gave an average calculated length difference from measured length in the test buildings of 10%. However, it was not possible to produce good results using any of the other basic building parameters which are known in the early design stages. The same lack of good results occurred when calculating pipes in shafts.

Table 3.3. Pipe length (in meters) equations and lengths difference from measured value (Publication IV Table 5).

Factor	Equation to Calculate the Pipe Length, m	R^2	Difference between Measured and Calculated, %			MBE (Mean Bias Error)			RMSE (Root Mean Square Error)		
		Test Buildings	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average
One parameter model	Pipe length in basement										
x = Volume	l = 0.0034·x + 46	0.56	23.8	9.2	19.2	−0.57	−5.8	−2.2	24.4	9.5	20.8
x = Heating area	l = 0.0109·x + 53	0.52	23.2	6.8	18.0	−0.04	−4.6	−1.5	25.4	9.2	21.6
x = Net area	l = 0.0112·x + 49	0.57	24.6	7.8	19.2	0.03	−4.5	−1.4	23.9	9.4	20.5
x = Gross area	l = 0.1235·x − 2	0.82	17.1	8.4	14.4	−0.01	0.2	0.1	15.7	7.7	13.6
x= Apartments per floor	l = 7.2845·x + 13	0.68	22.5	14.5	19.9	0.00	−4.6	−1.5	1.0	14.6	18.9
x = No. shafts	l = 6.1258·x + 11	0.89	13.0	28.7	18.0	0.00	17.1	5.4	12.3	28.4	18.9
x = Perimeter of building	l = 0.8015·x − 31	0.85	15.6	11.8	14.4	0.00	−8.9	−2.8	14.1	16.4	14.9
One parameter model	Pipe length in shafts										
x = Volume	l = 0.0163·x − 24	0.87	33.9	31.6	33.2	−0.1	−48.4	−15.5	50.7	65.2	55.7
x = Heating area	l = 0.0538·x + 3	0.88	26.8	31.6	28.3	0.1	−45.8	−14.5	48.7	65.0	54.4
x = Net area	l = 0.0522·x − 11	0.87	33.9	29.9	32.6	−0.1	−54.1	11.3	50.7	71.9	60.0
x = Gross area	l = 0.4471·x − 151	0.74	55.9	32.5	48.5	0.0	−23.8	−7.6	69.9	56.8	66.0
x = Apartments per floor	l = 25.768·x − 91	0.59	36.9	34.7	36.2	0.0	−41.1	−13.1	88.2	85.8	87.4
x = Tot apartments	l = 3.6964·x − 24	0.86	34.7	34.7	34.7	0.0	−58.2	−18.5	53.5	83.3	64.5
x = No shafts	l = 21.648·x − 98	0.77	36.5	25.1	32.8	0.0	35.5	11.3	66.1	44.4	60.0

Factor	Equation to Calculate the Pipe Length, m	R^2	Difference between Measured and Calculated, %			MBE (Mean Bias Error)			RMSE (Root Mean Square Error)		
		Test Buildings	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average
x = Perimeter	l = 2.5985·x − 211	0.62	59.3	37.4	52.3	0.0	−54.1	−17.2	85.0	71.9	81.1
Two parameter model	Pipe length in basement										
x = Gross area and y = No. shafts	l = 1.04236·x + 3.56701·y	0.94	9.7	18.4	12.5	0.8	10.9	4.0	9.4	18.9	13.2
x = No. shafts and y = Perimeter	l = 3.02566·x + 0.44814·y − 16	0.96	10.3	18.4	12.9	0.5	4.1	1.7	9.7	18.2	13.0
EN 15316–3			42.6	30.6	38.8	33.3	20.6	29.3	36.8	27.9	34.2
Two parameter model	Pipe length in shafts										
x = no. shafts and y = heating area	l = 10.1399·x + 0.03717·y − 67	0.94	23.8	14.3	9.8	0.0	−5.7	−1.8	20.2	20.6	20.4
EN 15316–3			325.3	144.7	267.8	515.2	−94.6	321.2	610.3	114.3	508.0

Figure 3.25, left, shows how well the floor gross area equation corelates with measured pipe lengths. DHW pipe lengths in shafts are detailed in Figure 3.25, right. Calculations showed that, on average, the pipe length difference from measured values was lowest when using this equation (in test buildings 35 m). Measured pipe length in 6 reference buildings was larger, which showed that by using this equation for calculations, it is probable that results will be over–optimistic, compared to measured values in the future. Building 1.9 is the largest building in the study which explains why the pipe length, when compared to the other studied buildings, is significantly greater.

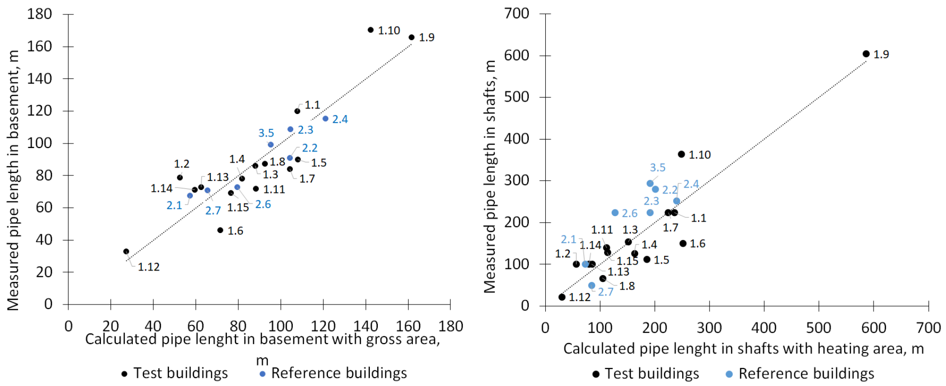


Figure 3.25 DWH pipe length in basement: measured pipe length compared with calculated pipe lengths in basement (left); measured pipe length compared with calculated pipe lengths in shafts (right).

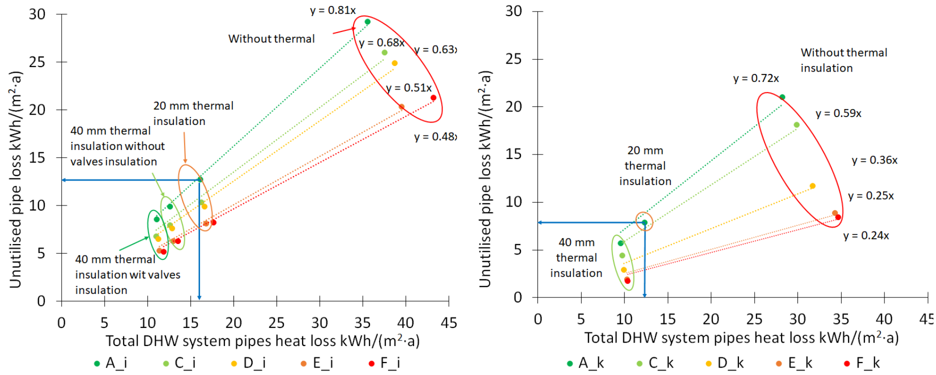
3.4.2 Parameters influencing heat loss from DHW circulation piping

DHW pipe heat losses in the reference building Figure 1.2 were investigated:

- Different thickness of thermal insultation (no insulation (0 mm), 20mm, and 40 mm);
- With and without DHW circulation balancing valve's insulation;
- Temperature in basement 21 °C or unheated;
- Different energy performance classes (EPC) (A, C, D, E, and F);
- Circulation pump working time (always on compared to working between 6.00 to 9.00 and 16.00 to 22.00).

To visualise how the various parameters influence energy loss from pipes it was decided to compare all EPC classes separately with different thicknesses of DHW pipe thermal insulation when the basement is both unheated and heated. In Figure 3.26, left, it can be seen that with different EPC classes, unutilised DHW system losses vary between 48% to 81% in the unheated basement, and this variance doesn't depend on the thickness of the pipes thermal insulation. In the heated basement, unutilised heat loss from DHW pipes is between 24% to 71% (Figure 3.26, right). Figure 3.26 shows the influence of pipe thermal insulation. When DHW system pipes are insulated with 20 mm of thermal insulation (EPC class A) than the total heat loss from pipes is 16 kWh/(m^2·a) but unutilised pipe losses are 13 kWh/(m^2·a) which means that utilised pipe losses, as an internal gain, are 3 kWh/(m^2·a). The same situation is apparent in the heated basement with 12 kWh/(m^2·a) total loss, 8 kWh/(m^2·a) unutilised losses and a utilised pipe loss of 4 kWh/(m^2·a). An analysis was also done of what occurs when the circulation pump is switched off during the night (22:00 until 6:00) and day–time (9:00 until 16:00), when

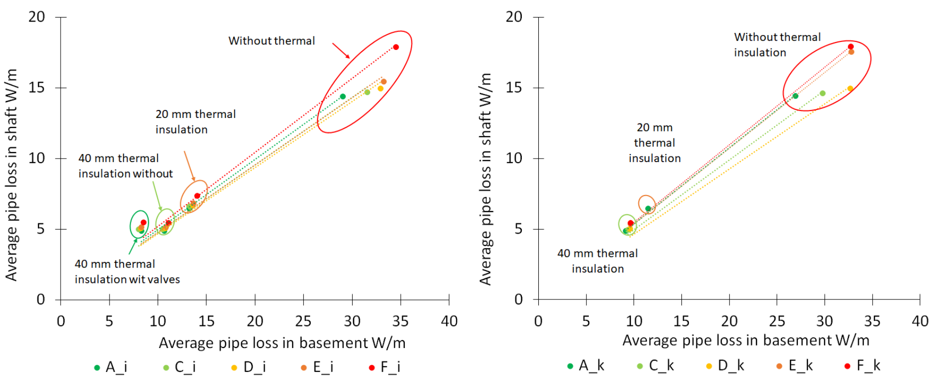
DHW usage is low. For the calculations a measured usage profile was used and the results indicated that energy loss was decreased by only 0.5 kWh/(m^2·a) compared with constant circulation. As this effect was so low, this analysis was not included in the other conditions.



(**a**) (**b**)

Figure 3.26. Total DHW pipe heat losses per heated area compared with unutilised pipe heat loss with different EPC classes and pipe thermal insulation: (left) when basement is not heated (i–unheated basement); (right) when basement is heated (k–heated basement).

In those cases where the equation for pipe length was found separately in basement and shafts, it was necessary to see how large was the piping heat loss per length (W/m). Results showed that that in all EPC classes, pipe losses from pipes covered with the same thickness of pipe thermal insulation are almost the same (Figure 3.27). With 40 mm of pipe thermal insulation the pipe heat loss in an unheated basement averaged 11 W/m and in a heated basement 9.5 W/m. In shafts the loss is more or less the same at 5 W/m. From Figure 3.26, it is possible to see how much of the entire losses are unutilised, but it was not possible to separate these losses between basements and shafts.



(a) (b)

Figure 3.27 Pipe loss in basement and in shafts (W/m): (left) when basement is not heated (i–unheated basement); (right) when basement is heated (k–heated basement).

In Figure 3.28, left, it can be seen that in unheated basements, the unutilised pipe losses in EPC classes C to F are more or less the same, between 58% and 70%. Only class A has unutilised losses of more than 80%. In Figure 3.28, right, it is apparent that there is a bigger gap between unutilised pipe losses in basements. In pipes with thermal insulation, the unutilised pipe losses in classes D, E and F are on average 18%, whereas for classes A and C these are over 60%. When the basement is heated, it is more realistic to assume that the basement envelopes are insulated and most of the pipe losses there are not utilised. Unutilised losses in shafts are, in classes E and F, on average 35% and in other classes from 55% to 80%.

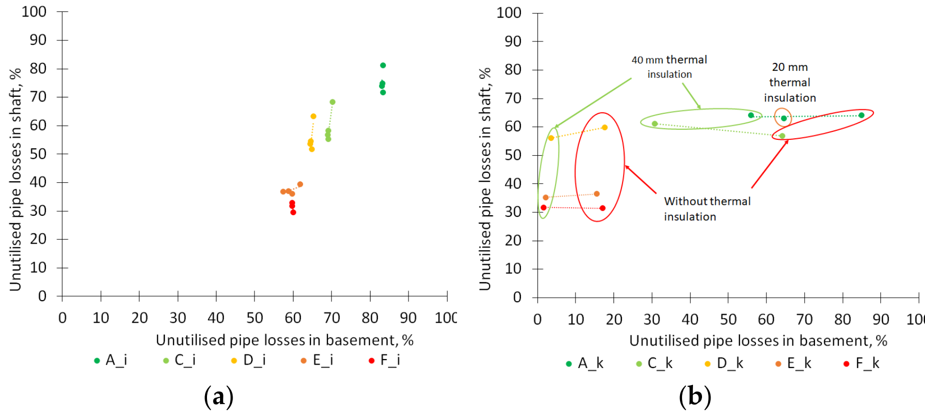


Figure 3.28 Unutilised pipe losses in basements and in shafts: (left) when basement is not heated (i–unheated basement); (right) when basement is heated (k–heated basement).

3.4.3 Heat loss from DHW piping

From the research it was possible to generate an equation for DHW system heat loss using the case study building losses analyses. In Table 3.4 there are presented pipe losses per length with different thicknesses of pipe thermal insulation and also how much pipe losses are unutilised as internal heat gain.

Table 3.4 Pipe losses per length with different thicknesses of pipe thermal insulation (q_a) and how much of the losses are unutilised as internal heat gain ($Q_{unut.}$).

	Insulation of pipes	Basement is unheated		
Basement losses		$q_{a.basement}$, W/m	$Q_{unut.\ basement}$, %	
			EPC "A"	EPC "C"
	40 mm (insulated valves) 40 mm (uninsulated valves) 20mm	8.3 10.8 13.6	83	70
		Basement is heated +21°C		
		$q_{a.basement}$, W/m	$Q_{unut.\ basement}$, %	
	40 mm (insulated valves) 40 mm (uninsulated valves) 20	7.0 9.2 11.5	56	48
Shaft losses		$q_{a.shaft}$, W/m	$Q_{unut.\ shaft}$, %	
	40 mm 20 mm 0 mm	5.1 6.8 15.5	69	59

From this we can generate a different heat loss equation for unutilised DHW system heat loss in the basement ($\Phi_{aDHW\ basement}$ equation 3) and in shafts ($\Phi_{aDHW\ shaft}$ equation 4):

$$\Phi_{aDHW\ basement} = l_{DHW\ basement} \cdot q_{a.basement} \cdot Q_{unut.\ basement} \cdot 8760 \cdot 10^{-3}/A_{heat},\ \text{kWh/(m}^2\cdot\text{a)} \quad (3)$$

$$\Phi_{aDHW\ shaft} = l_{DHW\ shaft} \cdot q_{a.shaft} \cdot Q_{unut.\ shaft} \cdot 8760 \cdot 10^{-3}/A_{heat},\ \text{kWh/(m}^2\cdot\text{a)} \quad (4)$$

A_{heat} is building heating area (m²)
l_{DHW} is calculated pipe length (l)
q_a is pipe heat loss per calculated length (W/m)
$Q_{unut.}$ is unutilised pipe loss (%)
8760 is hours per year (h)

Using for calculations the best equation to find pipe length in basements (equation with floor gross area) and in shafts (equation with heating area), in all test and reference buildings with pipe thermal insulation of 40 mm (without thermal insulation on circulation pipe valves), the annual heat loss per heated area (basement is unheated) can be calculated. In Figure 3.29 it is evident that there is a good correlation with heating area. Buildings which have a larger heating area have lower pipe losses. The minimum unutilised pipe heat loss in a building is 5.5 kWh/(m^2·a) (total 7.6 kWh/(m^2·a)) even though the heated area is more than twice as large as the second biggest building. From this graph it can be said that, for over 5000 m^2 of heated area, the pipe heat losses are the same. In smaller buildings however, there can be unutilised losses of up to 12.1 kWh/(m^2·a).

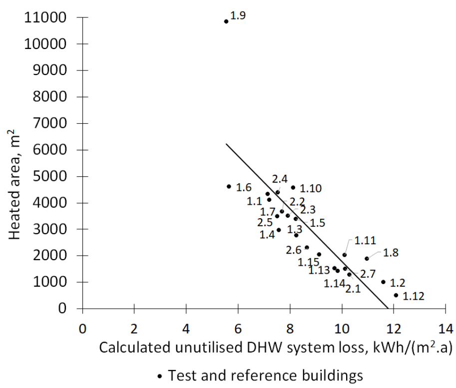


Figure 3.29. Test and reference building calculated unutilised DHW system pipe heat loss with 40 mm pipe thermal insulation without circulation valve thermal insulation and basement heating (EPC A).

All buildings calculated average unutilised DHW system loss was 8.7 kWh/(m^2·a) and median 8.2 kWh/(m^2·a).

4 Discussion

4.1 Performance gap in energy saving targeted renovated buildings

Half of the 20 studied buildings which fulfilled energy saving targets achieved the targeted thermal energy savings (heat + DHW heat). In several buildings, the real energy savings are higher than calculated. This is due to the lower ventilation airflow in buildings. This result is distressing because energy savings should not be achieved at the expense of a worsened indoor climate. The airflow was at the required level only in one building. As a result of this study, it is apparent that it is not possible to ensure proper airflow with natural ventilation. Of ventilation equipment, room based ventilation equipment also proved problematic (noise, draughts, efficiency, etc.) Simson, Mikola, and Kõiv (2014). Therefore, it is no longer recommended to use these units for renovation of residential buildings in Estonia with KredEx renovation grants.

A number of calculation errors were found in energy audits. Most of the errors were related to the reduction of heat energy use to the reference year and wrong allocation of electricity use for heating, DHW, lighting and appliances. In some cases, the energy auditor had also taken into account some energy usage twice. This means that there is motivation to show energy savings more optimistically than can be realised or to show energy consumption in the existing situation more pessimistically. This finding was also the motivation for writing guidelines for energy audits of apartment buildings (Hamburg & Jõesaar, 2015). Also, there must be better control for energy audits. This would help to avoid mistakes which can affect building energy balance. In the future, there should be trained consultants in place to check for the most common errors.

There is no requirement to separate hot water circulation from domestic hot water supply in the Estonian energy efficiency regulations. However, this research brought forth the idea of analysing DHW and DHW circulation energy more deeply. Another reason why the target and real energy savings vary may be due to the difference between the calculated and actual temperature and different ventilation airflow. In four apartment buildings (15.1, 15.5, 25.5, and 35.7) where measured indoor temperature was comparable to calculated temperature and real airflow was more than 50% lower than required, it was clear that energy saving calculations made by auditors contained mistakes. It is likely that auditors showed better energy saving targets in order to secure financial support. This problem shows that thermal energy saving is not a good base point for financial support. A possible solution is to show only target heating energy consumption after renovation, which is also connected with Estonian energy labelling calculations.

The second possibility as to why auditors' energy saving targets were too high may have been that the existing energy auditing form for calculating heat losses is too simplified. The current form enables taking into account thermal conductivity heat losses through envelopes and envelope junctions. Comparing renovated buildings' energy consumption, it becomes apparent that there are other parameters which should be accounted for differently (Kalinic & Krarti, 2010). This requires updating the energy auditing methodology.

A comparison of thermal energy efficiency levels between different renovation packages shows that there is almost statistical significance ($p = 0.07$) between buildings with minor renovation (target level 30% and 15% financial support) and others. This shows that minor renovation does not guarantee energy savings and it is not feasible for the state to support it. The importance of comprehensive renovation was also shown by Kuusk & Kalamees (2015) and Majcen et al. (2016).

Main points from performance gap in energy saving targeted renovated buildings analyses:

- Heating energy savings targets are not a good target for renovation grants because the achievement of the target heating energy consumption is unclear. It is also very unclear, in many cases, when the pre-renovation consumption was measured. Was it at the time of construction, just pre-renovation, or at some point in the intervening period?
- Heating energy savings should be calculated and shown in energy audits, otherwise these savings cannot be inspected.

4.2 Performance gap in energy performance level targeted renovated buildings

Even when energy–related refurbishment work decreased the energy use in buildings, the designed energy performance targets were not achieved in most of the renovated buildings that were part of the study (74%). The rebound effect (shown in many earlier studies (Calì et al., 2016; R Haas & Biermayr, 2000; Hens et al., 2010)) still exists. This result is somewhat worrying from an investor and energy policy point of view. Many studies have shown a large discrepancy between the predicted and actual measured energy use in buildings. As this result was observed several decades ago (H Bagge & Johansson, 2009; Branco et al., 2004; Elmroth, 2002), more thorough controls are required in energy refurbishment work on buildings, with such controls governing research, surveying, energy auditing, designing, construction and quality.

The energy use for room heating and ventilation showed the largest energy performance gap. The average primary energy consumption for heating (between measured and designed) was on average 38% larger than for measured heating–delivered energy (between 10% and 67%). Heating energy use in the nZEB renovation case was, after renovation, 40% greater than designed, which is similar with the other 15 buildings analysed previously. The delivered energy for room heating (in 15 analysed buildings) after refurbishment works (M) was on average more than 35% greater than calculated values in the design phase (D). Delivered energy for room heating energy depends directly on the heat loss levels of the building envelope (J. Kurnitski et al., 2012) and also on system efficiency. Heat loss for the building envelope depends upon thermal transmittance, thermal bridges and air leakages. From the figures for total heat loss, the share of thermal bridges could be between 10% – 40% (Berggren & Wall, 2013; Ilomets, Kuusk, et al., 2017) and air leakages between 7% – 30% (Jokisalo et al., 2009; Ren & Chen, 2015). The quality of the building envelope in terms of thermal bridge air leakages is relatively easy to measure. The largest single heat loss component, thermal transmittance, is usually not measured. A literature review by (Roels et al., 2017) showed that none of the studied building envelopes realised the intended performance levels and, in some cases, actual performance rises to about twice that value. This performance gap could be caused by workmanship quality levels (Huttunen & Vinha, 2013; Kalamees et al., 2017) or poor modelling predictions (Marshall et al., 2017). Using safety factors or, better, taking into account the non–ideal nature of such things, together with quality checking and providing instructions for the workmanship involved in refurbishment, are needed in order to minimise the performance gap in the thermal envelope. On the other hand, the analyses in the nZEB case building showed that the building envelope performed as expected in the energy calculations. Thus, the use of prefabricated insulation elements was worthwhile to guarantee a high–quality building envelope. Heat losses of the building envelope are in the same range as calculated values. Previous measurements of the building envelope (Pihelo et al., 2017) have also shown that measured thermal transmittance of external walls and the air tightness of the building envelope is similar to the calculated values. This means that envelope transmission difference is not a problem in this study's research case.

Large variations were seen between buildings in terms of their room heating energy use. In Figure 3.14, Figure 3.15 and Figure 3.19, it was apparent that user–related parameters (such as indoor temperature and ventilation airflow) were not equal to the standard use for the building. The measured average indoor temperature of 22.4 °C corresponded to the targets in the ICC II (EN 15251, 2007), but it was higher than the heating set–point temperature used in simulations: 21 °C in standard building use (RT I, 19.01.2018, 2018). (Ilomets et al., 2018) and (Hans Bagge et al., 2014) showed in their cross–sectional indoor climate study on dwellings, that indoor temperature is more likely to be 22 °C than anything lower. In addition to thermal comfort, the balance for heat loss and heat gains also influences indoor temperature in energy–efficient buildings. In order to avoid a performance gap due to input parameters, 22 °C could be a more relevant set–point for a heating system. (Földváry et al., 2017) also showed that indoor temperature changes after refurbishment work has been carried out. Higher indoor temperatures have also been investigated earlier (Branco et al., 2004; Broderick et al., 2017; Földváry et al., 2015; La Fleur et al., 2017). This study's investigation of the nZEB case building showed that a 1 °C increase in indoor temperatures increased heating energy consumption by 15%.

Calculations and visual observations in the nZEB case building show that occupants are using opened windows to regulate heat and ventilation. Opening the windows is not studied in detail in this building, but this study's results shows that this can increase the heating energy use on average by 20%. Window opening behaviour and effects must be studied in more detail in this building. One possibility could be similar to that which Bourikas et al. (2018) have shown in their study where they analysed a camera based system to automatically diagnose the status of window opening on the facade. They found that this system has an accuracy level of 90% – 97%. Bourikas et al. also showed that occupants like to have open windows and they often forget to close them. In their study they analysed an EPC "G" class building and, with window opening, the annual heating energy consumption increased by 19%. In this study, it was assumed that it would be around 15%. Further studies have also shown that user behaviour can affect building energy use significantly. La Fleur et al (Lina La Fleur et al., 2017) also showed that window airing affects heating energy consumption, but at the same time, can lead to a reduced use of electricity heating energy consumption. Linden et al. (Lindén et al., 2006) showed that user behaviour should be taken into account when analysing energy consumption because it is an important factor.

Occupant behaviour affects building energy consumption a lot. Window airing is known as user behaviour, but exact opening times and duration are hard to identify. It does not always appear to be when people are using the apartment and therefore using electricity for lights and appliances, which shows as internal heat gain. In the current building, it was known, for every apartment, the number of occupants and the daily electricity usage but the detailed use profile is unknown. Bellia et al. (2018) also showed in their study that, when calibrating the simulation model, it is important to know scheduled occupancy, internal loads and interaction between occupants and windows to give better calibration results.

The analyse of user related heating energy consumption such as window airing and times when occupants are absent from their apartment shows that the authors need a more detailed study to understand the energy balance of the building in a more comprehensive manner. As the importance of heat losses from pipes is higher in nZEB buildings, then this type of study would help decrease the gap between the calculated and measured energy consumption.

In this research (Figure 3.9) heating energy consumption was analysed more deeply with the program IDA ICE, and calculation steps showed that the influence of using a multi–zone simulation tool compared with a simplified tool changed the results for heating energy significantly. Different models and model simplification influence simulation results; even when input parameters are similar (Klimczak et al., 2018; Shiel et al., 2018). In this study, results which were calculated using a detailed dynamic simulation model gave results more similar to those achieved with measured data than they were to the simplified model. The main reason was an overestimation of solar heat gains in the simplified model. This decreased heating energy use to a level which was lower than that which the measurements showed. The main shortcoming in the calculations was a lack of knowledge when it came to calculating the unheated basement's ceiling thermal transmittance in a one–zone calculation tool where it is important to involve the basement envelopes and air flow in the overall calculations. In all of the calculations, this figure has been incorrectly calculated. (Hoffmann & Geissler, 2017) showed that in the energy calculations, the basement ceiling's thermal transmittance levels have been taken into account at a greater rate than they were in reality, but in this study's case, it was vice versa.

Calculation step B (Figure 3.9) showed that after correcting other envelope transmittances, smaller differences with measured heating energy consumption are seen. After the corrections, heating energy was re–calculated with measured indoor temperatures and air flows and used average values for all apartments in the same buildings. A gap between measured and calculated values also exists after using measured indoor temperature and airflow, which shows that in further studies there is a requirement to measure indoor air temperature and air flow in more apartments per building. Calculations also showed that a change in air flow of 0.05 $l/(s \cdot m^2)$ can affect heating energy consumption in well renovated buildings by about 8%.

In the nZEB case building 10% of delivered heating energy losses came from the heating pipes located in the unheated basement, between the central heat meter and radiator district heating heat exchanger, and also heating pipes which are located in the service shafts and are connected with the central AHU heating coil in the roof.

One reason why measured (M) and re–calculated (B) PE need was more than 20% different (in 15 studied buildings) was the difference between measured and standard use DHW. DHW energy use in the nZEB case building where renewable energy was also used in the renovation solution was analysed in more detail. There is hot water stored in large accumulation tanks and during the day, when DHW use is low, heat losses from the tanks cause energy losses from the solar collector system. Solutions for how to optimise heat loss from water tanks should be analysed in future studies. One solution could be optimising water tank volume which has also been discussed by Li et al. (Li et al., 2015). The methodology for calculating solar collector heating energy production and the design of these solutions should be analysed in more detail. In the investigated building, the system production was similar to the calculated value but the efficiency of using produced energy was only 50%. From this, it can be said that the entire solar collector system in the nZEB case building can be improved in the future and that it is not working as expected today.

In the studied building, the measured DHW consumption is 1.5 times higher and occupation density is 1.2 times higher than the standard value. This shows that occupants of the pilot building use more DHW than estimated in the standard user profile. In PUBLICATION III have shown that, on average, people use 28 l/(d·pers) of domestic hot water, which is lower than the standard value. In the investigated building, the higher DHW consumption could be caused by young families (university's family dormitory) who have children and are using more DHW. In an average apartment building, the inhabitant mix is more varied, which leads to a lower DHW usage.

In an investigation of 182 Finnish apartment buildings (Ahmed et al., 2015) the average DHW consumption was 43 l/(d·pers) and in Swedish buildings 33 l/(d·pers) (Ferrantelli et al., 2017). Comparing this study's results with neighbouring countries, the measured DHW (49 l/(d·pers)) use is also higher. One possibility to lower DHW consumption is to use faucets with which it is possible to limit maximum water consumption. Earlier studies by Toode and Kõiv (2005) have shown that from 1999 to 2003 DHW usage decreased (from 59 to 45 l/d·pers)) and the main reason was the increasing cost of DHW. In the current building, all apartments are paying based on consumption, but this has not led to a decrease in DHW use.

The Estonian energy calculation method (RT I, 19.01.2018, 2018) does not include DHW circulation losses, which in the studied pilot building was 24% of measured DHW from district heating and, from entire DHW energy use, 20%. Part of the DHW circulation losses are utilised as internal heat gain. But outside the heating season it is not possible to utilise most of the circulation losses. Also, in the pilot building there was no information available on how much of this energy is utilised. In this building, circulation losses are measured in detail which enables a more in–depth analysis of the problem. As the DHW energy share from the entire heat balance in nZEB buildings is higher than in common buildings, then heating energy losses of DHW systems should be taken into account in energy performance design. This study showed the need to have a calculation method for DHW circulation.

Re–calculation in the nZEB case building with standard use values (S) showed that primary energy consumption criteria of nZEB can be achieved when heat losses from the DHW and AHU heating coil are not taken into account. When measured AHU heating coil pipe losses and DHW losses are added to the calculation, then it is not possible to reach the nZEB energy performance level using the designed solutions. Results shows that distribution losses from pipes are 10% of the primary energy need. As the real occupational behaviour is different from the standard usage then the primary energy need for heating is 10% higher compared with calculated consumption. This comparison has highlighted the effect when window opening is not considered. The real occupational behaviour means that the primary total energy need is 14% higher compared with calculated consumption. When we compare the calculated heat energy use with the standard use, the higher temperature and higher airflow cause the rise of primary heating energy consumption by 60% (from 18.7 kWh/(m^2·a) to 30.1 kWh/(m^2·a)). Together with predicted window opening figures, the rise of primary energy consumption goes up to 34.4 kWh/(m^2·a) which is 84% higher than the standard use case, and with extra pipe losses it doubled the standard primary energy consumption for heating.

Main points from performance gap in in energy performance level targeted renovated buildings analyses:

- Heating energy calculations should be done with a dynamic simulation tool or with a validated simple tool which is easy to control and understandable. This can avoid the biggest performance gap between calculated and measured heating energy consumption.
- Indoor temperature in calculations should be 22 °C, this can also negate the performance gap between measured and calculated heating energy consumption.
- DHW system heat losses should be included in EPC calculations.

4.3 Use of buildings

Indoor temperature was, on average, 1.6 °C higher after renovation (22.4 °C), which is 1.4 °C higher than the value used for indoor climate and energy modelling. If thermostatic valves were installed during the renovation, occupants now had the possibility to regulate their living temperature. This could be a reason for higher indoor temperatures. After renovation, the building is well insulated and should use less energy for space heating. As the heating bill is now not so high for occupants, they enjoy a higher temperature. This phenomenon can be described by the rebound effect. Higher room temperatures after renovation have been shown in other studies (Branco et al., 2004; Broderick et al., 2017; Földváry et al., 2015; Lina La Fleur et al., 2017). Higher room temperatures also causes higher heating energy consumption. Földváry et al. (2017) showed that a room temperature increase of 1 °C increases the heating energy consumption in energy efficient buildings by 16.8%. Based on the questionnaire, occupant satisfaction about indoor temperatures was good. Some difference existed between the reported and the calculated PMV based on measured values in the range outside of the neutral zone. Occupants reported more severe conditions than had been calculated based on measurements. This may be caused by different clothing and activity levels, and of course there will always be some people who are never satisfied (Fabbri, 2013).

This situation is much better than previous cross–sectional studies about the building's technical condition and occupant behaviour have shown. Kalamees, Ilomets, et al., (2010) showed that the main problems are related to building physics, indoor climate, HVAC systems and energy efficiency. Typical indoor climate related problems have been stuffy air, uneven temperature in different rooms, problems with temperature regulation possibility, etc.

Based on the questionnaire, occupants were satisfied with the indoor temperature even though the temperature was more than 1 °C higher than that used for energy modelling. To achieve realistic estimates for energy use after renovation, increasing the model room temperature to 22 °C is suggested.

It is proposed that an individual heating metering system in apartments could motivate occupants to avoid a too high room temperature. (Hamburg et al., 2014; Hamburg & Kalamees, 2017) showed that instead of lowering the room temperature, occupants started decreasing the ventilation airflow and neighbouring heating (where heat is flowing through surrounding internal envelops from neighbouring apartments) in well insulated buildings.

Ventilation airflow was lower than designed in buildings with natural ventilation, mechanical exhaust ventilation, and supply–exhaust room units. In apartments with outdoor air inlets, drafts occur during the cold period. Therefore, occupants start closing the ventilation air inlets, thereby also decreasing exhaust airflow. In apartments with room–based supply and exhaust ventilation units, the drawbacks of using designed airflow are a high noise level, low pressure drop, operation management and inefficient heat recovery. To achieve the designed airflows, it is recommended to use, in the renovation of residential buildings, central supply and exhaust ventilation units with heat recovery or apartment–based supply and exhaust ventilation units with heat recovery that showed a satisfactory performance in detached houses in a cold climate (Kurnitski J. et al., 2005). Based on a questionnaire, only 20% of occupants were dissatisfied with indoor air quality even when required ventilation airflows were not guaranteed after renovation. This shows that occupants adopt to the worsened air quality.

After measuring, it was clear that the use of DHW was similar with other Estonian apartment buildings (Arumägi & Kalamees, 2014; Kuusk et al., 2014) but higher than in other countries: the EU average is 25 kWh/(m^2·a), Sweden 29 kWh/(m^2·a), and Norway 30 kWh/(m^2·a) (Ahmed et al., 2015). This study showed a difference in the use of energy in buildings with and without DHW circulation. A difference in the energy use for DHW with and without circulation shows the need to calculate DHW circulation losses separately. (Calì et al., 2016) has also showed that DHW distribution losses can be very high. Calculating DHW circulation separately from DHW to get comparable values with standard use is recommended following the results of this research.

The use of electricity in buildings showed a good match between the use before and after the renovation. This shows that it does not influence occupant behaviour too much. (Liu et al., 2015) showed that household electricity usage can increase after renovation, but this was related to new installations. When comparing the use of household electricity with standard use, a large variation can be seen between buildings. The relative difference varied between –54% to 35% but the average difference between before and after renovation is 3.1 kWh/(m^2·a). In three buildings, the electricity use difference was more than 5 kWh/(m^2·a). In the same buildings, the difference in electricity use was also apparent for a three–year period before the renovations.

The installation of mechanical ventilation increased the use of electricity due to electric fans. The increase was significantly higher in buildings with a central air handling unit. Compared with other ventilation systems, the higher values were due to the better performance of ventilation, as the ventilation airflow was much lower than required in buildings with other ventilation systems. Even though the electricity use increases when installing mechanical ventilation, the total energy balance is positive in cold climate conditions. Many studies have shown that installation of mechanical ventilation with heat recovery in cold climates is cost–effective in total (Alev et al., 2015; Arumägi & Kalamees, 2014; Kuusk et al., 2014).

Main points from use of building analyses:

- Indoor temperature after renovation is 1.6 °C higher. After renovation occupants seem to become more comfortable with increasing their indoor temperatures.
- DHW heating energy use changes when the DHW system is changed. After installing DHW circulation, the energy use in affected buildings was 13.4 kWh/(m^2·a) higher compared with to use before renovation.
- Electricity use after renovations either does not change or the changes are insignificant.

4.4 DHW system heat loss

In existing buildings where circulation losses are not measured separately, it is hard to separate the share of these losses from the entire building energy use. In a previous study, DHW circulation losses were analysed. In 23 buildings, the DHW circulation losses were not directly measured but were calculated from measured DHW consumption and the known total energy consumption for DHW. The graph in Figure 3.29 presents all buildings DHW circulation heat loss against heating area. In those buildings DHW circulation heat loss was 16.3 kWh/(m^2·a) except in one outlier building, where it was extremely high (34 kWh/(m^2·a)). Earlier studies of other buildings measured DHW system heat loss showed that, in similar buildings, it can vary considerably.

From the figure it can be seen that across the same types of building (code 1.2), measured DHW system energy loss can be from 9.5 to 34 kWh/(m^2·a) and the calculated loss (with 40 mm pipe insulation) 15.4 kWh/(m^2·a). In all 7 of these buildings, the DHW and DHW circulation pipe lengths are very similar. Differences in heat losses come from the quality of the pipe thermal insulation installation work and the thickness of insulation. Basement heat losses in those buildings are also different.

In studied buildings it has been noticed, when comparing volume based measured DHW calculated energy use with measured entire DHW energy consumption, that losses from pipes are on average 16.3 kWh/(m^2·a) (PUBLICATION I, III, V). From the entire buildings DHW energy need this was 27% – 62%, the average from 22 buildings was 44%. Very similar results have been found in earlier studies. Bøhm and Danig showed, from the entire DHW heating energy need, a 65% loss (Bøhm & Danig, 2004) and later Bøhm specified it as 23% – 70% (Bøhm, 2013). Similar losses have also been shown by Gassel (Andreas Gassel, 1999) and Zhang et al. (Yanda Zhang et al., 2012). Horvath et al. (Horvath et al., 2015) showed a slightly lower DHW system heat loss of between 5.7 and 9.9 kWh/(m^2·a). This study's calculations showed that 5.5 kWh/(m^2·a) is the minimum loss in apartment buildings.

If DHW system pipe losses are not integrated into energy efficiency calculations, it has been shown that predicted energy consumption is lower than the actual measured values taken in use. Also, the expected EPC might be one class higher ("C" class improved to "D" class). One of the goals of this study was to find an equation for DHW system pipe lengths with which, in the design phase, it would be possible to make accurate predictions of the probable future energy consumption of apartment buildings.

In this research such different factors as building volume, heating area, net area, floor gross area and total number of apartments were analysed. A decision was made not to analyse as per EN standard (EN 15316–3, 2017) with building lengths and DHW pipe lengths in the basement.

From analyses it was decided to consider in the future calculation method for assuming DHW and DHW circulation pipe length, that for pipes located in basements, the building gross area should be used and for pipes located in shafts, the building heating area. Analyses showed that the two parameter model quality is no better than the one parameter model, which is why the decision was to use only the one parameter model for length calculations.

As data was available from DHW system pipe losses from earlier studied buildings, it was possible to see how calculated length corelated with measured pipe losses. Using detailed measured DHW losses in the reference building, it was possible to analyse pipe losses in different EPC classes (A, C, D, E and F) with different thickness of pipe thermal insulation and with heated and without heated basements. From these analyses it was found that in different EPC class buildings, pipe loss per heated areas was more or less the same. The difference was in how these losses can be utilised as an internal heat gain, and here there was a difference between heated and unheated basements. In an EPC class C building with an unheated basement, it is possible to utilise, over the entire building, approximately 33% of pipe heat losses but separately basement losses of 30% and shaft losses of 40%. Focusing just on 40 mm of pipe insulation, then heat loss per pipe length in the basement was 10.5 W/m and in shafts 5.0 W/m. From this can be calculated, for a similar building with calculated pipe length, the entire DHW system pipe losses. With a larger heated area, the heat losses from pipes are lower and calculations showed (Figure 3.29) that, in buildings of over 5000 m^2 heated area, the unutilised loss cannot get below 5.5 kWh/(m^2·a) (total 7.6 kWh/(m^2·a)) with 40 mm of pipe thermal insulation, when the basement is unheated. Also, it has been shown that the maximum unutilised heat loss is 12.1 kWh/(m^2·a) (total 15.7 kWh/(m^2·a)). This shows that in smaller apartment buildings, the same piping heat loss from DHW systems is over 6 kWh/(m^2·a) greater. The EPC class in smaller buildings can be affected by the net DHW system loss of 12.1 kWh/(m^2·a) with a primary energy factor 0.65 (efficient district heating), 8.7 kWh/(m^2·a) (district heating efficiency 0.9) and with factor 1.0 (heating with gas) 12.7 kWh/(m^2·a) (gas boiler efficiency 0.95). To reach current EPC limits it will be necessary, in the future, to also include in the calculations the DHW unutilised system losses.

Comparing the calculated length in all buildings (test and reference) then, on average, pipe length in shafts are 0.11 m/m^2 (per heated area) with the Finnish method for calculating heat loss for EPC classes giving 0.2 m/m^2 (Ympäristöministeriö, 2018). According to this regulation, the loss from pipes in heated areas (depending on pipe insulation) is 6 or 10 W/m. Compare these figures to the calculations in this study, which gave an average of 5 or 7 W/m. The Finnish regulation for calculated length in basements was not simplified. There is however a sentence in the regulation which states that pipe length in basements should be measured.

If volume based DHW energy use by Estonian regulations (RT I, 19.01.2018, 2018) is 30 kWh/(m^2·a) and calculated unutilised circulation loss is between 5.5 kWh/(m^2·a) and 12.1 kWh/(m^2·a), then circulation loss is between 18% and 40%. This is more than Grasmanis at.al. (Grasmanis et al., 2015) have found. Burke et al., (2020) investigated about 200 multifamily dwellings of different ages in Sweden and their question was "is it possible to have DHW system losses of under 4 kWh/(m^2·a)?". They then showed that it is almost impossible, and, in reality, this figure is more than 3 times higher.

Himpe, Vaillant Rebollar, and Janssens (2013) concluded that simplified heat loss calculation methods can be significantly improved when the estimation of two influential parameters, that is the average temperature of the heat conducting medium and the working time of the system, reflects the actual design and operation of the systems. In their suggested equation, there is a simple question regarding the length of DHW and DHW circulation pipes. This study showed that EN standard equations give an overly pessimistic pipe length in basements and shafts and also that indoor temperatures in basements vary depending on the basement's thermal envelope properties.

Recommendation for DHW pipe losses calculations in the EPC:

- Calculations for pipe length located in basements should use building gross area for the calculation and for pipes located in shafts, the building heating area (Table 3.3).

- Calculations for unutilised annual heat losses from pipes located in basements should use equation 3 and for losses from pipes located in shafts, equation 4, using data from Table 3.4.

4.5 Future work

Most of the important factors as to why the performance gap exists between pre– and post–renovation energy usage and why calculation errors have been prevalent have been analysed in studies. Needs for improvements in EPC calculation methodology have been found as has a requirement for dynamic simulation tools to be used for calculations with multi–zone models.

These studies have not analysed in detail the effects of the quality of construction work or heating and ventilation system efficiency. In the nZEB renovated building it was found that window airing should be subjected to a more detailed analysis in the future. It is also important to examine how energy savings are related to life–cycle assessments and construction economics (where is the balance point?).

5 Conclusions

The energy saving target was achieved in only 40% of buildings with minor renovations (heat saving target: 30%), 40% in buildings with average renovations (heat saving target: 40%) and 50% in buildings with comprehensive energy renovation (heat saving target: 50%).

Several mistakes were done in analysing existing energy consumption by energy auditors. In the future it is important to improve controls to avoid such mistakes. For this, in addition to supplementary training of auditors, additional consultants should also be trained to detect possible mistakes in audits. This requires improving and updating the existing energy auditing form and methodology.

From knowledge collected from this research it is important to ensure that, in the future, the renovation grant scheme is no longer linked to the energy saving target but with the final energy use that is also linked to Estonian energy performance certificate calculations.

This study showed that where renovation financial support was related to the targeted energy performance level, the EPC was reported as being up to 30% higher. This was the most important factor as to why there was a performance gap between design and measured energy consumption. The re–simulated and design–related PE performance gap approximates at between 10% and 30% with one exception. The average difference between designed and re–simulated PE is at 29 kWh/(m^2·a), which is one EPC class, and there is no difference with the energy performance target.

Of fifteen buildings, only four reached the targeted EPC goal (27%), but with those cases, the fact was not connected to heat consumption. Three of them had lower DHW energy use than was calculated.

The most important factor when it came to working out why the calculated values were different between re–simulated values was caused by a lack of knowledge in terms of how to complete the basement ceiling's heat loss calculations in a one–zone building, as well as highlighting the fact that there must be better regulated competence rules regarding who can carry out these calculations. In addition, there is knowledge from previous studies that the BV^2 program provides lower–than–actual heat consumption for room heating between 15% – 30%. This study proposes to avoid using this simplified energy calculation model in future nZEBs, where heat gains play an important role in energy use for room heating.

The measured primary energy use of the nZEB renovated building was 147 kWh/(m^2·a). As the designed primary energy consumption was 95 kWh/(m^2·a) then the performance gap between measured and designed primary energy consumption was 34%. The results show that the nZEB target level (100 kWh/(m^2·a)) was not achieved in measured use of building. If the renovated building was used according to standard use conditions and design methodology, the nZEB target (PE $\leq$ 100 kWh/(m^2·a)) could be achieved. This shows that the building itself is built well and there wasn't a gap between design and re–simulated energy consumption, but at the same time, if the existing heating pipe losses, DHW losses and real user behaviour are added to the calculation, then it is not possible to reach nZEB energy performance. This study showed that dynamic energy simulation should be used for energy calculations for post– as well as pre–renovation apartment buildings.

Results of this study showed that occupant related energy use affects the achievements of energy performance goals significantly. In the investigated 35 renovated apartment buildings, room temperature increased after the renovation. Temperature after the renovation is, on average, 1.6 °C higher than before the renovation, which shows a rebound effect during the renovation. Even though the indoor temperature was higher compared to the standard use, occupants were satisfied with the temperature. In the nZEB renovated building the average temperature in 80 apartments was even higher, at 23.6 °C. To achieve a realistic estimation for energy use after the renovation, this study suggests increasing the room temperature in simulations to 22 °C.

This study shows the importance of analysing indoor temperature and airflows in more apartments during indoor climate and energy audits before renovation than is done currently (2–4 apartments).

Results of this study confirmed that the current standard electricity and DHW use in Estonian energy modelling regulations is more or less averagely correct and can also be used for renovated apartment buildings. It also showed that installing DHW circulation significantly influences the energy use for DHW ($p \le 0.001$). Due to these findings, it is recommended to separate DHW energy use for water heating and circulation energy use in the future. In the nZEB renovated building DHW and DHW circulation are measured separately and, in the other buildings where DHW circulation systems were not installed prior to renovation, the DHW usage was measured before renovation, and after renovation, when DHW circulation systems had been installed, the DHW energy use was measured.

DHW pipe heat losses in Low–energy or nZEB apartment buildings can be more than 10% of the entire primary energy consumption. At this point in time, DHW and DHW circulation energy consumption heat losses are based on the volume of water consumption. Most apartment buildings have unheated basements where the main pipelines for DHW and DHW circulation are located.

National methodology to calculate energy performance of buildings does not take this into account in most of the member states of the EU. This study proposes requirements for improvements of energy calculation methodology. If the suggestions proposed in the current study could be taken into account in future studies, the performance gap will be smaller.

This study shows that pipe length is the most important value to use when assessing pipe heat losses in apartment buildings. However, pipe length as per the EN standard equation is not relevant for Estonian apartment buildings, because the length and width of buildings in the Estonian Registry of Buildings database is presented as a maximum and is therefore not useful for non–rectangular shaped buildings. Also pipe length according to EN 15316–3 standard for pipe gives over–long pipe lengths compared to Estonian apartment buildings.

Pipe heat loss calculations in the reference building showed that the difference between thermal insulation levels on pipes does not affect how much heat losses from pipes can be utilised as internal heat gain. Heat loss from calculated lengths compared between different thicknesses of pipe thermal insulation are more or less the same in buildings with different EPC classes and the actual value itself is more or less the same. Which enables the equations proposed by this study to be used in all EPC classes of buildings.

This study gives an alternative method for calculating heat losses from DHW systems in apartment buildings.

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How well are energy performance objectives being achieved in renovated apartment buildings in Estonia?

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ABSTRACT

In Estonia, the majority of multi-storey apartment buildings were built during the period between 1960 and 1990. Systematic refurbishment of residential buildings on an energy-efficiency basis began in the 2000s, when the energy performance regulation came into force, although the main reason was to save on energy costs.

From 2010, the Estonian Ministry of Economic Affairs and Communication fund, KredEx, started supporting the renovation of apartment buildings. A grant scheme which was established in 2015 is related to targeted energy performance certificate classes.

In this study, we analyse how well the energy performance targets are being reached following major energy efficiency-related refurbishment work on buildings and how big the performance gap is between measured and calculated energy consumption levels, along with an analysis of the reasons for any differences. The analysis is based on collected energy consumption levels and indoor measurements. In order to analyse heating energy consumption levels, we have constructed simulations of indoor climate and energy use in fifteen renovated apartment buildings.

We found that in most cases, the calculated heating energy consumption levels in the design phase were much lower than the measured values have shown. In addition, we discovered that re-simulated values with the same thermal transmittance values are, in most cases, up to 50% larger than heating-related energy consumption levels in the design stage. From this knowledge, we can say that predictions for energy performance levels following refurbishment are too optimistic. For the future, we recommend calculating heating energy consumption levels with the use of a multi-zone simulation tool or by developing a better simplified calculation tool for renovated apartment buildings. In addition, we found out that the reason for heating energy consumption levels being higher following refurbishment work is due to higher indoor temperatures.

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1. Introduction

Currently, about 35% of buildings in Europe are over fifty years old, and are responsible for 40% of energy consumption [1] and 36% of CO_2 emissions in the EU. In Estonia, the proportion of buildings in the total energy consumption is significantly higher than the EU average – around 50%. A large number of buildings in Europe are old and in need of refurbishment, which would improve their functionality and energy performance levels. In Estonia, there are a total of approximately 27,000 apartment buildings, and approximately 80% of all these apartment buildings were built between 1945 and 1990, using the same mass production technology. The majority of these buildings have the same typical problems: high energy consumption levels, insufficient ventilation, unstable indoor temperatures, and insufficient thermal comfort levels [2–4]. Previous studies [5,6] have shown that average heating-related energy consumption levels for apartment buildings falls between 136 and 150 kWh/(m^2·a), while for heating domestic hot water, the figures are 27–39 kWh/(m^2·a), and for electricity 32–35 kWh/(m^2·a).

Semprini et al. [7] demonstrated that a deeper level of energy efficiency-related refurbishment of the existing building stock provides a rare major opportunity to decrease energy consumption levels whilst improving the quality of life for residents. Designing a solution for a deeper level of energy efficiency-related refurbishment is a multidisciplinary process, but in many cases, solutions would be economically viable, especially over a long term perspective [8–13]. Sandberg et al. [14] provided an estimate for future refurbishment activity in eleven European countries due to the need for the housing stock to receive additional maintenance as a result of ageing, and their results showed only minor future increases in refurbishment rates. In addition, Filippidou et al. [15] showed that

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the energy refurbishment pace is too low to fulfil the ambitious goals set. Kuusk and Kalamees [16] showed that the investment capability of apartment owner associations is not sufficiently high for them to be able to achieve the required energy efficiency improvement levels, and subsidies will increase investments into energy efficiency improvements by apartment owner associations.

Various financial instruments exist to support energy refurbishment. The vast majority take the form of grants, followed by 'soft' loan schemes and tax incentives [17,18]. In Estonia, energy-related refurbishment work on apartment buildings is supported by three refurbishment grant share levels, which are calculated to meet certain energy efficiency targets. During the period between 2010 and 2014, a total of 663 apartment buildings have undergone refurbishment work and average energy savings for each apartment building were 43% [19]. In 2015, a new grant scheme started supporting more intensive energy efficiency-related refurbishment work with a total of 102 million euros for existing apartment buildings in Estonia. The new grant scheme consists of three refurbishment grant share levels for construction work. These are divided by calculating the designed energy performance levels that will be achieved after refurbishment work has been completed.

It is important from the point of view of quality, finances, and energy usage that the actual energy consumption levels of buildings do not differ significantly from the predicted, calculated consumption levels. Nevertheless, there is often a significant difference between the predicted energy performance for buildings and the actual, measured energy use levels once buildings become operational [20–23]. Gram-Hanssen [24] showed that user behaviour is at least as important as building physics when it comes to energy consumption related to heating, though the user behaviour can only to a very limited degree be explained by objective characteristics of the inhabitants. van den Brom et al. [25] indicate that occupants with a high income save on average more energy than occupants with low income. Other studies have also shown that the energy saving gap can be caused by incorrect assumptions of building characteristics in older buildings [26–28]. Laurent et al. [29] also showed that energy saving policies are based on the use of theoretical normative calculations and there is a risk that evaluation of energy saving potential and the speed of its achievement could be overestimated and that this risk requires investigation.

Guerra Santin et al. [30] showed that building characteristics determine a large part of the energy use in a dwelling. Marshall et al. [31] showed that the calibration of building energy models using accurate measurements for the building's fabric properties reduces the observed performance gap. Hamburg and Kalamees [32] showed that in many cases, energy saving targets are not achieved mainly because energy auditors have not assessed existing structures and ventilation correctly or energy saving targets for post-refurbishment operations were too optimistic.

Another possibility when it comes to analysing the achievement of energy performance targets is to analyse the achievement of targeted energy performance levels which are usually set as delivered or primary energy needs. In this study, we investigate how well energy performance objectives are achieved in renovated apartment buildings in Estonia. The study questions are as follows:

- How much will the performance gap depend upon energy performance targets?
- What are the most important factors influencing energy performance achievements?
- What needs to change in terms of current energy performance design to reduce the performance gap?
- How much can a simulation tool using same design values influence heating energy use?
- How accurate are input parameters in the design of energy refurbishment work and how do they influence heating energy use?
- How much does the actual indoor temperature and ventilation air flow rate cause a performance gap in heating energy consumption levels?

2. Methods

2.1. An assessment of energy performance levels in buildings

The heating energy which is in use for room heating, ventilation, domestic hot water (DHW), and electricity for lighting, appliances, fans, and pumps was all taken into account when calculating delivered energy (DE). Primary energy use (PE) is calculated by multiplying delivered energy by weighting factors [33] according to the energy supplier (2.0 for electricity, 1.0 for fossil fuels, 0.9 for district heating, and 0.75 for fuels based on renewable energy sources). Residential buildings are divided into 'Energy Performance Certificate' (EPC) classes based on the design's primary energy use:

- EPC 'A' PE $\leq$ 100 kWh/(m^2·a), a nearly-Zero Energy Building (nZEB);
- EPC 'B' PE $\leq$ 120 kWh/(m^2·a), a low-energy building;
- EPC 'C' PE $\leq$ 150 kWh/(m^2·a), the minimum requirement for new buildings;
- EPC 'D' PE $\leq$ 180 kWh/(m^2·a), the minimum requirement for major refurbishment work;
- EPC 'E' PE $\leq$ 220 kWh/(m^2·a), minor refurbishment work

2.2. The requirements for energy refurbishment work

In 2015, a new grant scheme started, which was based mainly on the designed energy performance level. In addition, some specific rules for thermal transmittance were introduced, as described by Kuusk and Kalamees [16]. In the following Table 1, the minimum requirements are detailed for energy refurbishment work funded by grants:

2.3. The investigated buildings

The energy performance levels after refurbishment work had been carried out in fifteen apartment buildings was investigated in detail. The studied buildings were built between 1953 and 1986, with an average age of 46 years. Fig. 1 shows an example of a renovated apartment building which was built in 1972 (building code 2.5).

The net heated area for buildings varied between 1029 m^2 and 3904 m^2, and the number of apartments in buildings varied between 12 and 55. Three of them have been renovated using the 25% financial grant rules, while others used the 40% rules – see Table 2. All of the buildings have access to district heating.

2.4. Measurements and a calculation of indoor climate and the energy performance of buildings

We measured indoor temperatures after renovation in every apartment building in three apartments. Apartments have been selected in buildings randomly. Indoor measurements were taken from the beginning of December 2016 until the end of February 2017. Temperatures were measured at fifteen-minute intervals. The temperature was measured with portable data loggers (EVIKON E6226, measurement range −10 °C … +50 °C with an accuracy of ±0.6 °C). The data loggers were located on the separating walls mainly in master bedrooms.

Table 1
Refurbishment grant rules [34].

Grant rules	Grant support	
	25%	40%
EPC and primary energy needs	'C' ≤ 180 kWh/(m²·a)	'D' ≤ 150 kWh/(m²·a)*
Indoor climate category (ICC) [35]	II	II
Mechanical ventilation	Required	Required
Ventilation heat recovery	Not required	Required
Minimum ventilation air flow	0.35 l/(s· m²) (0.5 1/h)	0.35 l/(s· m²) (0.5 1/h)
U_{wall}	≤ 0.25 W/(m²·K)	≤ 0.22 W/(m²·K)
U_{roof}	≤ 0.15 W/(m²·K)	≤ 0.12 W/(m²·K)
$U_{windows}$ (for new windows)	≤ 1.1 W/(m²·K)	≤ 1.1 W/(m²·K)

* Some exceptions from the aforementioned targets were accepted, depending upon the location of the building and the particular nature of the specific building's service systems. For example, 40% financial support was accepted for EPC 'D' when buildings were not able to access DHW heating from the district heating system (they had electrical boilers for their supply of DHW).

Fig. 1. Building 2.5 before (left) and after (right) energy refurbishment work has been carried out.

Airflow was measured in apartments twice, generally at the beginning of December and again at the end of February. In all apartments we measured exhaust air outlet airflow. The criteria for the selection of apartments was that they should be located on different floors and that in the selected apartments there should be living more persons than there are bedrooms. Ventilation airflow was measured with a Testo 435 hot wire anemometer sensor (measurement range 0–20 m/s, with an accuracy ±0.03 + 5% m/s) together with a volume flow funnel Testovent 410 (Ø 340 mm).

Measured energy consumption data was collected by building managers (involving electricity, room heating, and ventilation air heating, and domestic hot water (DHW)). As with those apartment buildings that had access to district heating where there was only one heating meter (which measured the heating being used for room heating and DHW), we calculated the heating requirements for DHW based on water use (DHW forms 40% of the entirety of measured water use) and temperature rises (50 °C). Circulation heat loss was calculated by using the difference between theoretical and measured energy use for DHW during the summer months. Electricity use for central air handling units (AHU) or for exhaust fans (if specific fan power is for one fan at 0.75 or for a central air handling unit at 1.5) in standard use at 6 kWh/(m²·a) ± 3 kWh/(m²·a).

When it came to designing the refurbishment solution, in most cases designers used a program known as BV² [36] which is a one-zone energy efficiency calculation tool. BV² takes into account air leakage, thermal bridges, temperature variations, and solar radiation. Our earlier studies [37,38] have showed that BV² underestimates heating energy use by between 15 and 30%.

The indoor climate and energy performance of the buildings were re-simulated (so that we could see the difference between dynamic and semi-dynamic results) using the energy and indoor climate simulation program, IDA Indoor Climate and Energy (IDA-ICE). The accuracy of the IDA-ICE simulation tool has been examined in a good many validation studies in recent years [39–41] and has been used in many analyses of predicted and actual indoor climate and the energy performance of buildings [42–44].

We have used for indoor climate and energy models the same buildings energy audits which were done before refurbishment works. These energy audits were undertaken by consultants. The audits used energy consumption data from a three year period prior to the renovations for heat balance calculations, they also used the existing building thermal transmittance values. In buildings which used an exhaust ventilation heat pump (EXHP) after renovation we have been calculating the heat pump electricity required from the use of general electricity (the same is true for lighting for common areas), according to the earlier electricity requirements (2.10). In buildings 2.11 and 2.12, we also measured heat pump electricity and produced heating energy separately, so that we could analyse EXHP real efficiency levels and compare them to the design values. The Estonian Test Reference Year for the outdoor climate (annual heating degree days at t_i +17 °C: 4160 °C) [45] was used for simulation purposes and a reduction of measured heating energy under the same climate conditions.

Simulations of the standard use of the building were carried out using input parameters from the Estonian regulations for energy performance calculations [46].

- Indoor temperature heating set point: 21 °C
- Ventilation air flow: 0.42 l/(s·m²).
- The standard use for DHW is in apartment buildings: 520 l/(m²·a) (30 kWh/(m²·a)
- Air tightness levels for the building envelope: q_{50} = 3 m³/(h·m²).
- Internal heat gains were as follows:
  - Inhabitants: ~10.5 kWh/(m²·a). Heat generated by inhabitants was calculated using 2 W/m² and 85 W per person (1.2 met, 1.1 clo).

Table 2
The properties of the building that were studied after energy refurbishment work had been carried out.

Building code	Number of apartments	Heated net area, m^2	Ventilation	Calculation software	Additional insulation for walls	Additional insulation for roof	Windows
25% grant. Target: EPC 'D', PE ≤ 180 kWh/(m^2·a)							
1.1	25	1665	Exhaust fan/old shaft	BV²	+20 cm /U_{wall}0.16 W/(m²·K)	+30 cm / U_{roof}0.10 W/(m²·K)	$U_{windows}$ ≤ 1.1 W/(m²·K)
1.2	18	1673	Exhaust fan/old shaft	Riuska	+15 cm / U_{wall}0.18 W/(m²·K)	+45 cm / U_{roof}0.10 W/(m²·K)	$U_{windows}$ ≤ 1.6 W/(m²·K)
1.3	18	1592	Exhaust fan/old shaft	BV²	+15 cm / U_{wall}0.18 W/(m²·K)	+30 cm / U_{roof}0.12 W/(m²·K)	$U_{windows}$ ≤ 1.5 W/(m²·K)
40% grant. Target: EPC 'D', PE ≤ 180 kWh/(m^2·a) (DHW with electrical boilers							
2.1	12	1029	Central AHU/new ducts	BV²	+15–20 cm / U_{wall} 0.21 W/(m²·K)	+23 cm / U_{roof}0.13 W/(m²·K)	$U_{windows}$ ≤ 1.4 W/(m²·K)
2.2	18	1490	Central AHU/ new ducts	BV²	+15–20 cm / U_{wall} 0.20 W/(m²·K)	+30 cm / U_{roof}0.11 W/(m²·K)	$U_{windows}$ ≤ 1.3 W/(m²·K)
2.3	18	1508	Central AHU/ new ducts	BV²	+15 cm / U_{wall}0.24 W/(m²·K)	+21 cm / U_{roof}0.15 W/(m²·K)	$U_{windows}$ ≤ 1.1 W/(m²·K)
2.4	24	1370	Central AHU/ new ducts	BV²	+15 cm / U_{wall}0.20 W/(m²·K)	+30 cm / U_{roof}0.12 W/(m²·K)	$U_{windows}$ ≤ 1.3 W/(m²·K)
2.7	18	1180	Central AHU/ new ducts	BV²	+15 cm / U_{wall}0.21 W/(m²·K)	+40 cm / U_{roof}0.09 W/(m²·K)	$U_{windows}$ ≤ 1.1 W/(m²·K)
40% grant. Target: EPC 'C' PE ≤ 150 kWh/(m^2·a)							
2.5	18	1306	Central AHU/ new ducts	BV²	+15 cm / U_{wall}0.20 W/(m²·K)	+28 cm / U_{roof}0.11 W/(m²·K)	$U_{windows}$ ≤ 0.9 W/(m²·K)
2.6	18	1306	Central AHU/ new ducts	BV²	+15 cm / U_{wall}0.21 W/(m²·K)	+28 cm / U_{roof}0.12 W/(m²·K)	$U_{windows}$ ≤ 1.1 W/(m²·K)
2.8	18	886	Central AHU/ new ducts	BV²	+15 cm / U_{wall}0.21 W/(m²·K)	+35 cm / U_{roof}0.09 W/(m²·K)	$U_{windows}$ ≤ 1.1 W/(m²·K)
2.9	12	903	Central AHU/ new ducts	BV²	+15 cm / U_{wall}0.20 W/(m²·K)	+28 cm / U_{roof}0.12 W/(m²·K)	$U_{windows}$ ≤ 1.3 W/(m²·K)
40% grant. Target: EPC 'C' PE ≤ 150 kWh/(m^2·a) (with an exhaust air heating pump)							
2.10	55	3378	Exhaust fan/ old shaft	BV²	+20 cm / U_{wall}0.16 W/(m²·K)	+25 cm / U_{roof}0.13 W/(m²·K)	$U_{windows}$ ≤ 1.1 W/(m²·K)
2.11	32	1505	Exhaust fan/ old shaft	Unknown	+15 cm / U_{wall}0.21 W/(m²·K)	+30 cm / U_{roof} 0.12 W/(m²·K)	$U_{windows}$ ≤ 0.9 W/(m²·K)
2.12	50	3904	Exhaust fan/ old shaft	BV²	+20 cm / U_{wall}0.19 W/(m²·K)	+35 cm / U_{roof} 0.15 W/(m²·K)	$U_{windows}$ ≤ 1.1 W/(m²·K)

- Appliances, equipment: 12.6 kWh/(m^2·a). Heat generated by appliances and equipment was calculated using 2.4 W/m^2 and the use rate was 0.6. The use of electricity for appliances and equipment was 30% higher (some of that energy leaves the building via the sewerage).
- Lighting: 7 kWh/(m^2·a). Heat generated by lighting was calculated using 8 W/m^2 and the use rate was 0.1.

Having analysed the performance gap between design and measured energy consumption levels, we have carried out several comparisons (Table 3). In calculation steps from D to B we have used the standard use of buildings for simulations, and in calculations step C and M we have used measured indoor temperature and air flow.

To compare the gap between calculated and measured or designed and re-simulated energy consumption levels, we have used the following equation (example):

$$\text{Gap} = \frac{100 \times (\text{Measured (M)} - \text{Designed (D)})}{\text{Measured (M)}}\% \quad (1)$$

3. Results

3.1. Indoor climate after refurbishment work during the annual heating period

The average indoor temperature during the annual heating season was at +22.7 °C (the apartment's average varied between +21.1 °C and +23.8 °C) and therefore higher than the standard value [46] for energy simulations (+21 °C, Fig 2, left). The average ventilation airflow in apartments was at 0.57 h^{-1}, 0.40 l/(s·m^2) (the apartment's average varied between 0.18 h^{-1}, 0.13 l/(s·m^2) and 0.95 h^{-1}, 0.67 l/(s·m^2)) and therefore similar to the standard value [46] for energy simulations (0.5 h^{-1}, 0.35 l/(s·m^2), Fig 2, right).

3.2. Energy use after refurbishment work

The average use of electricity at 32 kWh/(m^2·a) (this varied between 22 and 43 kWh/(m^2·a) in different apartments) was close to the standard value [46] for energy simulations at 36 kWh/(m^2·a) (±3 kWh/(m^2·a) and depended upon the type of ventilation being used (see Fig 3, left). The average use of energy for DHW heating was 32 kWh/(m^2·a) (this varied between 14 and 61 kWh/(m^2·a) in different apartments) was also close to the standard value [46] for energy simulations (30 kWh/(m^2·a)) but depended significantly upon the circulation or otherwise of DHW (Fig 3, right).

The target EPC class after refurbishment work had been achieved only in 26% of buildings (four of fifteen). None of the buildings that had higher energy performance targets (EPS 'C') reached their targets. The largest energy performance gap between designed energy use – which was calculated before refurbishment work – and actual energy use – which was measured after refurbishment work – was in the energy use for room heating and ventilation (Fig 4). While the average calculated PE use for heating in the design phase was at 51 kWh/(m^2·a), the measured heat use after refurbishment work was at 83 kWh/(m^2·a). This is approximately 40% higher.

The average use of room heating in EXHP buildings (which also includes heating for ventilation air) was at 91 kWh/(m^2·a) (this varied in different apartments between 48 and 140 kWh/(m^2·a)). The decrease for room heating in EXHP buildings after refurbishment work had been completed was, on average, 48% (this varied between 0% and 73%).

Under standard use, the delivered energy use in buildings for room and ventilation heat (buildings which have access to district heating) should be less than 56 kWh/(m^2·a) (a PE value that is less

Table 3
Analysed energy consumption levels and their descriptions.

Calculation step code	Description	Input data parameters for indoor climate, ventilation, DHW, infiltration, internal heat gains
0	Measured energy consumption levels before refurbishment	As measured before renovation
D	Energy consumption levels as designed (using software Table 2)	Standard use of buildings
A	Re-simulated energy consumption levels (using IDA ICE 4.8 dynamic software) (building envelopes have been taken from preliminary design)	Standard use of buildings
B	Re-simulated energy consumption levels with corrected building envelope properties (building envelopes have been taken from detailed design)	Standard use of buildings
C	Re-simulated energy consumption levels with corrected building envelopes, internal heat gains, and measured indoor temperature and ventilation rates	As measured after renovation
I	Ideally corrected re-simulated energy consumption with changed indoor temperature and ventilation rates (same envelopes and internal heat gains as model C)	Indoor temperature and air flow have been changed to get best correlation with measured heating energy need
M	Measured energy consumption levels after refurbishment work	As measured after renovation

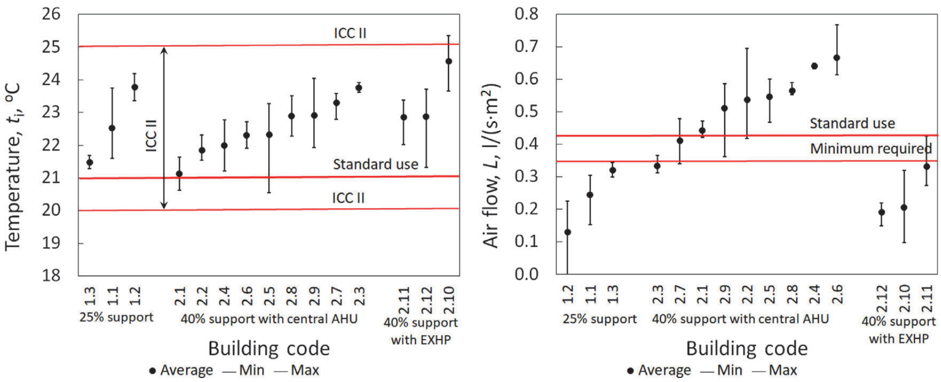

Fig. 2. Average indoor temperature (left) and ventilation airflow (right) after refurbishment work during the annual heating period in the buildings being studied.

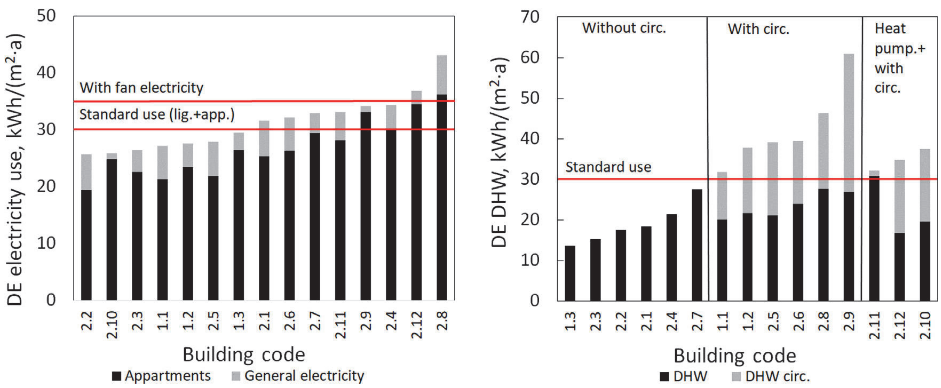

Fig. 3. Delivered electricity for lighting, appliances, ventilators, and pumps (left) and DHW heat (right).

than 51 kWh/(m^2·a)) on average to reach EPC 'C' targets. Nevertheless, the measured delivered heating energy was higher in almost all cases, averaging 91 kWh/(m^2·a). This is more than 35% greater (see Fig 5, right).

We can see a big gap between the calculations for delivered heating energy in the design phase and the measured heating energy consumption (see Fig 5, right). The following deeper analysis shows that there were various methodological errors present on the existing energy labels. All energy efficiency calculations have been made after the preliminary design phase and these also have lots of simplification for heating energy calculations.

The first check on the energy efficiency calculations showed that the calculation of heating flow through the basement ceiling may be wrong. A recalculated thermal transmittance level for the basement ceiling showed that in fourteen out of fifteen buildings, it had been incorrectly calculated. The main mistake was that air change in the basement was not taken into account, as is required in European standard EN 13370 [47]. Minor mistakes also existed

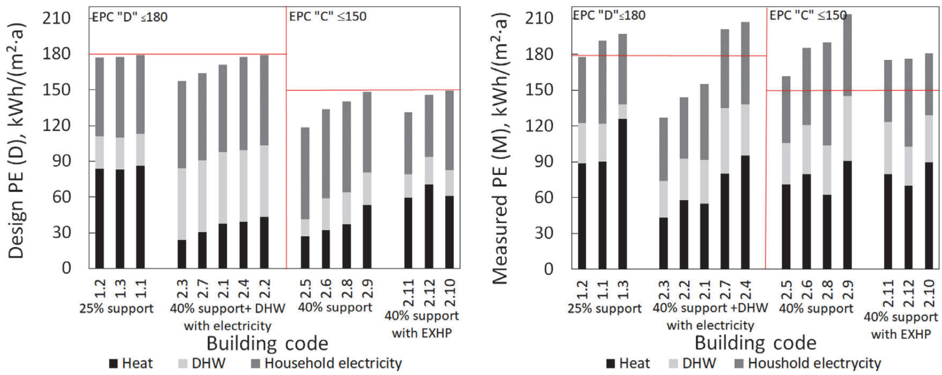

Fig. 4. Designed PE under standard building use prior to refurbishment work (left) and for measured PE values after the refurbishment work has been completed (right).

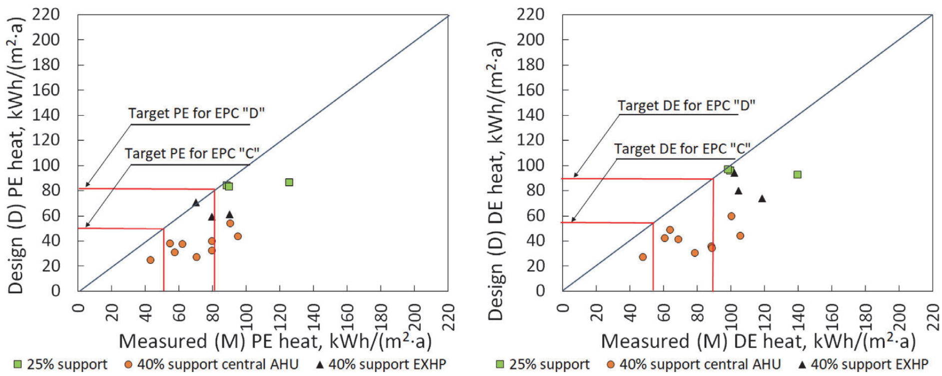

Fig. 5. Designed PE heating energy compared to measured PE heating energy (left), with designed delivered heating compared to measured delivered heating energy and designed and measured heating energy use (space heat + ventilation heat).

Table 4
Energy consumption levels in the buildings being studied in different calculation phases.

		Calculation step codeAverage (min-max)					
	Energy use/code	0	D	A	B	C	M
EPC 'C'	Heat(space + vent)	183(145–219)	59(30–94)	87(60–119)	92(58–135)	92(68–107)	95(69–119)
	DHW	42(28–72)	30(30–30)	30(30–30)	30(30–30)	41(32–61)	41(32–61)
	Household electricity+ fans	34(25–46)	36(33–39)	36(33–39)	36(33–39)	32(26–43)	32(26–43)
	PE	271(222–326)	138(119–149)	159(146–167)	164(149–174)	181(160–216)	184(162–214)
EPC 'D'	Heat(space + vent)	157(130–195)	60(27–97)	90(49–156)	93(47–143)	86(49–129)	88(48–140)
	DHW	20(16–26)	30(30–30)	30(30–30)	30(30–30)	23(14–38)	23(14–38)
	Household electricity + fans	27(22–32)	36(33–39)	36(33–39)	36(33–39)	29(26–34)	29(26–34)
	PE	237(215–296)	173(158–179)	201(177–234)	203(175–223)	173(127–207)	175(127–207)

in the calculations for other thermal transmitters. Also there were mistakes with envelope areas and mistakes which over simplified the one-zone BV^2 model.

Table 4 shows energy calculation results in different phases before any refurbishment work has been carried out. In models D to B, we have used standard usages and, in models 0, C, and M, measured consumption levels.

Firstly we start to build up an energy efficiency multi-zone model in IDA ICE (calculation step A) with same input data as in existing calculations (phase D) but with unheated basement air flow as in ISO 13370 [47] and existing basement ceiling as in original design documents.

Comparing these calculated heating energy needs with measured heating we can see a gap between −58% to 45%-see Fig 6. Re-simulated values are very different for the designed heating energy consumption but these are still far from measured heating energy consumption.

In the second phase (calculation step B) we were looking at the influence of detail design. In this phase we were taking into account all changes in the design phase and included all re-calculated thermal transmittances and thermal bridges transmittances in the calculations. In most buildings the changes are small but in several buildings there are big differences between windows and thermal bridges thermal transmittances. After simulation we can see differences between measured and detail design heating energy from −37% until 20%.

In the third step (calculation step C) we made calculations with detail design thermal transmittances and with measured temper-

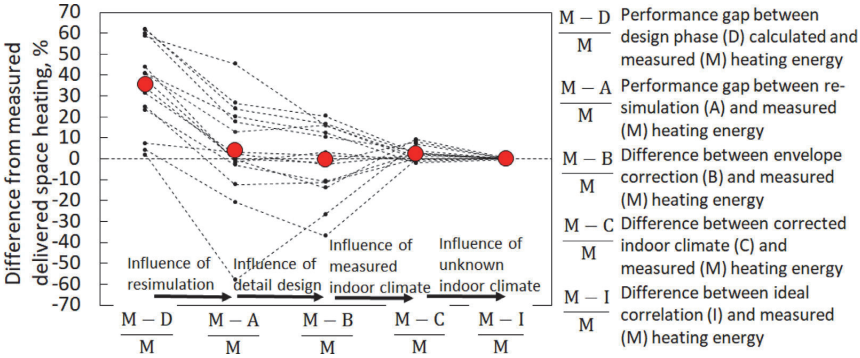

Fig. 6. Heating energy differences from the measured (M) values when compared to the design (D), re-simulation (A), corrected envelopes (B), and measured temperatures and air flows (C).

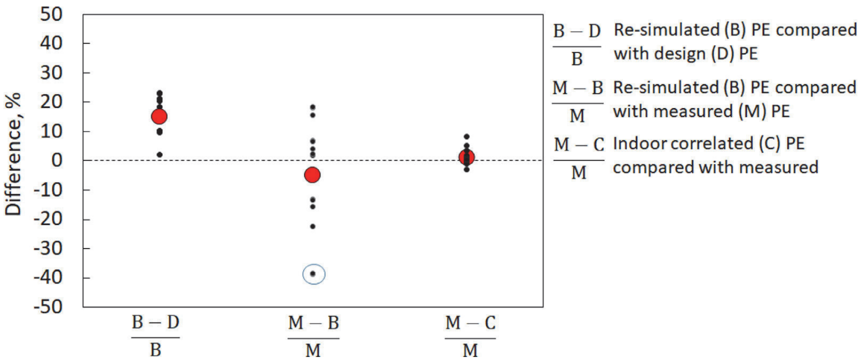

Fig. 7. The difference between re-simulated (B) and designed (D) PE, between measured (M) and re-simulated (B) PE, and between measured (M) and indoor climate corrected heat (C)PE (and also between measured DHW and electricity).

atures and air flows. After calculations we can see differences between measured and calculated heating energy is averaged in all buildings at 2.4% (between −2% and 9.3%). Our assumption was that in the third step we would have more or less the same results as measured, but in 2 buildings there was a difference of more than 5%. In all buildings we have measured air temperature and airflow in three apartments and it is possible that more measuring points are needed.

When we calculated heating energy consumption in building 1.2 using air temperatures as measured and changing airflow from 0.13 to 0.17 $l/(s\cdot m^2)$ our results gave us the same heating energy consumption as actually measured, while in building 2.11 we had to change airflow from 0.34 to 0.4 $l/(s\cdot m^2)$ to get the same result. In these buildings we can see how much effect changing air flow has on heating energy needed. However, the heating energy difference between the measured and corrected indoor climate models (C) can be caused by different indoor air temperatures.

When taking into account these adjustments, we were also able to calculate new PE values. The recalculated primary energy level is more than 10% larger than the design values (with one exception) (see Fig 7(A)). The performance gap between recalculated PE and measured energy averages at 5% (see Fig 7(B)). There are two buildings (Fig 7 in circle) where the difference between measured and re-simulated values is more than 20% and in these buildings measured DHW energy was more than 10 $kWh/(m^2\cdot a)$ lower than in standard use (building code 2.2 and 2.3 – see Fig 3 right). Measured PE is mainly bigger in buildings in which DHW energy use is greater than calculated. In buildings in which measured DHW consumption is lower than calculated, the measured PE levels are also lower. When using these in calculations which measured electricity, DHW, indoor temperatures, and ventilation airflow (Fig 7(C)), the measured and calculated PE energy difference can be up to10%.

In Fig 8 (left), we can see a comparison between measured PE and calculated PE with the measured indoor temperature, ventilation airflow, DHW, and household electricity levels. If we calculate primary energy using the calibrated simulation model, we can see that the average difference between designed and recalculated PE averages 29 $kWh/(m^2\cdot a)$ – see Fig 8 (right).

4. Discussion

Even when energy-related refurbishment work decreased the energy use in buildings, the designed energy performance targets were not achieved in most of the renovated buildings that were part of the study (74%). The rebound effect (shown in many earlier studies [21,48,49]) still exists. This result is somewhat worrying from an investor and energy policy point of view. Many studies have shown a large discrepancy between the predicted and actual measured energy use in buildings. As this result was observed several decades ago [50–52], more thorough controls are required in energy refurbishment work on buildings with such controls governing research, surveying, energy auditing, designing, construction, and quality.

The energy use for room heating and ventilation showed the largest energy performance gap. The average primary energy consumption for heating (between measured and designed) was 38%

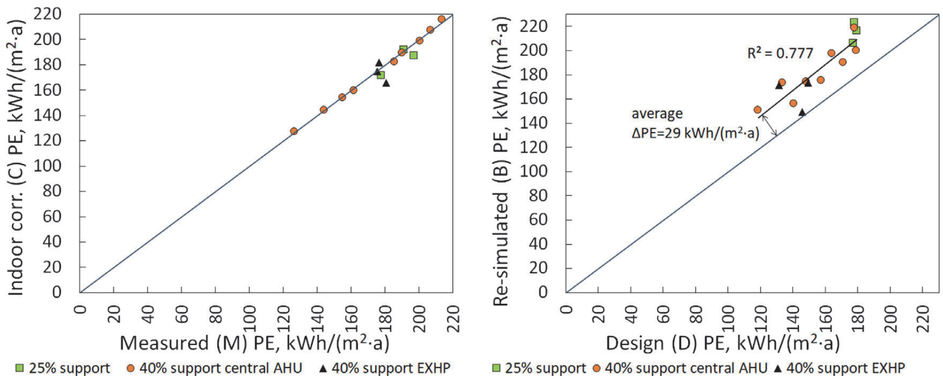

Fig. 8. Indoor climate corrected primary energy needs when compared to measured primary energy needs (left), plus recalculated EPC when compared to designed EPC (right).

larger than for measured heating-delivered energy (between 10% and 67%). The delivered energy for room heating after refurbishment works (M) was on average more than 35% bigger then calculated values in the design phase (D). Delivered energy for room heating energy depends directly on the heat loss levels of the building envelope [53] and also on system efficiency. Heat loss for the building envelope depends upon thermal transmittance, thermal bridges and air leakages. From the figures for total heat loss, the share of thermal bridges could be about 10–40% [2,54] and air leakages about 7–30% [55,56]. The quality of the building envelope in terms of thermal bridge air leakages is relatively easy to measure. The largest single heat loss component, thermal transmittance, is usually not measured. A literature review by Roels et al. [57] showed that none of the studied building envelopes realised the intended performance levels and, in some cases, actual performance rises to about twice that value. This performance gap could be caused by workmanship quality levels [58,59] or poor modelling predictions [31]. Using safety factors or, better, taking account of the non-ideal nature of such things, together with quality checking and providing instructions for the workmanship involved in refurbishment, are needed in order to minimise the performance gap in the thermal envelope. We saw large variations between buildings in terms of their room heating energy use. In Fig 2, we saw that user-related parameters (such as indoor temperature and ventilation airflow) were not equal to the standard use for the building. The measured average indoor temperature of +22.7 °C corresponded to the targets in the ICC II [35], but it was higher than the heating set-point temperature used in simulations: +21 °C in standard building use [46]. Ilomets et al. [60] and Bagge et al. [61] showed in their cross-sectional indoor climate study on dwellings, that indoor temperature is more likely to be +22 °C than anything that is lower. In addition to thermal comfort, the balance for heat loss and heat gains also influences indoor temperature in energy-efficient buildings. In order to avoid a performance gap due to input parameters, +22 °C could be a more relevant setpoint for a heating system. Földváry et al. [62] also showed that indoor temperature changes after refurbishment work has been carried out.

In our study (Fig 6) we analysed heating energy consumption more deeply with the program IDA ICE and our calculation steps showed that the influence of using a multi-zone simulation tool compared with a simplified tool changed the results for heating energy a lot. Different models and model simplification influence simulation results; even when input parameters are similar [63,64]. In our study results, which were calculated using a detailed dynamic simulation model, more similar results were achieved with measured data than they were with the simplified model. The main reason was an overestimation of solar heat gains in the simplified model. This decreased heating energy use to a level which was lower than that which the measurements showed. The main shortcoming in the calculations was a lack of knowledge when it came to calculating the unheated basement's ceiling thermal transmittance in a one-zone calculation tool where it is important to involve the basement envelopes and air flow in the overall calculations. In all of the calculations, this figure has been incorrectly calculated. Hoffmann and Geissler [65] showed that in the energy calculations, the basement ceiling's thermal transmittance levels have been taken into account at a greater rate than they were in reality, but in our case, it was vice versa.

Calculation step B (Fig 6) showed that after correcting other envelop transmittances, we can see smaller differences with measured heating energy consumption. After that we re-calculated heating energy with measured indoor temperatures and air flows and used average values for all apartments in same buildings. A gap between measured and calculated values also exists after using measured indoor temperature and airflow, which shows that in further studies there is a requirement to measure indoor air temperature and air flow in more apartments per building. Our calculations also showed that a change in air flow of 0.05 $l/(s \cdot m^2)$ can effect heating energy consumption in well renovated buildings by about 8%.

The one reason why measured (M) and re-calculated (B) PE need was more than 20% different was the difference between measured and standard use DHW. Also there are differences between measured and standard use electricity consumptions.

5. Conclusions

The mistakes made in the original designed calculations for heating energy resulted in an average performance gap in the calculated PE of 29 $kWh/(m^2 \cdot a)$. This absolute difference, 3–45 $kWh/(m^2 \cdot a)$, and relative difference, 2–30%, resulted in an increase of one EPC class in all of the studied buildings. This increase in EPC class was independent of the original PE level.

Because of the lower use of DHW and energy for its heating, four buildings of the fifteen reached their designed EPC class, even though mistakes were made in their heating energy calculations.

The main reasons for mistakes made in the original design were a lack of knowledge around calculations of heat loss through the basement ceiling in a one-zone model, linear thermal transmittance and thermal transmittance of existing windows. The fact that less mistakes were present in the design calculated by a designer who had occupational qualifications in the energy performance of buildings shows the importance of qualification and continuing education. The current study repeated the knowledge from previous studies that the BV^2 program provides lower-than-actual heating energy consumption levels of between 15 and 30%. We propose to avoid using this simplified model in future nZEBs, where heat gains play an important role in energy use for room heating.

We discovered that people prefer the higher temperatures that we used in our calculations. Measurements indicated an indoor temperature during the heating season of 22 °C rather than the 21 °C that is used as a standard value in current regulations. This knowledge of real usage is good to take into account in future regulations and simulations.

Our study showed that indoor temperature and ventilation airflow measurements from three apartments in one building (which is common practice in Estonia) does not provide enough data points to establish a comprehensive overview of the indoor climate.

Conflict of Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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Realisation of energy performance targets of an old apartment building renovated to nZEB

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Energy performance of buildings directive sets a goal to achieve a highly energy efficient and decarbonised building stock by 2050. In this study, a pilot nZEB (nearly zero energy building) renovation of an existing apartment building is analysed. nZEB criteria of new apartment buildings was set as the energy performance target in designing renovation solutions. The whole building envelope was additionally insulated with prefabricated modular panels and new service systems were installed. Measured energy consumption after the renovation showed that the pilot building fulfilled the minimum energy performance requirements for new apartment buildings, but nZEB target was not achieved. Measured heating energy consumption is 1.6 times higher (mainly because of the higher indoor temperature, supply air temperature, window airing, and higher ventilation airflow rates which methodology for heating energy calculations are not taken into account) and measured energy need for DHW is 4.4 times higher (mainly because of the real use profiles as well unexpected performance of solar collector and sewerage heat recovery system) than expected in building design. Results show that in renovation projects (also in new projects), occupant behaviour and the real use of building should be used as more realistic input parameters for designing energy performance. Distribution and circulation losses of air handling units, heating coils and DHW (domestic hot water) systems should be taken into account in the national energy calculation methodologies as service system heat losses can be a significant part of energy consumption at nZEB levels. If the renovated building would be used according to design methodology, the nZEB target can be achieved.

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1. Introduction

The new recast of the energy performance of buildings directive [1] requires adoption of a long-term renovation strategy to support the renovation of the national stock into a highly energy efficient and decarbonised building stock by 2050. An average annual renovation rate of 3% would be needed to accomplish the energy efficiency ambitions. Today, the renovation rate is around 1% [2]. Less than 3% of the building stock in the European Union has an Energy Performance Certificate (EPC) label A [3]. A certain percentage of the building stock will be demolished but approximately 90% of the building stock must be upgraded in order to achieve the goal of transforming the existing buildings into nearly-zero energy buildings. About 70% of the building stock of 2050 already exists today. This means that most of the energy reductions will have to be achieved by deep retrofitting of existing buildings [4]. D'Agostino et al. [5] provide an overview of the status of implementation of nZEBs in Europe and concluded that only a few Member States have planned new measures for energy efficiency in buildings, while the vast majority refers to already existing policies. Member States should provide more information and measures specifically targeted to nZEBs renovation. A study conducted in Spain [6] detected the insufficiency of current economic incentives for energy renovations. Support programs are essential for the economic feasibility of deep renovations [7].

Previous studies have shown that energy renovation is a cost-efficient way to improve indoor climates and achieve energy savings up to 80% [8,9]. For residential buildings, the most cost-effective renovation measure is additional insulation on the external walls [10,11]. In addition to the insulation of the building envelope, renovation must include the renewing of building heating and ventilation systems. Renovation of existing apartment buildings can negatively affect the indoor environment of the

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apartments if renovation does not include measures to improve indoor environmental quality [12].

Differences between the predicted and real energy performance can be significant [13]. The same study advised implementing an effective metering and monitoring strategy to improve the real energy performance and allow a comprehensive understanding of the breakdown of energy use in buildings and take necessary actions. Research by Zou et al. [14] identified 8 critical factors that cause an energy performance gap: inaccurate design parameters, failure to account for uncertainties, lack of accountability, poor communication, lack of knowledge and experience, inefficient and over-complicated design, lack of post-testing, and lack of feedback. Liang et al. [15] found that user-profile related energy use (building occupants use more energy, more occupants are in the building) and failures with energy-efficient technologies are important factors for the energy performance gap.

Energy performance modelling is often done with standard user profiles. A study conducted in Estonia [16] showed that the behaviour of occupants does not significantly change after the renovation. Using the standard use model for energy calculations is unavoidable for calculation-based EPCs but for calculations of cost-efficient energy renovation measures it was recommended to consider building-specific user-profiles [16]. Desideri et al. [17] showed that by combining monitoring data with predictive energy modelling, it was possible to increase the accuracy of the calculation model to within 3% of actual consumption values. The study highlighted the need for a better understanding of occupancy behaviour patterns and the use of more realistic input parameters in energy models needed, to bring the predicted figures closer to reality.

An apartment building, with a goal to meet the nZEB target for new buildings after the renovation, was used as the subject of this study. The research questions of the study are the following:

- How different renovation measures (insulating building envelope, renewing of service systems, on-site renewable energy production) contribute to the achievement of the nZEB energy efficiency level?
- How occupant related energy use affects the achievements of energy performance goals?
- How calculating methodology affects the gap between calculated and measured energy consumption after the renovation?

2. Methods

2.1. Pilot building

A five storey concrete large panel apartment building with 80 apartments was selected to realise the nZEB renovation pilot [18]. The building was constructed in 1986 and renovated in 2017. This building type was dominant during the construction industrialisation period between 1970 and 1990. Approximately two million square meters of apartments buildings were constructed with prefabricated concrete large panels during that period in Estonia. As prefabricated concrete large panel apartment buildings were also widely used in other countries, results of this pilot are useable in other countries. Fig. 1 shows the building before and after the renovation.

The thermal transmittances of the building envelope before renovation was: external walls: U_{wall} ~1.1 W/(m^2·K) (70 mm wood-chip + 50 mm phenolic foam for insulation); roof: U_{roof} ~1.0 W/(m^2·K) (100 mm wood-chip insulation); windows: U_{window} ~1.6 W/(m^2·K))(some windows were old wooden windows with double panes, some windows were changed to new PVC frame windows) [19]. The concrete large panel apartment building type has serious thermal bridges [20]. One indicator of lower temperatures in the connections of building envelope elements was mould growth on the interior surfaces, especially in the corners of the exterior walls and roof.

The building had a natural passive stack ventilation system with ventilation shafts and one-pipe radiator heating system without thermostats. Room temperature for the whole building was regulated by a heat substation depending on the outdoor temperature. Measured room temperature varied before renovation between 20.1 and 24.4 °C [21].

Total primary energy (PE) use before renovation was 302 kWh/(m^2·a).

2.2. Renovation solution

nZEB criteria for new buildings (EPC class A, PE ≤ 100 kWh/(m^2·a)) was set as the energy performance target in designing the renovation solution. The whole building envelope was additionally insulated [22] and new heating and ventilation systems were installed. To minimise the influence of thermal bridges and to get an additional living area, the existing balconies were changed to indoor spaces. A small attic was constructed to insulate the roof with prefabricated elements and to get space for ventilation pipes. Table 1 presents design solutions to achieve nZEB. EPC for design solution (Table 2) was class A (PE = 97 kWh/(m^2·a)).

2.3. Evaluating energy consumption

The energy performance was evaluated by measurements and calculations. The energy consumption (electricity consumption of apartments, electricity consumption of ventilation units, space heating, ventilation air heating, DHW heating, cold and hot water consumption) and indoor temperature and ventilation airflow were measured by a building control and automation system.

Energy performance of the buildings was calculated using the IDA Indoor Climate and Energy 4.8 (IDA-ICE) energy and indoor climate simulation program. IDA-ICE has been validated tested against measurements by Moinard and Guyone in 1999 [23], several independent inter-model comparisons have been made by Achermann and Zweifel in 2003 [24] In the comparisons, the performance of radiant heating and cooling systems using five simulation programs (CLIM2000, DOE, ESP-r, IDA-ICE and TRNSYS) were compared and IDA ICE showed a good agreement with the other programs. IDA-ICE has been successfully used in many studies of indoor climate and energy performance of buildings in cold climate [25–28]. Fig. 2 shows the 3D building model and floor plan in simulation software.

Energy performance simulation in standard use condition was done using input parameters from the Estonian regulations for energy performance calculations [29].

- Indoor temperature set point for heating: 21 °C;
- Air flow rate for apartments with apartment-based air handling units (AHU) 0.42 l/(s·m^2) and apartments with central AHU 0.5 l/(s·m^2). Supply air temperature 18 °C;
- Standard use of DHW: 516 l/(m^2·a) (ΔT 50 K → 30 kWh/(m^2·a));
- Standard use of electricity for appliances, lighting: 29.5 kWh/(m^2·a) and circulation pumps: 0.5 kWh/(m^2·a);
- Internal heat gains: occupants 15.8 kWh/(m^2·a) with usage rate 0.6, appliances and equipment: 15.8 kWh/(m^2·a) with usage rate 0.6, lighting 7.0 kWh/(m^2·a) with usage rate 0.1. Detailed internal heat gain time schedule for dynamic simulation are in Fig. 3 [29,30].

Fig. 1. View of the pilot building before (2015) (left) and after (right) the renovation (2018).

Table 1
Design solutions for nZEB renovation.

	Design solution
Building envelope	Additional insulation with prefabricated modular elements with designed thermal transmittance values: $U_{external\ wall} = 0.11$ W/(m^2·K), $U_{roof} = 0.10$ W/(m^2·K), $U_{basement\ wall} = 0.10$ W/(m^2·K), $U_{basement\ floor} = 0.26$ W/(m^2·K)), $q_{50} = 2$ m^3/(h·m^2)
Windows	New triple glazed windows ($U_{windows} = 0.80–0.84$ W/(m^2·K)) were installed into prefabricated insulation elements in the factory.
Ventilation	Mechanical supply and exhaust ventilation system with heat recovery was installed. Half of the building (40 apartments) have a central ventilation unit (η-83%, $SFP = 1.8$ kW/(m^3·s)) in the attic and ventilation ducts are embedded into the wall insulation elements. Half of the building (40 apartments) have apartment-based ventilation units (η-89%, $SFP = 0.88$ kW/(m^3·s)). Basement, and staircases have separate ventilation units (η-80%, $SFP = 1.8$ kW/(m^3·s)).
Heating	A new two-pipe heating system with hydronic radiators and room thermostats. District heating remained as heat source.
Domestic hot water	District heating remained as heat source for heating the domestic hot water. Half of the building has an additional heat source from solar collectors (50 collectors with total effective area of 100 m^2, 4 × 1.5 t storage tanks). Half of the building has an additional heat source to pre-heat the incoming cold water before the heating sub-station from a passive wastewater (grey water from showers and sinks) heat recovery system.
Renewable electricity	PV-panels (55 panels, total peak power of 14 kW)

Table 2
Energy need and on-site energy production of design solution (kWh/(m^2·a)).

	Heat	Electricity
Energy need	**51**	**36**
Space heating	18	
Heating of ventilation air	3	2
Domestic hot water	30	4
Appliances and lighting		26
Fans and pumps		4
Onsite energy production	**22**	**2**
Solar collectors	7	
Wastewater heat recovery	15	
PV panels		2
Delivered energy	**30**	**35**
Primary energy[a]	**95**	

[a] Weighing factor for electricity = 2.0 and for district heating = 0.9.

Primary energy use is calculated by multiplying delivered energy by weighting factors according to the energy carrier: 2.0 for electricity and 0.9 for district heating.

Calculations for energy need were performed for different efficiency levels and with different input data parameters (Table 3).

To compare the performance gap between calculated and measured energy consumption levels, we have used the following equation (example) (Equation (1)):

$$\text{Gap} = \frac{100 \times ((M\,(measured) - D\,(designed))}{M\,(measured)}\% \quad (1)$$

3. Results

3.1. Measurements

3.1.1. Energy use

Measured annual delivered energy (DE) use after this was 124 kWh/(m^2·a) (Fig. 4 left) and primary energy (PE) 147 kWh/(m^2·a) (Fig. 4 right), fulfilling minimum requirements for energy performance of new buildings (EPC class “C”). The performance gap between measured and design primary energy is 35%.

The aim of the renovation was to achieve the energy efficiency

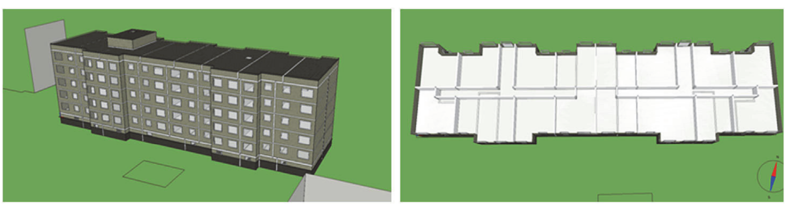

Fig. 2. View of building model (left) and floor-plan layout with zones (right) in simulation software.

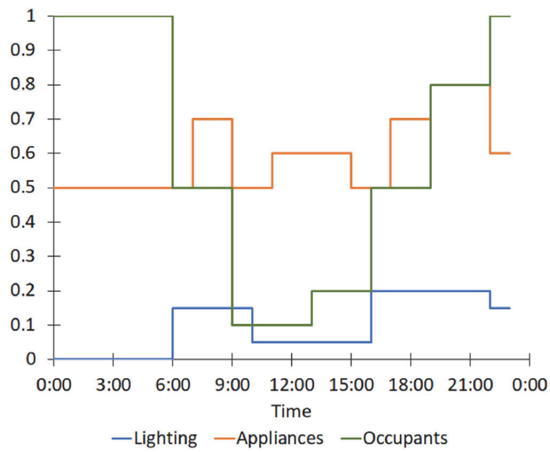

Fig. 3. Internal heat gain time schedules.

requirement for nZEB (EPC class A). The most important parameter causing the difference was energy use for DHW between the designed figure and the figure measured after renovation. Although energy use for DHW decreased 19% (from 59 kWh/(m^2·a) to 48 kWh/(m^2·a)) it stayed higher than predicted by the design solution (19 kWh/(m^2·a) (8 kWh/(m^2·a) from district heat), standard use of building with designed efficiency of service systems). This showed that the prediction was a little bit too optimistic, or there is some calculation error, or the DHW system does not perform as it is designed.

The heat use for space heating and heating of ventilation air after renovation decreased 76% (from 168 kWh/(m^2·a) to 41 kWh/(m^2·a)) but remained 1.8 times higher than predicted by the design EPC solution (23 kWh/(m^2·a) (space heating 18 kWh/(m^2·a) + heating of ventilation air 5 kWh/(m^2·a)) (Fig. 4 left).

Also, the electricity use (appliances, lighting, ventilators and pumps) after renovation decreased 27% (from 49 kWh/(m^2·a) to 36 kWh/(m^2·a)) but it stayed 20% higher (29 kWh/(m^2·a) than predicted by design (standard use).

3.1.2. *Indoor temperature and air flow rate in apartments*

Measured average indoor temperature in apartments during winter months (from December to March) was 23.6 °C (Fig. 5). Ventilation airflow flow rate with central AHU was similar to standard use profile (0.47 l/(s·m^2)) but in apartments with apartment based AHU-s, the average airflow rate was 0.69 l/(s·m^2) which is a 60% higher airflow rate than the value used in the standard use profile (0.42 l/(s·m^2)). Ventilation supply air temperature on average was 21 °C, which is 3 °C higher than the supply air temperature in standard use.

Higher supply airflow rate, supply air temperature, and indoor temperature increased the heating energy need.

Table 3
Analysed energy consumption levels.

Calculation step code	Description	Input data parameters for calculations
0	**Measured** energy consumption levels **before renovation**	
D	Energy consumption levels as **designed**	Standard use of buildings
M	**Measured** energy consumption **after renovation**.	
C	Model **calibration**: simulation model with measured indoor air parameters, measured internal heat gains and measured thermal transmissions. window airing.	Form every apartment separately measured indoor temperature, ventilation air flow, electricity use of lighting and appliances, real number of occupants. Measured supply air temperature from every ventilation unit (half of apartments with apartment based unit used average supply air temperature from 4 units) and building heat loss.
W	The influence of **window airing**: building as build and used but with window airing (that is not considered in design methodology).	Same as "C" but with window airing. One window in every apartment is 10% open in total for half an hour a day
DHW 1.2	The influence of 1.2 higher population difference DHW use	1.2 times the standard usage
DHW1.5	The influence of 1.5 higher DHW use	1.5 times the standard usage
S	Energy consumption with **standard use** parameters [29]	Standard use parameters and measured envelope transmittances from earlier studies in this building

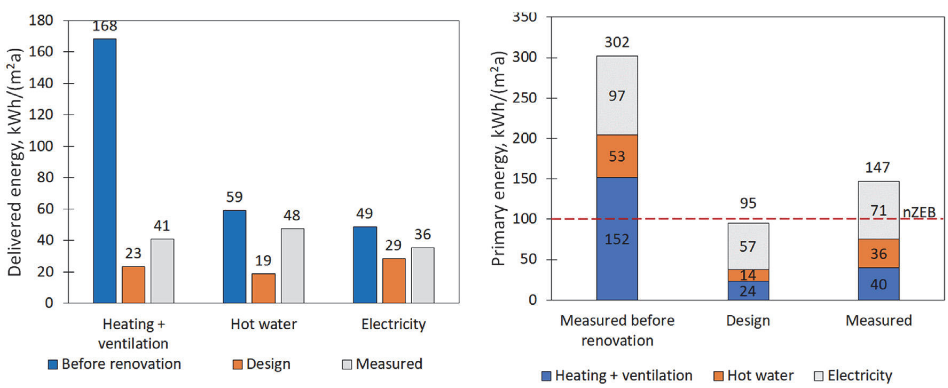

Fig. 4. Building delivered energy need (left) and primary energy need (right) measured before the renovation, calculated by design, and measured after the renovation.

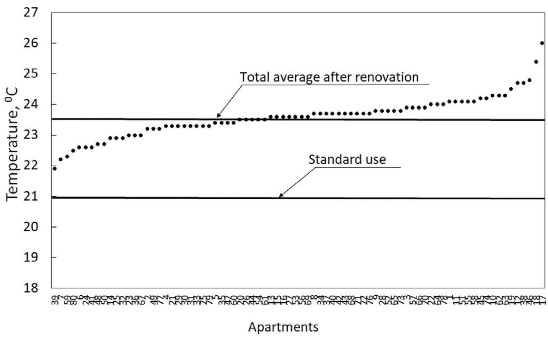

Fig. 5. Average indoor temperature in apartments between December and March.

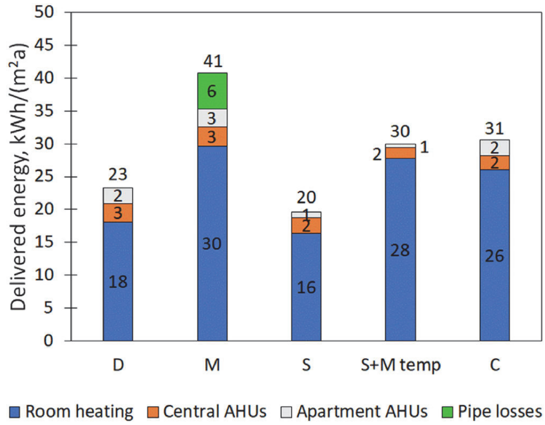

Fig. 7. Measured energy need for space heating and ventilation air heating.

3.2. Calculations to find reasons for performance gap in delivered energy use

3.2.1. Calibration of simulation model

The reasons for the performance gap were analysed by using IDE ICE 4.8 simulation. The simulation model was calibrated based on field measurements (Fig. 6). The calculated energy use for space heating and heating of ventilation air without window airing is 30.6 kWh/(m^2·a) (in Fig. 7 W). Measured heating energy need is 40.8 kWh/(m^2·a) (Fig. 7 M) from which 5.5 kWh/(m^2·a) is from the heating system's pipe heat losses. Without pipe losses, measured heating energy consumption is 35.3 kWh/(m^2·a) (room and ventilation heating (Fig. 6 left) which is 15% higher than the calculated consumption without window airing.

In the second calculation a window opening of 10% of the total window area was used for half an hour a day in all apartments. Recalculated energy use for space heating and heating of ventilation air after that was 35.4 kWh/(m^2·a) (in Fig. 7 as C) which is in same range as the measured value.

Fig. 6 shows a comparison of measured and calculated model heating energy use by months. The biggest differences are in January and December where measured heating energy consumption was 10% higher than calculated values with window airing. The probable cause for this higher consumption can be differences between real and calculated opened windows.

3.2.2. Energy for room heating and heating of ventilation air

To provide a more in-depth analyse of the heating use and to find the main factors contributing to the performance gap, several simulations were done.

From measured heating energy 5.5 kWh/(m^2·a) is the heating system's pipe heat losses. The main pipe losses come from the 50 m of main district heating pipe in the basement and from central AHU heating coil pipes in the service shaft running from the basement to the attic floor. District heating pipes losses provide heat to the basement area but from spring until autumn these losses are not utilised and not needed. The same situation occurs with pipe losses in the service shaft. In the current study there was no investigation into how much this heat gain is utilised.

Without window airing, the calculated (W) heating energy consumption was 30.6 kWh/(m^2·a). Of the entire consumption, 26 kWh/(m^2·a) is for room heating, 2.3 kWh/(m^2·a) is for central AHU heating and 2.3 kWh/(m^2·a) for apartments AHUs heating (Fig. 7). Using standard use values in the same calculation simulation model, re-calculated heating energy consumption for room heating is 16.3 kWh/(m^2·a) which together with ventilation air heating comes to 19.7 kWh/(m^2·a) (Fig. 7 as S). Compared with design consumption this is 15% lower (D). The differences from design use come from differences between the air flow rate in

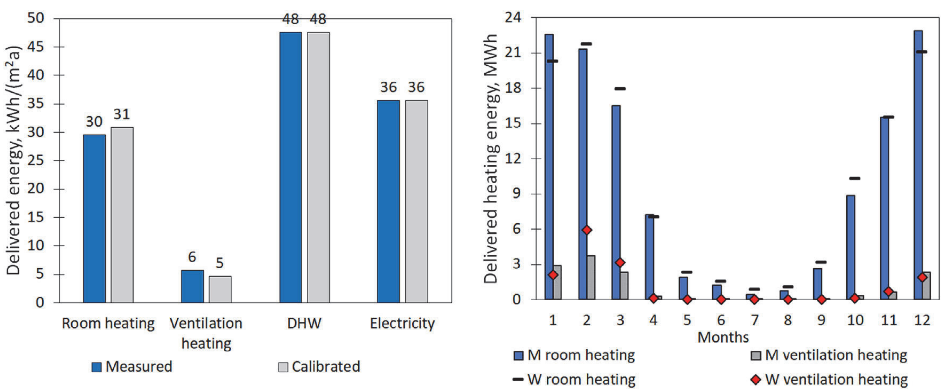

Fig. 6. Annual delivered energy in calibration model (left) Calibrated energy need for space heating and ventilation air heating by months (right).

apartments. In standard use, airflow in apartments should be 0.42 l/(s·m^2) but the design figure was 0.5 l/(s·m^2).

The biggest difference between standard use, and calibrated model without window airing (Fig. 7 as C) room heating energy consumption is caused by the indoor temperature which is on average 3.6 °C higher than the standard use temperature. Changing the calculation model to use indoor temperature as measured gives a calculated room heating energy use (Fig. 7 as S + M temp) that is 70% higher but, together with ventilation heat, is 52% higher. This means that a 1 °C raise in temperature caused a 15% heating energy consumption growth. In Fig. 7 we can see that the difference from standard use consumption, where we have used measured indoor temperature and without window airing model heating energy consumption, is small (2%), which is caused mainly from differences in the supply airflow rate and supply air temperature. A 3 °C higher supply air temperature increased ventilation heating energy use but at the same time decreased room heating energy consumption. From this we can see that heating energy consumption differences are caused mainly by air flow rate differences which increase heating energy consumption and also heat gains from a higher density of people and higher electricity use decreasing heating energy consumption.

When window airing is not taken into account, energy consumption is 15% lower than the measured energy consumption.

3.2.3. Energy for DHW

The biggest difference between measured and design energy performance of buildings is heating energy need for DHW. Part of the difference between designed (19 kWh/(m^2·a) and measured (48 kWh/(m^2·a)) energy use is caused by the standardised water use in energy performance modelling. Fig. 8 shows that designed delivered energy need for DHW from district heating was only 7.5 kWh/(m^2·a) but the measured value is 30.6 kWh/(m^2·a).

One part of the problem is that circulation losses are not taken into account in energy calculation methodology. Measured energy use for DHW circulation was 9.4 kWh/(m^2·a) which accounts for 30% of the energy needed for DHW in the standard use profile (30 kWh/(m^2·a)).

Measured DHW need was 775 l/(m^2·a) and the calculated standard value is 516 l/(m^2·a) (1.5 times difference). The standard value for population density is 28.3 m^2/pers. Population density in the pilot building was 1.2 times higher: 23.6 m^2/pers. DHW use per one person was 49 l/(d·pers.). In standard use, the DHW use per one person is 40 l/(d·pers). This cause additional increase of water use compared with designed values.

Another reason for the large difference is the performance of renewable energy systems which did not produced the amount of energy expected in the building design. Measured energy production from wastewater and solar collectors is significantly lower than was expected in the energy calculations. Most of the energy need for DHW was designed to be covered by a waste-water heat pump (50%) and solar collectors (25%). During the construction, the wastewater heat pump system was replaced with a passive heat recovery system from wastewater. Measurements conducted after the renovations showed that heat recovery from wastewater was only 2.6 kWh/(m^2·a) that is lower than designed: 15 kWh/(m^2·a). Designed electricity use for wastewater heat pump was 3.8 kWh/(m^2·a). Designed heat production of solar collectors was 7.5 kWh/(m^2·a) and re-calculated standard in standard use was 10.7 kWh/(m^2·a) that was similar with measured value: 10.1 kWh/(m^2·a). Nevertheless only half of the produced heat (5.0 kWh/(m^2·a)) was transferred to DHW system. The unexpected performance of solar collector system was caused by large heat loss of the DHW tanks and pipes (uninsulated valves and heat exchangers) and complicated and inefficient functional scheme of the system (three heat exchangers, mistakes in control system).

For the standard use of DHW energy requirements we have used measured wastewater preheating as the wastewater heat exchanger efficiency is unknown, and calculated the solar collector energy production. From this, DHW energy from district heating is 18.6 kWh/(m^2·a) (in Fig. 8 as S). Using the same assumptions as used for calculating standard use energy requirements, we calculated energy requirements with a population difference of 1.2 times greater (Fig. 8 as DHW 1.2) and DHW usage of 1.5 times greater (larger population + larger water use per person) (Fig. 8 as DHV 1.5). Fig. 8 shows that DHW district heating energy use is 25.3 kWh/(m^2·a) (DHW 1.2) and 35.3 kWh/(m^2·a) (DHW 1.5). The performance gap between measured district heating DHW use with a larger population is 17% and with the larger consumption is plus 15%. Together with measured DHW circulation the gap is gap 37% and 12%.

3.2.4. Electricity need

Designed electricity use without the electricity needed for apartment-based ventilation units' heating coils is 30.5 kWh/(m^2·a) and measured 39.2 kWh/(m^2·a). In standard use, electricity consumption is 32.7 kWh/(m^2·a).

Measured electricity (household appliances and lighting) consumption in apartments is in a similar range as designed. Measured electricity use in common areas (basement, staircase) is 5 kWh/(m^2·a) higher than designed (Fig. 9). Higher energy consumption in common areas can be caused by consumption in the common room used for presenting nZEB renovation solutions and the inhabitants laundry rooms which are located in the heated basement.

The difference between measured apartments AHUs and central AHUs ventilators electricity use from the designed energy use is 40%. Measured energy use is 6.2 kWh/(m^2·a) and design was 3.8 kWh/(m^2·a).

Designed energy use for ventilators of apartment-based ventilation units was 0.9 kWh/(m^2·a) and measured use was 2.75 kWh/(m^2·a). Re-calculated value in standard use (S), using the same input parameters as in design, is 1.7 kWh/(m^2·a). The difference from design is caused by calculation mistake in the design and the difference from measured (M) and standard use (S) is caused by a higher air flow rate in apartments. At the same time, central AHUs measured electricity use for ventilators is 3.4 kWh/(m^2·a) while the standard use calculated consumption was 4.3 kWh/(m^2·a). This is caused by slightly lower airflow in apartments and common rooms

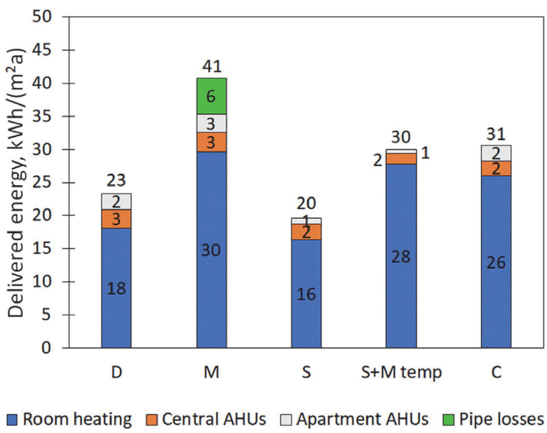

Fig. 8. Delivered DHW heating energy consumption.

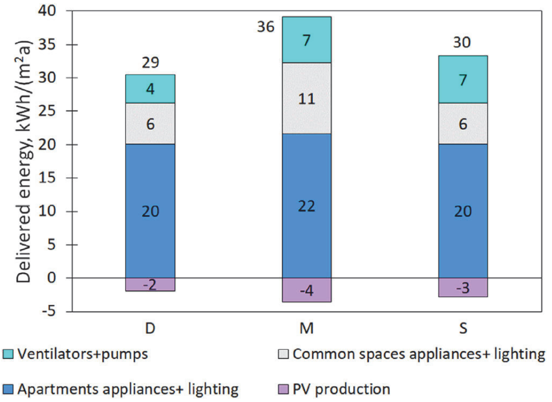

Fig. 9. Delivered electricity need: as measured after renovation, as designed and as in standard use.

compared to the standard use.

PV panels electricity production by design was 1.9 kWh/(m^2·a). Re-calculated energy production in standard use was 2.8 kWh/(m^2·a) and measured in 2018 was 3.6 kWh/(m^2·a) which is 47% higher than design and 22% higher than in standard use.

3.3. *Delivered energy need gap*

If we compare the gap between measured (124.0 kWh/(m^2·a)) and standard use (81.5 kWh/(m^2·a)) delivered energy then the total difference is 42.5 kWh/(m^2·a) (39%). A breakdown of the various reasons for higher energy consumption in Fig. 10 shows that 39% of the difference is caused by higher heating energy consumption where: 25% is higher energy needs for room heating, 4% higher ventilation heating needs and 10% is caused by heating pipe losses. The total DHW heating gap between measured is 50% and in detail: 22% from higher district heating use, 17% caused by DHW circulation and 10% caused by lower energy from solar collector system. The gap between electricity use is 11%. The main reason is an 8% higher energy consumption in common area appliances and lighting. Other differences are lower than 4%.

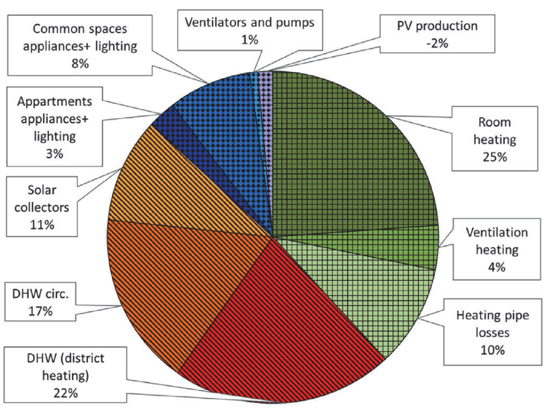

Fig. 10. Building delivered energy need gap between measured and standard use.

3.4. *The total primary energy use*

Measured total primary energy use after the renovation is 147 kWh/(m^2·a) which was 35% higher than the designed value ("D"): 95 kWh/(m^2·a) (Fig. 4 right). When the calculations are made in the calibrated simulation model with standard use values for indoor temperatures, ventilation airflow rates, energy need for DHW and electricity consumption based on standard user profiles ("S"), the primary energy consumption is 95 kWh/(m^2·a). With standard user profiles and parameters, the pilot building meets the nZEB requirements. Design and standard use PE consumption is same but there are differences between: heating energy consumption (21%) mainly caused by differences in apartments air flow rate, DHW heating energy consumption (15%) caused by system differences and electricity consumption (5%) caused by differences in PV electricity production and ventilators electricity use.

When heat losses of the heating system and DHW system distribution pipes are also taken into account, the primary energy need is 109 kWh/(m^2·a) (Fig. 11 as S + circ).

Calculations with the assumption that windows are partly open and the building has measured indoor gains, indoor temperature and air flows (also with heating and DHW distribution losses), give a primary energy consumption ("W + circ") of 126 kWh/(m^2·a). The gap between measured use and designed use is still 14% (without distribution losses is gap 23%). For calculations with a 1.2 times higher DHW heating energy need than the standard use ("W + DHW1.2 + circ"), the primary energy consumption is 141 kWh/(m^2·a) which is still more than a 4% difference from the measured energy use. Which is mainly caused by higher electricity consumption in common rooms.

The results show that heating pipe distribution losses are 9% of the primary energy need and the user-affected primary energy use is 25% which is different from the standard use.

Primary energy use difference between measured and standard use is 52 kWh/(m^2·a) which means that the total gap is 35%. Fig. 12 shows where the main differences and how big they are. The biggest gap is between measured and standard use room heating (23%) which is caused mainly by a higher indoor temperature. 8% from 52 kWh/(m^2·a) is caused by ventilation air heating and this is mainly connected with apartments AHUs heating coil electricity use. 37% of the entire gap is from DHW heating (Fig. 12). One part of DHW (21%) is caused by 1.5 times larger DHW use and the other part (16%) is caused by DHW circulation which is not taken into account in the standard use calculation. Electricity for common spaces appliances and lighting is also larger (18%) than in standard use.

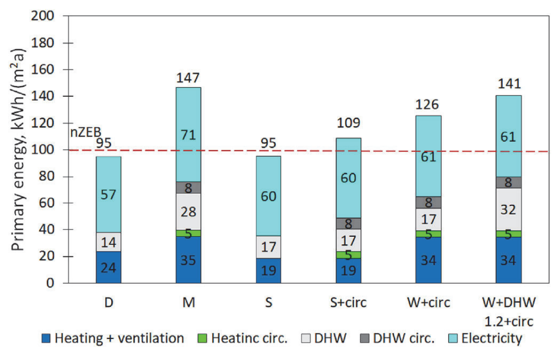

Fig. 11. Primary energy use by design, standard use of building without and with circulation losses and by calibrated simulation results where windows were closed showing the different DHW use.

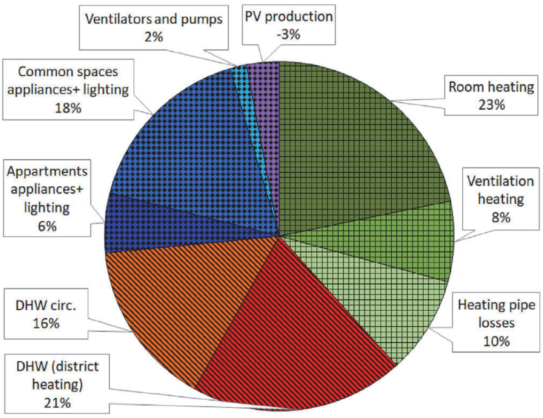

Fig. 12. Building primary energy need gap between measured and standard use.

4. Discussion

Heating energy use after renovation is 40% greater than designed because of a higher temperature in apartments, higher ventilation air flow and supply air temperature, as well as window airing. These are all occupant related consumptions and from this study we can say that occupants behaviour affect a lot heating energy consumption. Higher indoor temperatures have also been investigated in earlier studies [16,31] and have also featured in other studies abroad [32–35]. Our investigation showed that a 1 °C increase in indoor temperatures increased heating energy consumption by 15%.

Calculations and visual observations show that people are using opened windows to regulate heat and ventilation. Opening the windows is not studied in detail in this building, but our results shows that this can increase the heating energy use on average by 20%. Window opening behaviour and effects must be studied in more detail in this building. One possibility could be similar to that which Bourikas et. all [36] have shown in their study where they analysed a camera based system to automatically diagnose the status of window opening on the façade. They found out that this system accuracy level is 90–97%. Also from this investigation, we can see that people like to have open windows and they often forget to close them. In their study they analysed an EPC “G” class building and, with window opening, the annual heating energy consumption increased by 19%. In our study we assumed that it would be around 15%. Further studies have also shown that user behaviour can affect building energy use significantly. La Fleur et al. [37] also showed that window airing affects heating energy consumption, but at the same time, lead to a reduced use of electricity heating energy consumption. Linden et al. [38] showed that user behaviour should be taken into account when analysing energy consumption because it is an important factor.

From delivered energy losses. 10% was from heating energy losses from the heating pipes located in the unheated basement, between the central heat meter and radiator district heating heat exchanger, and also heating pipes which are located in the service shafts and are connected with the central AHU heating coil in the roof. These losses must be investigated in more detail in the future.

The analyses showed that the building envelope performed as expected in the energy calculations. Thus, the use of prefabricated insulation elements was worthwhile to guarantee a high-quality building envelope. Heat losses of the building envelope are in the same range as calculated values. Previous measurements of the building envelope [22] have also shown that measured thermal transmittance of external walls and the air tightness of the building envelope is similar to the calculated values. This means that envelope transmission difference is not a problem in our research case.

Hot water is stored in large accumulation tanks and during the day, when DHW use is low, heat losses from the tanks cause energy losses from the solar collector system. Solutions for how to optimise heat loss from water tanks should be analysed in future studies. One solution could be optimising water tank volume which has also been discussed by Li et al. [39]. The methodology for calculating solar collector heating energy production and the design of these solutions should be analysed in more detail. In the investigated building, the system production was similar to the calculated value but the efficiency of using produced energy was only 50%. From this, we can say that entire solar collector system can be improve in the future and this is not working as expected today.

In the studied building, the measured DHW consumption is 1.5 times higher and occupation density is 1.2 times higher than the standard value. This shows that occupants of the pilot building use more DHW than estimated in the standard user profile. Previous studies [16] have shown that, on average, people use 28 l/(d·pers) of domestic hot water, which is lower than the standard value. In the investigated building, the higher DHW consumption could be caused by young families (university’s family dormitory) who have children and are using more DHW. In an average apartment building, the inhabitant mix is more varied which leads to a lower DHW usage.

In an investigation of 182 Finnish apartment buildings [40] the average DHW consumption was 43 l/(d·pers) and in Swedish buildings 33 l/(d·pers) [41]. Comparing our results with neighbouring countries, our measured DHW (49 l/(d·pers)) use is also higher. One possibility to lower DHW consumption is to use faucets where is possible to limit maximum water consumption. Earlier studies by Toode and Kõiv [42] have shown that from 1999 was DHW until 2003 was decreased (from 59 to 45 l/d·pers)) and main reason was increasing cost of DHW. In current building all apartments are paying also based on consumption but this is not motivate to decrease DHW use.

The Estonian energy calculation method [29] does not include DHW circulation losses, which in the studied pilot building, was 24% of measured DHW from district heating and, from entire DHW energy use, 20%. Part of the DHW circulation losses are utilised as internal heat gain. But outside the heating season it is not possible to utilise most of the circulation losses. Also in the pilot building we do not have any information how much this energy is utilised. In this building, circulation losses are measured in detail which enables a more in-depth analyse of the problem. As the DHW energy share from the entire heat balance in nZEB buildings is higher than in common buildings, then heating energy losses of DHW systems should be taken into account in energy performance design. This study showed the need to have a calculation method for DHW circulation. This shows that regulation for calculating primary energy consumption must be improve.

High (19%–66%) DHW circulation heat losses have shown by Cali [43]. Choleva et al. [44] have also been investigating DHW circulation heat losses. They discovered that a significant part (56.7%–70.5%) of the DHW heating is related to the circulation losses. Their solution was to use temperature control valves to limit circulation flow which can reduce losses by 19.4%, or lower DHW temperature at night which decreases losses by 13.2%. These solutions can also be used in our investigated building.

A previous study about DHW use in 35 apartment buildings also showed high energy consumption for DHW circulation [16]. In previous studies we separated DHW and circulation heating energy using DHW consumption, summer moths heating energy use, and a prediction that temperature rise from cold water is 50 °C. In this study, the temperature of the cold water was measured and the temperature is between 2 and 17 °C (on average + 9.7 °C) and the temperature rise on average is 45.3 °C. Using this temperature difference in the calculations, the calculated DHW energy consumption is 5% higher than the measured consumption. The cold water temperature is not measured directly in the front of the DHW heating system and the difference could be caused by a cold water temperature rise in the heated basement. At the same time, in different buildings, the temperature of the cold water can be different and this is dependent on the water distribution network and the water source. The cold water intake temperatures have also been analysed by Bors et al. [23]. They found that in Australia, the cold water temperatures varied between 12 and 28 °C during summer and 9–15 °C during the winter period and this affects the DHW energy need.

The electricity use (appliances and lightning) in common areas is higher than in similar apartment buildings [45,46]. This could be caused by a higher density of people (staircase lighting energy use) and also because one part of the basement is used as an nZEB renovation showroom where is possible to conduct small seminars. Apartment household electricity use is a little bit higher than in the calculations but this is directly connected with the higher density of people.

Re-calculation with standard use values (S) showed that primary energy consumption criteria of nZEB can be achieved when heat losses from the DHW and AHU heating coil are not taken into account. When measured AHU heating coil pipe losses and DHW losses are added to the calculation, then it is not possible to reach the nZEB energy performance level using the designed solutions. Results shows that distribution losses from pipes are 10% of the primary energy need. As the real occupational behaviour is different from the standard usage then the primary energy need for heating is 10% higher. This comparison has highlighted the effect when window opening is not considered. The real occupational behaviour means that the primary total energy need is 14% higher. When we compare the calculated heat energy use with the standard use, the higher temperature and higher airflow cause the rise of primary heating energy consumption by 60% (from 18.7 kWh/(m^2·a) to 30.1 kWh/(m^2·a)). Together with predicted window opening figures, the rise of primary energy consumption goes up to 34.4 kWh/(m^2·a) which is 84% higher than in standard use, and with extra pipe losses it doubled the standard primary energy consumption for heating.

Occupancy affect building energy consumption a lot. If window airing is known as user behaviour but exact opening time and duration is hard to identify. Same timing when people are using apartment and when they use electricity for lights and appliances as internal heat gain. In current building, we know in every apartment number of residence and every day electricity use but detailed use profile is unknown. Bellia et al. [47]. showed in their study also that calibrating simulation model is important to know occupancy scheduled, internal loads and interaction between people and windows to understand better calibration results.

The analyse of user related heating energy consumption such as window airing and times when people are absent from their apartment shows that the authors need a more detailed study to understand the energy balance of the building in more comprehensive manner. As the importance of heat losses from pipes is higher in nZEB buildings, then this type of study would help decrease the gap between the calculated and measured energy consumption.

5. Conclusions

The measured primary energy use of the studied renovated building is 147 kWh/(m^2·a). As the designed primary energy consumption was 95 kWh/(m^2·a) then the performance gap between measured and designed primary energy consumption is 34%. The results show that the nZEB target level (100 kWh/(m^2·a)) was not achieved in real use of building. If the renovated building would be used according to standard use conditions and design methodology, the nZEB target (PE $\le$ 100 kWh/(m^2·a)) can be achieved. This shows that building itself is built well but at the same time, if the existing heating pipe losses, DHW losses and user real behaviour are added to the calculation then it is not possible to reach the nZEB energy performance. Which mean that also energy performance methodology for standard use must be developed to take the real user behaviour better into account and to prognoses future energy use.

The main reasons why the nZEB target level was not achieved are:

- The average indoor temperature is 2.6 °C higher (23.6 °C) than the standard temperature (21 °C);
- The density of people (28.3 m^2/pers.) is 1.2 times higher than the standard value (23.6 m^2/pers.);
- DHW use (775 l/(m^2·a)) is 1.5 times higher than the standard value (516 l/(m^2·a)):
- Heat losses of DHW circulation system (20% from DHW energy use) and heat losses of heating pipes to central AHU which is located in the roof space (14% from heating energy use).
- DHW energy from solar collectors system (5.0 kWh/(m^2·a)) is 2 times lower than the standard value (10.7 kWh/(m^2·a)) and wastewater heat recovery doesn't work as designed.

Our study showed that occupant related energy use affects the achievements of energy performance goals a lot. Also showed current study shows distribution losses from heating pipes and DHW circulation system plays important role in nZEB renovated building. National methodology to calculate energy performance of buildings do not take this into account in most of member stated in EU. Current study proposes requirements for improvements of energy calculation methodology. If suggestions, proposed in current article will be taken into account in new studies, performance gap will be smaller.

Author contributions

Anti Hamburg, Alo Mikola and Kalle Kuusk carried out the analysis. Anti Hamburg and Kalle Kuusk wrote the paper. Targo Kalamees was designed the scientific research in the building and revised the paper.

Conflicts of interest

The authors declare no conflict of interest.

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Article

The Influence of Energy Renovation on the Change of Indoor Temperature and Energy Use

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Abstract: The aim of the renovation of apartment buildings is to lower the energy consumption of those buildings, mainly the heating energy consumption. There are few analyses regarding those other energy consumptions which are also related to the primary energy need for calculating the energy efficiency class, including the primary energy need of calculated heating, domestic hot water (DHW), and household electricity. Indoor temperature is directly connected with heating energy consumption, but it is not known yet how much it will change after renovation. One of the research issues relates to the change of electricity and DHW usage after renovation and to the question of whether this change is related to the users' behavior or to changes to technical solutions. Thirty-five renovated apartment buildings have been analyzed in this study, where the data of indoor temperature, airflow, and energy consumption for DHW with and without circulation and electricity use in apartments and common rooms has been measured. During research, it turned out that the usage of DHW without circulation and the usage of household electricity do not change after renovation. Yet there is a major increase in indoor temperature and DHW energy use in buildings that did not have circulation before the renovation. In addition, a small increase in the use of electricity in common areas was discovered. This study will offer changes in calculations for the energy efficiency number.

Keywords: indoor temperature after renovation; electricity use; DHW energy use; user behavior; standard use

1. Introduction

Buildings are responsible for approximately 40% of energy consumption in the European Union countries. Final energy use in Estonia is 33.0 TWh/a and the share of buildings is 50% [1]. The Energy Performance of Buildings Directive (EPBD) [2], the Energy Efficiency Directive (EED) [3], and the Renewable Energy Directive (RED) [4] define a framework for long-term improvements in the energy performance of Europe's building stock.

To decrease energy use, EU Member States shall establish a long-term renovation strategy to support the renovation of the national stock, into a highly energy efficient and decarbonized building stock by 2050, facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings (nZEB) [2]. D'Agostino et al. [5] provide an overview of the status of implementation of nZEBs in Europe and showed that building retrofit is one of the biggest challenges that Europe is facing.

Energy renovation is one of the most effective and cost-efficient ways to improve indoor climate and achieve energy savings. Indoor climate and energy modeling have estimated the savings potential to be in the range of 40–80% of energy use [6–9]. Modeling has usually been done on the standard use of buildings [10]. In reality, the use of user-related energy can be different compared with the standard use because of the density of occupants or the number of apartments in a building [11]. The use of standardized user profiles for modeling is good for comparing similar buildings and to work out the building stock level. To work out cost effective energy renovation measures for specific buildings, this peculiarity has to be taken into account. That is why it is important to investigate user-related indoor climate and energy consumptions before renovation and to compare that with standard use energy.

The rebound effect has been investigated by Sorrell [12]. He has found that most governments are seeking solutions to improve energy efficiency to fulfill their energy policy goals. But measured energy savings generally turn out to be appreciably lower. He postulates that one explanation could be that improvements in energy efficiency encourage a higher use of those services which are provided by the energy supply. This situation where the calculated energy savings are not being achieved due to behavioral responses has come to be known as the energy efficiency 'rebound effect'. In some cases this rebound effect is high enough to lead to an overall increase in energy consumption, an outcome termed as 'backfire' [13]. In general, the rebound effect is not taken in to account in energy efficiency calculations, which may lead to an overestimation of the future energy savings [12]. The occupants' behavior has also been identified as one of the reasons for the energy performance gap in other studies [14,15]. The systematic review of the literature on occupant and building energy performance by Zhang et al. [16] estimated that the occupant behavior-related energy-saving potential could be in the range of 10–25% for residential buildings. Menezes et al. [17] highlighted the need for a better understanding of occupancy behavior patterns and the use of more realistic input parameters in energy models; needed to bring the predicted figures closer to reality.

This study investigates indoor climate and energy consumption, which is connected with occupant behavior before and after renovation. Energy renovated apartment buildings in Estonia are used as an example. The research questions of the study are the following:

- Whether and how much does energy renovation influence indoor climate and human related energy use?
- How well do real indoor climate parameters correspond to the standard use of a building before and after the renovation?
- Is it appropriate to use a different standard use for the energy certification process for apartment buildings?

2. Methods

2.1. Studied Buildings

In Estonia, the majority of apartment buildings that have been constructed between WWII and 1990 have the same typical problems: high energy-consumption levels, insufficient ventilation (natural ventilation without any outdoor air inlets), uneven indoor temperatures, and insufficient thermal comfort levels [18–20]. From the year 2010, more than 1000 apartment buildings have undergone renovation, the majority of them supported by Fund KredEx. The energy renovation of 663 apartment buildings resulted in average energy savings of 43% [21]. The main challenge was to achieve the same level of heating energy consumptions as estimated by modeling before renovation [22].

The energy use and indoor climate were investigated in 35 apartment buildings (Table 1).

The average number of apartments in one building was 27 (varied between 12 and 72, standard deviation is 17), average heated area was 1757 m^2 (varied between 550 m^2 and 5030 m^2, standard deviation is 1046). Average occupancy in one apartment was 2.2 persons (varied between 1.1 and 3.3, standard deviation is 0.5) and the average area per person was 31 m^2/person (varied between 16 m^2/person and 55 m^2/person, standard deviation is 7.7).

Table 1. Studied buildings. DHW: domestic hot water.

Code	No. of Apartments	Heated Net Area, m^2	No. of People	Ventilation	DHW Circulation before/after Renovation	Additional Insulation, cm/Thermal Transmittance (U W/(m^2·K))		
						Walls	Roof	Windows
1.1	25	1665	47	Exhaust fan	−/+	+20/0.16	+30/0.10	≤1.1
1.2	18	1673	45	Exhaust fan	−/+	+15/0.18	+45/0.10	≤1.6
1.3	18	1592	44	Exhaust fan	+/+	+15/0.18	+30/0.12	≤1.5
Target: EPC "D", PE ≤ 180 kWh/(m^2·a) (DHW with electrical boilers). 40% grant.								
2.1	12	1029	40	Central AHU	−/−	+15–20/0.21	+23/0.13	≤1.4
2.2	18	1490	27	Central AHU	−/−	+15–20/0.20	+30/0.11	≤1.3
2.3	18	1508	40	Central AHU	−/−	+15/0.24	+21/0.15	≤1.1
2.4	24	1370	41	Central AHU	−/−	+15/0.20	+30/0.12	≤1.3
2.7	18	1180	40	Central AHU	−/−	+15/0.21	+40/0.09	≤1.1
Target: EPC "C" PE ≤ 150 kWh/(m^2·a) (with central Air Handling Unit (AHU)). 40% grant.								
2.5	18	1306	45	Central AHU	−/+	+15/0.20	+28/0.11	≤0.9
2.6	18	1306	35	Central AHU	−/+	+15/0.21	+28/0.12	≤1.1
2.8	18	886	25	Central AHU	−/+	+15/0.21	+35/0.09	≤1.1
2.9	12	903	24	Central AHU	+/+	+15/0.20	+28/0.12	≤1.3
Target: EPC "C" PE ≤ 150 kWh/(m^2·a) (with exhaust air heat pump). 40% grant.								
2.10	55	3378	89	Exhaust fan	+/+	+20/0.16	+25/0.16	≤1.1
2.11	32	1505	96	Exhaust fan	+/+	+15/0.21	+30/0.12	≤0.9
2.12	50	3904	130	Exhaust fan	+/+	+20/0.19	+35/0.15	≤1.1
Target: Heating energy saving 30% (with natural ventilation and extra outdoor air inlets (FAI)). 15% grant.								
15.1	60	3163	150	NAT	−/−	+10/0.38	+15/0.20	≤1.8
15.2	36	1718	61	NAT+FAI	+/+	+15–20/0.21	+0/0.4	≤2.0
15.3	60	2959	150	NAT	+/+	+0–10/0.75	+23/0.15	≤2.0
15.4	24	1737	60	NAT+FAI	+/+	+15/0.21	+20/0.17	≤1.8
15.5	40	3075	100	NAT	+/+	+0–10/0.75	+10/0.25	≤2.0
Target: Heating energy saving 40% (with natural ventilation (NAT) and extra outdoor air inlets (FAI)). 25% grant.								

Table 1. *Cont.*

Code	No. of Apartments	Heated Net Area, m^2	No. of People	Ventilation	DHW Circulation before/after Renovation	Additional Insulation, cm/Thermal Transmittance (U W/(m^2·K))		
						Walls	Roof	Windows
25.1	12	777	27	NAT+FAI	−/−	+15/0.21	+25/0.13	≤1.6
25.2	40	2623	80	NAT+FAI	+/+	+10–15/0.30	+25/0.13	≤1.4
25.3	60	3519	150	NAT+FAI	+/+	+15/0.21	+20/0.17	≤1.6
25.4	12	550	24	NAT	−/−	+15/0.21	+25/0.13	≤1.6
25.5	16	1903	38	NAT+FAI	−/−	+10–15/0.28	+30/0.11	≤1.6
Target: Heating energy saving 50% (supply-exhaust room units (SERU)). 35% grant.								
35.1	18	1064	40	SERU	−/+	+10–15/0.30	+13/0.20	≤1.4
35.2	18	1285	44	SERU	−/+	+15/0.21	+13/0.20	≤1.6
35.7	18	1026	34	SERU	+/+	+5–15/0.28	+23/0.15	≤1.6
35.9	12	940	30	SERU	−/−	+15–20/0.20	+20/0.17	≤1.6
Target: Heating energy saving 50% (with exhaust air heat pump). 35% grant.								
35.3	21	1527	60	Exhaust fan	−/+	+15/0.21	+25/0.15	≤1.6
35.4	18	1041	40	Exhaust fan	−/+	+15/0.21	+23/0.16	≤1.6
35.5	18	1162	40	Exhaust fan	+/+	+10/0.28	+23/0.16	≤1.6
35.6	15	1151	38	Exhaust fan	+/+	+15/0.21	+23/0.16	≤1.6
35.8	72	5030	200	Exhaust fan	+/+	+15/0.21	+23/0.16	≤1.6
Target: Heating energy saving 50% (with central Air Handling Unit (AHU)). 35% grant.								
35.10	15	561	16	Central AHU	−/−	+15/0.21	+10/0.25	≤1.6

An example of a building before (a) and after (b); a renovation is shown in the following Figure 1.

(a) (b)

Figure 1. An example of a building (**a**) before and (**b**) after the renovation.

All 35 buildings have district heating for space heating. The heating system was renovated in all of the buildings: a hydronic radiator with thermostat valves (TRV) was installed in all apartment buildings, (before renovation, the existing one pipe system didn't have TRV). In ten buildings, the performance of natural ventilation was improved by adding outdoor air inlets. In 11 buildings, centralized exhaust ventilation (without ventilation heat recovery (VHR)) was installed. In eight buildings, the exhaust ventilation was equipped with an exhaust air heat pump (EXHP) for heat recovery. Supply and exhaust ventilation with heat recovery was installed in 14 buildings: four apartment buildings had supply-exhaust room units (SERU) and ten buildings had central air handling units (AHU).

In 11 buildings, DHW was heated by electrical boilers, located in apartments, as before renovation. In nine apartment buildings, the DHW heating by local electric boilers was changed into a central system heated by district heating after renovation (installing DHW and DHW circulation pipes). In all other buildings, district heating for DHW was used before and after the renovation. In all those buildings where DHW is heated by district heating there also exists DHW circulation, (Table 1 shows where DHW circulation was in use before renovation and how the situation is after renovation).

2.2. Evaluating Energy Consumption before and after Renovation

Energy audits before renovation were done for each building by professional energy auditors. Energy audits are documents which show the energy consumption of a building for different requirements and how to renovate the building to decrease energy usage. There were no special standards or guides for auditing in existence during that period in Estonia. The majority of energy auditors were educated through special courses and most of auditors used the same audit methodology and form. From year 2015, a new energy audit procedure was developed by Fund Kredex [23]. The information about energy consumption (electricity, space heating together with ventilation air heating (heat) and domestic hot water (DHW)) and indoor temperature before renovation was taken from an energy audit. Energy consumption after renovation was measured and data was collected from building managers. In apartment buildings with district heating, where heat for space heating and DHW was measured together, the heat for DHW was calculated based on the assumption that 40% of the total water used is hot water [24] and the difference between the temperatures is 50 °C. Circulation heat loss was calculated by using the difference between theoretical (energy consumption from water use and temperature difference) and measured energy use for DHW during the summer months.

2.3. Indoor Climate Measurements

We measured indoor temperature and ventilation airflow as the most important parameters to guaranteeing thermal comfort and indoor air quality. Measurements were conducted in all buildings in at least 3–4 apartments (altogether 120 apartments) after the renovation during the heating period between the beginning of December until the end of February, (buildings coded from 15.1 to 35.10 during the period December 2013 until February 2014, and coded 1.1 to 2.12 during the period December 2016 until February 2017).

Temperatures were measured at fifteen-minute intervals. The temperature was measured with portable data loggers (EVIKON E6226, measurement range −10–50 °C with an accuracy of ±0.6 °C) (Evikon MCI OÜ, Tartu, Estonia). The data loggers were located on the separating walls mainly in master bedrooms.

Airflow was measured in apartments twice, generally at the beginning of December and again at the end of February. In all apartments we measured exhaust air outlet airflow. The criteria for the selection of apartments was that they should be located on different floors and that in the selected apartments there should be living more persons than there are bedrooms. Ventilation airflow was measured with a Testo 435 hot wire anemometer sensor (measurement range 0–20 m/s, with an accuracy ±0.03 + 5% m/s) (Testo SE & Co. KGaA, Lenzkirch, Germany) together with a volume flow funnel Testovent 410 (∅ 340 mm).

In every apartment, where indoor temperature and ventilation airflow were measured, we collected data regarding the appropriateness of the indoor temperature via a questionnaire (5 step scale: rather cool, slightly cool, neutral, slightly warm, and rather warm). Also, we asked a question on how they feel temperature after renovation (5 step scale: warmer, slightly warmer, neutral, slightly cooler, and cooler). In most buildings the ventilation system has been renovated. That is why we asked also how they evaluated ventilation air quality (5 step scale: fresh, rather fresh, neutral, rather stuffy, and stuffy).

Thermal comfort was calculated based on ISO 7730 standard [25] by using Excel based tool [26]. Air temperature and relative humidity values were taken from measurements from all 120 apartments. The surface temperature of external wall (1/5 from all surface area) was calculated based on its thermal resistance (taken from design documentation) and typical surface resistance (0.13 $m^2 \cdot K/W$). For other input parameters (clothing = 1.0 clo, activity level = 1.2 met, and air velocity = 0.1 m/s) we used values recommended in EN 15,251 standard [27] for indoor climate category Indoor climat calss (ICC) II.

2.4. Standard Use of Buildings and Performance Gap

Pursuant to an Estonian regulation [28], the standard use of a building (indoor climate, water and electricity use, and heat gains) for indoor climate and energy modeling of an apartment building are the following:

- Indoor temperature during heating period: 21 °C;
- Ventilation airflow: 0.42 $L/(s \cdot m^2)$ for apartments with a local air handling unit and 0.5 $L/(s \cdot m^2)$ for apartments with central air handling unit. The minimum requirement for renovation is 0.35 $L/(s \cdot m^2)$;
- The use of DHW:520 $L/(m^2 \cdot a)$, i.e., 30 $kWh/(m^2 \cdot a)$;
- The use of electricity for appliances, lighting, and circulation pumps is 30 $kWh/(m^2 \cdot a)$.

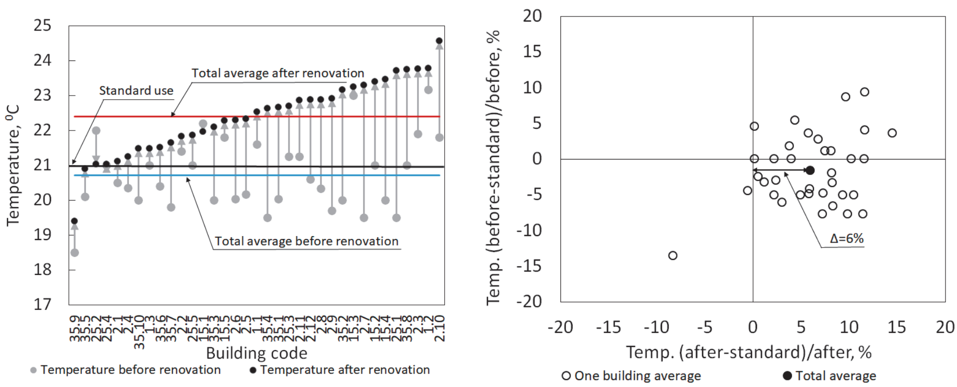
The performance gap is calculated as a relative difference between the measured and standard use values according to Equation (1):

$$\text{Performance gap} = \frac{100 \times (\text{Measured value} - \text{Standard use})}{\text{Measured value}} \% \quad (1)$$

3. Results

3.1. Indoor Climate

Before renovation, the indoor temperature during the heating period was 20.8 °C on average, which is slightly lower than the standard value [28] for energy simulations (21 °C). After renovation, the indoor temperature was higher than the standard value in almost all buildings: 22.4 °C on average (varied between 19.4 °C and 24.5 °C), Figure 2a, i.e., 1.6 °C higher than before renovation, on average. In Figure 2a, on the right Figure 2b, we can see that after renovation the room temperature is 1.4 °C on average (relative difference 6%) higher than the value for standard use.



(a) (b)

Figure 2. (**a**) Indoor temperature before and after renovation; (**b**) Indoor temperature performance gap from standard.

Based on the questionnaire, occupants were satisfied with the indoor temperature. 78% from 120 occupants answered that indoor temperature was comfortable (Figure 3). Only 11% of the occupants said that the temperature is lightly or rather warm.

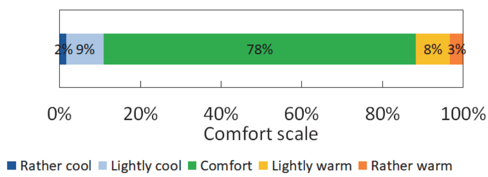


Figure 3. Occupant satisfaction with the room temperature in apartments.

The lower and higher calculated Predicted Mean Vote (PMV) (values are −0.66 and 0.67 and maximum Predicted Percentage of Dissatisfied (PPD) value is 14.4%. From 120 apartments 10 are outside from neutral thermal comfort ($-0.5 < PMV < 0.5$) zone. Based on calculations 89.8% of apartments inside of comfort zone are satisfied. Based on this we can conclude that there was not large difference between the reported satisfaction and the satisfaction calculated based on measurements (Figure 4).

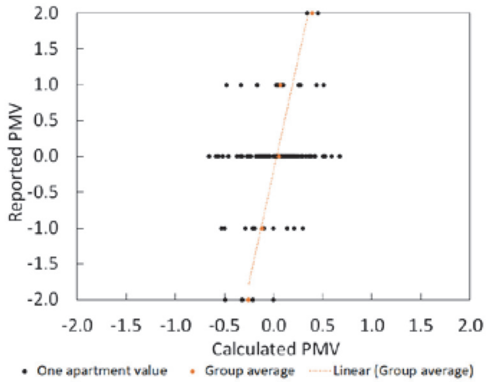


Figure 4. Calculated PMV index and PMV index by questionnaire.

Also, in Figure 5 we can see that 68% of occupants understand that the indoor temperature has increased after renovation. Only 8% of occupants said that the temperature has decreased.

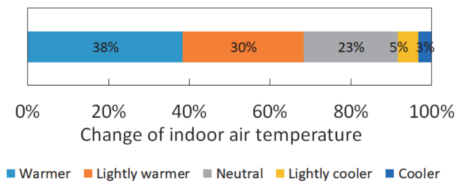


Figure 5. Occupant evaluation on the change of room air temperature after renovation.

The average ventilation air change rate of old Estonian apartments with natural ventilation before renovation was 0.24 h^{-1} and 0.17 $L/(s{\cdot}m^2)$ [20]. The ventilation airflow after renovation of 0.36 h^{-1}, 0.25 $L/(s{\cdot}m^2)$ (varied between 0.05 h^{-1} and 0.86 h^{-1}, 0.03 $L/(s{\cdot}m^2)$ and 0.60 $L/(s{\cdot}m^2)$) on average was much less than the standard value [28] for energy simulations 0.5–0.6 h^{-1}; 0.35–0.42 $L/(s{\cdot}m^2)$ (Figure 6).

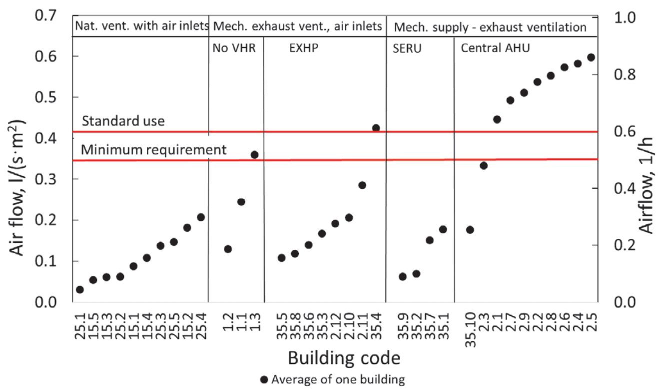


Figure 6. Ventilation airflow after renovation in studied buildings.

In our study we asked how the occupants rated also ventilation air quality after renovation. Based on the results of the measurements it can be said that airflows in most of building can be improved, but the questionnaire showed (Figure 7) that 56% of occupants feel that air is rather fresh after renovation.

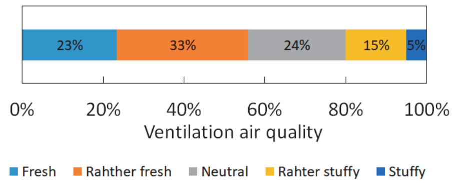


Figure 7. Occupant evaluation of ventilation quality.

3.2. Domestic Hot Water Use

The average DHW use in studied buildings was, on average, 31 L/(pers.·d) before renovation and 28 L/(pers.·d) after renovation (without circulation losses 24 L/(pers.·d) and 22 kWh/(m^2·a) correspondingly). DHW use with circulation losses was in all buildings, on average, 31 kWh/(m^2·a) before renovation and 33 kWh/(m^2·a) after renovation. We divided houses in three groups depending on DHW circulation. Table 2 features DHW energy use before and after renovation. Buildings with DHW circulation have an average DHW use of 38 kWh/(m^2·a) after renovation and without circulation, 21 kWh/(m^2·a). In buildings where circulation was installed during the renovation, the average increase of energy consumption for DHW was 13.4 kWh/(m^2·a) (Figure 8a).

Table 2. The influence of DHW energy consumption on circulation and renovation.

DHW before and after Renovation		DHW Circulation after Renovation: Yes	DHW Circulation after Renovation: No
DHW circulation before renovation	Yes	Before renovation: 42 kWh/(m^2·a) After renovation: 39 kWh/(m^2·a)	-
	No	Before renovation: 24 kWh/(m^2·a) After renovation: 37 kWh/(m^2·a)	Before renovation: 21 kWh/(m^2·a) After renovation: 21 kWh/(m^2·a)

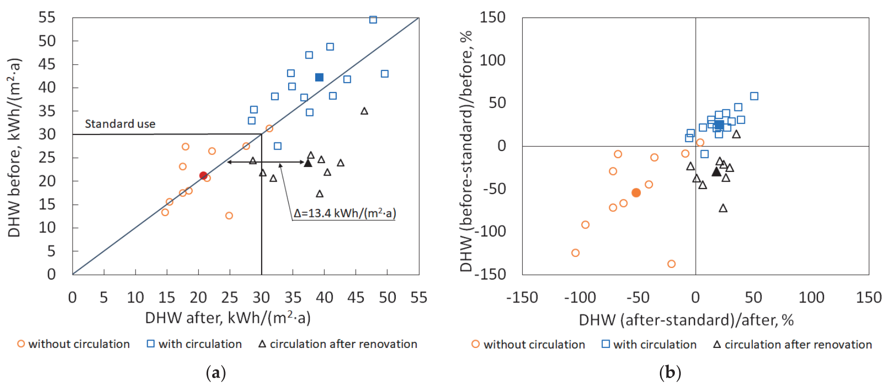
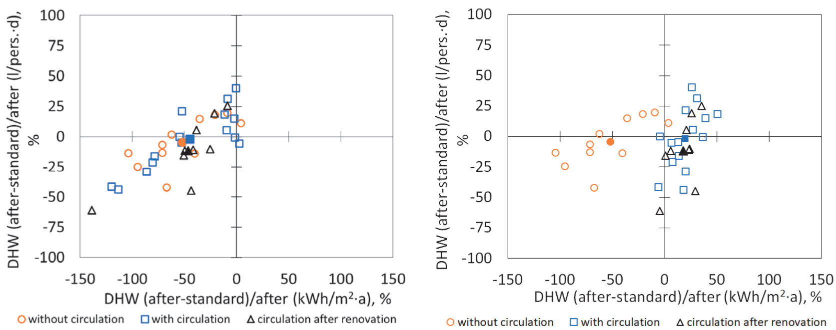


Figure 8. (**a**) DHW use before and after renovation; (**b**) DHW performance gap from standard (one building parameter is with hole and group average is filled).

Figure 8b shows the gap between the measured and standard use of DHW. Almost all buildings where there was no DHW circulation before and after the renovation used less DHW energy compared to the standard use. The relative difference between the measured energy and standard use was 54% before renovation and 52% after renovation. On the other hand, buildings with DHW circulation had a higher DHW energy use compared with standard use: before renovation 26% and after renovation 20%. Hence, independently from the availability of DHW, the energy for DHW decreased a little. The main difference in the change in DHW use was apparent in buildings where DHW circulation was installed during renovation: energy for DHW increased 56%.

In the regulations, DHW use is defined as water use per heated area. In reality, an area does not use the water; it is the occupants in the building who do it. To analyze what is the better DHW use presenting unit—L/(pers.·d) or kWh/(m^2·a), we measured energy use with average DHW usage per person (28 L/(pers.·d)) and with standard usage (30 kWh/(m^2·a)) with and without DHW circulation (Figure 8a). We can see that in most cases, DHW use without circulation compared with standard use per heated area is lower; the average gap from the standard use in all buildings is −48% (Figure 9a). The gap between the standard use (kWh/(m^2·a)) is −140% to +4%; from DHW use per person (L/(pers.·d)), it is between −61 and 40%. When we take into account DHW circulation, then we can see that the average use from standard use per heated area moves to the positive side and when hot water circulation is considered, then the average difference with standard use after renovation is +19%, which is between −5 and +50% (Figure 9b).

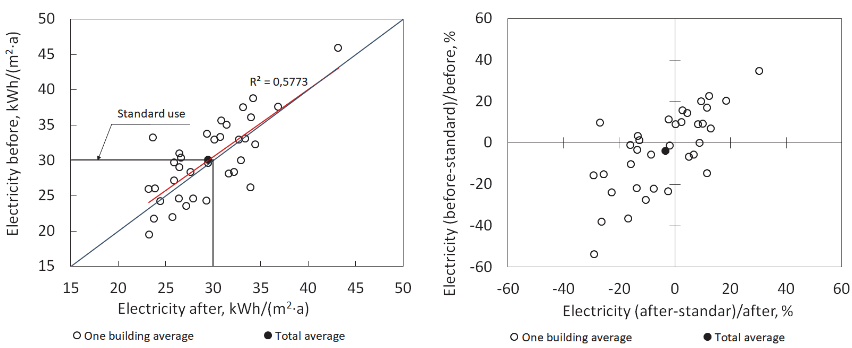


(**a**) (**b**)

Figure 9. (**a**) DHW use gap from average usage per person (L/(pers.·d)) and use gap from standard use per heated area (kWh/(m^2·a)) without DHW circulation and (**b**) with DHW circulation.

3.3. Household Electricity

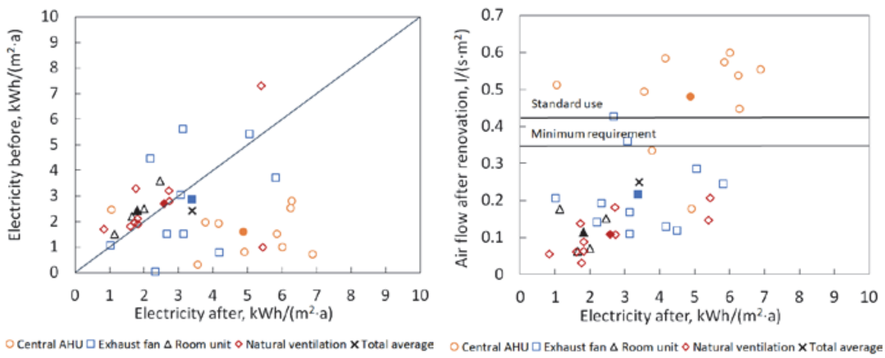
The renovation did not influence the average use of household electricity (apartments + common spaces): before renovation, it was 30.1 kWh/(m^2·a), and after renovation, approximately the same, 29.5 kWh/(m^2·a) (Figure 10a). In general, we see that the renovation did not change the use of electricity that much. The gap between the standard use, which has been taken without electricity use for ventilation (30 kWh/(m^2·a)), is, on average, −3% before renovation (between −54 until 35%) and after renovation −4% (between −29 until 30%) (Figure 10b).



(**a**) (**b**)

Figure 10. (**a**) Electricity use before and after renovation; (**b**) Electricity performance gap from standard use.

The use of electricity in common spaces (includes circulation pumps for DHW and heating, and electricity for central ventilation units) in all buildings was, after renovation, 0.9 kWh/(m^2·a) higher (Figure 11a) than before renovation. The increase of the use of electricity in common spaces was significantly higher ($p = 0.001$) in buildings with central AHU compared with buildings with other ventilation types. Figure 11a, shows that in buildings with a central AHU, the average electricity use increased from 1.6 kWh/(m^2·a) before renovation to 4.9 kWh/(m^2·a) after renovation. Figure 11b, shows that after the renovation, airflow in these buildings was also higher than in other buildings (average 0.5 L/(s·m^2)). An increase in the use of electricity in general spaces after the renovation was very small in buildings with other ventilation systems.



(**a**) (**b**)

Figure 11. (**a**) Electricity use in common spaces (including pumps and ventilators) before and after renovation; (**b**) Electricity use in common spaces (including pumps and fans) after renovation compared with airflow.

4. Discussion

Indoor temperature was, on average, 1.6 °C higher after renovation (22.4 °C), which is 1.4 °C higher than the value used for indoor climate and energy modeling. If thermostatic valves were installed during the renovation, inhabitants now had the possibility to regulate their living temperature. This could be a reason for higher indoor temperatures. After renovation, the building is well insulated and should use less energy for space heating. As the heating bill is now not so high for occupants, they enjoy a higher temperature. This phenomenon can be described by the rebound effect. Higher room temperatures after renovation have been shown in other studies [29–32]. Higher room temperature also causes higher heating energy consumption. Földveary et al. [33] showed that a room temperature increase of 1 °C increases the heating energy consumption in energy efficient buildings by 16.8%. Based on the questionnaire, occupant satisfaction about indoor temperatures was good. Some difference existed between the reported and the calculated PMV based on measurements values in the rage outside of neutral zone. Occupants reported very severe conditions than we may calculate based on measurements. This may be caused on different clothing and activity levels and there always exist some unsatisfied persons [34].

This situation is much better than previous cross-sectional studies about the building's technical condition and occupant behavior have shown. Kalamees at al. [35] showed the main problems related to building physics, indoor climate, HVAC systems, and energy efficiency. Typical indoor climate related problems have been stuffy air, uneven temperature in different rooms, problems with temperature regulation possibility, etc.

Based on our questionnaire, occupants were satisfied with the indoor temperature even though the temperature was more than 1 °C higher than that used for energy modeling. To achieve realistic estimates for energy use after renovation, we suggest increasing the room temperature to 22 °C.

It is proposed that an individual heating metering system in apartments could motivate occupants to avoid a too high room temperature. Hamburg et al. [36,37] showed that instead of lowering the room temperature, occupants started decreasing the ventilation airflow and neighboring heating in well-insulated buildings.

Ventilation airflow was lower than designed in buildings with natural ventilation, mechanical exhaust ventilation, and supply-exhaust room units. In apartments with outdoor air inlets, drafts occur during the cold period. Therefore, occupants start closing the ventilation air inlets, thereby also decreasing exhaust airflow. In apartments with room-based supply and exhaust ventilation units, the drawbacks of using designed airflow are a high noise level, low pressure drop, operation management, and inefficient heat recovery. To achieve the designed airflows, we recommend using, in the renovation of residential buildings, central supply and exhaust ventilation units with heat recovery or apartment-based supply and exhaust ventilation units with heat recovery that showed a satisfactory performance in detached houses in a cold climate [38]. Based on questionnaire only 20% of occupants were dissatisfied with indoor air quality even when required ventilation airflows were not guaranteed after renovation. This shows that occupants adapted to the worsened air quality.

We measured that the use of DHW was similar with other Estonian apartment buildings [39,40] but higher than in other countries: the EU average is 25 kWh/(m^2·a), Sweden 29 kWh/(m^2·a), and Norway 30 kWh/(m^2·a) [10]. Our study showed a difference in the use of energy in buildings with and without DHW circulation. A difference in the energy use for DHW with and without circulation shows the need to calculate DHW circulation losses separately. Cali [14] has also showed that DHW distribution losses can be very high. We recommend calculating DHW circulation separately from DHW to get comparable values with standard use.

The use of electricity in buildings showed a good match between the use before and after the renovation. This shows that it does not influence occupant behavior too much. Liu [41] showed that household electricity can increase after renovation, but this was related to new installations. When comparing the use of household electricity with standard use, we can see a large variation between buildings. The relative difference varied between −54% until +35% but average difference between after and before renovation is 3.1 kWh/(m^2·a). In three buildings the electricity use difference was more than 5 kWh/(m^2·a). In the same buildings the difference in electricity use was also apparent for a three-year period before the renovations.

The installation of mechanical ventilation increased the use of electricity due to electric fans. The increase was significantly higher in buildings with a central air-handling unit. Compared with other ventilation systems, the higher values were due to the better performance of ventilation, as the ventilation airflow was much lower than required in buildings with other ventilation systems. Even though the electricity use increases when installing mechanical ventilation, the total energy balance is positive in cold climate conditions. Many studies have shown that installation of mechanical ventilation with heat recovery in cold climates is cost-effective in total [39,40,42].

5. Conclusions

Our study room temperature increased after the renovation. Temperature after the renovation is, on average, 1.6 °C higher than before the renovation, which shows a rebound effect during the renovation. Even though the indoor temperature was higher compared to the standard use; occupants were satisfied with the temperature. To achieve a realistic estimation for energy use after the renovation, we suggest increasing the room temperature in simulations to 22 °C.

The current study confirmed that the current standard electricity and DHW use in Estonian energy-modeling regulations are correct. We showed that installation DHW circulation significantly influences the energy use for DHW ($p \leq 0.001$). We recommend in the future separating DHW energy use for heating and circulation energy use. The electricity usage before and after renovation depends in most cases only whether a central AHU is installed or not and on the ventilation airflow.

Ventilation airflow was lower than designed in buildings with natural ventilation, mechanical exhaust ventilation, and supply-exhaust room units. In the majority of buildings with central supply and balanced ventilation with heat recovery, ventilation airflow was as designed. To achieve required airflows, we recommend using, in the renovation of residential buildings, central or apartment-based supply and exhaust ventilation units with heat recovery.

Our study also showed that the behavior of people is more or less the same as it was before renovation. Even for energy performance certification, the standard use of buildings is unavoidable; for cost-efficient energy renovation measures we recommend taking into account building-specific user profiles.

In future studies it will be important to analyze DHW circulation losses more deeply, as our study showed that in renovated apartment buildings which are using less energy, distribution losses have an impact on energy efficiency. As after renovation the total energy use decreases, all deviation from target values makes large relative difference for more energy efficient buildings. As user behavior become more and more important topic in constructing new and renovating existing energy efficient buildings, it is important to analyze occupants behavior more deeply.

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PUBLICATION IV

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Article

Heat Loss Due to Domestic Hot Water Pipes

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Abstract: Domestic hot water (DHW) system energy losses are an important part of energy consumption in newly built or in reconstructed apartment buildings. To reach nZEB or low energy building targets (renovation cases) we should take these losses into account during the design phase. These losses depend on room and water temperature, insulation and length of pipes and water circulation strategy. The target of our study is to develop a method which can be used in the early stages of design in primary energy calculations. We are also interested in how much of these losses cannot be utilised as internal heat gain and how much heat loss depends on the level of energy performance of the building. We used detailed DHW system heat loss measurements and simulations from an nZEB apartment building and annual heat loss data from a total of 22 apartment buildings. Our study showed that EN 15316-3 standard equations for pipe length give more than a twice the pipe length in basements. We recommend that for pipe length calculation in basements, a calculation based on the building's gross area should be used and for pipe length in vertical shafts, a building's heating area-based calculation should be used. Our study also showed that up to 33% of pipe heat losses can be utilised as internal heat gain in energy renovated apartment buildings but in unheated basements this figure drops to 30% and in shafts rises to 40% for an average loss (thermal pipe insulation thickness 40 mm) of 10.8 W/m and 5.1 W/m. Unutilised delivered energy loss from DHW systems in smaller apartment buildings can be up to 12.1 kWh/(m^2·a) and in bigger apartment buildings not less than 5.5 kWh/(m^2·a) (40 mm thermal pipe insulation).

Keywords: DHW heat loss; DHW circulation; energy performance

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1. Introduction

Nearly zero energy (nZEB) apartment buildings have a relatively higher share of energy use for domestic hot water (DHW) because of reduced heat loss from the well-insulated building envelope, the use of ventilation heat recovery and LED lighting systems. DHW energy consumption can be divided between energy used to heat the water and energy consumed by system losses. Bøhm and Danig showed [1] that in apartment buildings the heat losses from the hot water system correspond to approximately 65% of the energy consumption for domestic hot water and the cause of these heat losses should be further investigated. Later, Bøhm specified [2] that most of the energy demand for DHW is lost in the circulation system. As the system's apartment building's DHW heat loss was 23–70%, its efficiency was 0.30–0.77. Gassel [3] showed that if the DHW circulation is constantly in operation, this equates to 15 kWh/m^2·a energy consumption, the circulation share being 19% of total DHW heating demand. Horvath et.al [4] showed that when the specific DHW annual heat demand is between 23.2 and 32.2 kWh/(m^2·a), the distribution and circulation losses are between 5.7 and 9.9 kWh/(m^2·a). Zhang et al. [5] indicated that recirculation loop pipes heat loss represented about one third of a system's fuel energy consumption and the average overall system efficiency was only about 34%. Similar results were found in the study by Marszal-Pomianowska et al. [6], where DHW accounted for 16% to 50% of total DHW heating consumption. Huhn and Davids [7] showed that the energy losses from hot water circulation are in the range of 25% to 75% of the energy used for DHW supply. In buildings with low DHW consumption, the efficiency is particularly poor. When DHW use is small than DHW circulation heat loss is more or less the same as in buildings with a bigger DHW consumption, but the relative share of DHW system losses in those buildings is bigger.

Minimising DHW distribution and circulation losses improves the efficiency of the system and the energy performance of the whole building. Kitzberger et al. [8] showed that minimising the runtime of the circulation pumps and decreasing hot water flow and storage capacities reduces the annual energy consumption for DHW by 15–25%. Mühlbacher and Carter [9] deduced a dependency between the energy loss and the operating time of the circulation pump in buildings with DHW circulation energy use from 21% to 65%. Without a reduction in the operating time of the circulation pump, energy loss from circulation was more than 60%. Cholewa et al. [10] showed in their long term field measurements on performance of DHW, that a significant part (57% to 71%) of the heat loss is allocated to the circulation of hot water. Using temperature control valves in the risers of the circulation installation to limit the circulation flow during periods of time when it is not required, generated average energy savings of 19%. Adam et al. [11] proposed shortening the circulation runtime (a minimum of 16 h per day) to decrease DHW circulation heat loss. Bøhm [2] suggested that replacing the bypass function with an in-line supply pipe and a heat pump can help to reduce the return temperature of the decentralised substation system. As a result, the annual distribution heat loss decreased by 12%.

Lowering circulation time is one possibility but it depends on how people use DHW. Ahmed et.al. [12] studied hourly DHW consumption in 86 apartments with 191 occupants over the course of one year and found that almost 90% of hourly consumption was between 0 and 20 L/(person·h). Two sharp peak consumption periods were present on week-days. Morning peak consumption was between 7:00 and 9:00 whereas evening peak consumption was between 20:00 and 22:00. The average consumption was 4.1 and 1.1 L/(person·h) for peak and non-peak hours respectively. Overnight, DHW consumption was almost zero.

Another possibility for decreasing DHW energy consumption is to lower the DHW temperature. Navalón [13] showed that by reducing the return temperature to 52 °C (limit temperature to avoid Legionella), the theoretical saving is 15–18%. The growth of Legionella bacteria is high risk and that is why water temperatures between 25 °C and 45 °C should be avoided, ideally maintaining hot water above 50 °C. To improve energy efficiency and avoid the risk of Legionella, Brand [14] suggested stopping the use of DHW circulation.

In old apartment buildings, heat from DHW distribution and circulation heat losses are distributed mainly in unheated basements and through shaft walls into apartments. Grasmanis et.al [15] showed that DHW circulation heat losses in an unheated basement vary between 10–12% during the non-heating season and 12–15% during the heating season. Depending on the season, the rate of circulation heat losses from vertical distribution circulation loop pipes varies from 55% to 60% for five floor buildings and 62% to 67% for 9 or 12 floor buildings. Rocheron [16] showed that the insulation of storage and distribution systems is an essential parameter in the process of energy savings, especially in the case of the DHW circulation.

Hamburg and Kalamees [17–19] have found that in reconstructed apartment buildings with DHW circulation, the energy consumption for circulation is on average 14 kWh/(m^2·a) higher than in buildings without circulation (apartment-based boilers) in the cold Estonian climate. To minimise the energy performance gap, more accurate design work is needed. During the early stages of design, exact and accurate input data for dynamic simulation is usually missing. Over-optimistic assumptions in the initial data and over-simplified energy calculations may lead to energy performance targets not being met [20]. Arumägi [21] studied the design of the first net-zero energy buildings in Estonia and concluded that more thorough analyses are needed in the very first stage of the design to find suitable solutions and possible compromises between architecture and energy efficiency. Attia and

De Herde [22] compared ten early design simulation tools for net zero energy buildings and showed that for nZEBs we should invest more in the early design applications and tools. At the detailed design stage, it is possible to get the exact length of DHW pipes from the final building information model (BIM), but this information is missing in the preliminary design, which is when the designer must demonstrate that energy performance has been achieved. The length of DHW pipes and their heat loss can be calculated with EN 15316-3 standard [23], based on the length and width of the building. However, these parameters are complicated to find in existing buildings which are not rectangular in shape. This is why using equations of lengths and widths in L-shaped and other irregular shaped buildings becomes so complex. Therefore, there is a need for a tool that estimates the DHW system parameters and energy performance that can be used at an early stage of design, and for the improvement of the methodology for assessing the energy performance of a building.

The working hypotheses of this study are the following:

- It is possible to estimate accurately enough the length of DHW piping based on the general characteristics of the building at the early design stage of the building.
- Based on the data of the early design stage, it is possible to calculate DHW circulation losses with sufficient accuracy and to propose a corresponding supplement to the calculation method.

Our goal was to find a better equation for calculating DHW and DHW circulation pipe lengths in basements and shafts than that used in EN 15316-3 standard equations [23].

2. Methods

2.1. Research Scheme to Investigate DHW and DHW Circulation Heat Losses

Our goal was to investigate DHW pipe length and heat loss in Estonian apartment buildings. We used for this a detailed model of an nZEB case building and compared the results with measured data from different apartment buildings:

Detailed calibrated dynamic indoor climate and energy simulation model for a nZEB apartment building (nZEB case building in the information we have from 4 types of building categories is shown in Table 1.

1. Detailed calibrated dynamic indoor climate and energy simulation model for a nZEB apartment building (nZEB case building in Table 1) to determine heat loss factors on room (21 °C heated and unheated basement) and water temperature, insulation (0, 20, 40 mm with and without valve insulation) and length of pipes and water circulation strategy (continuous circulation, clock based);
2. Design DHW pipe length from 15 apartment buildings (Test building in Table 1);
3. Generating a method for calculating pipe length and heat loss from pipes to be used in early stages of design;
4. Validating of pipe length equation in7 reference apartment buildings (Reference buildings in Table 1);
5. Validation of DHW heat loss with earlier studied 23 buildings measured heat losses.

In following Table 1 are shown which kind of information we have from 4 types of building categories.

2.2. nZEB Case Building

The nZEB case building has 80 small sized, one or two bedroomed apartments. More or less the same sized typical apartment buildings from the period end of 1970s until early 1990s usually have 60 apartments. The building is a 5-storey, large concrete panel apartment building with a total heated area of 3562 m^2, constructed in 1986 (Figure 1) d renovated to nZEB in 2018 [24,25]. We chose this building because it had a good monitoring system in place after its reconstruction, therefore we have hourly data from DHW use, DHW heating and DHW circulation.

Table 1. Research scheme and description of studied buildings.

Characteristic	nZEB Case Building	Test Buildings	Reference Buildings	Earlier Studied Buildings
Target	Calibration of model and energy use of DHW	Determination of pipe length equations	Validating of pipe length equation	Validating of DHW heat loss
		Description		
No. of buildings	1	15	7	23
Building's basic data	Heated area, net area, layout area (floor gross area), volume, length, width, height, number of: floors, apartments, DHW shafts.			
Building pipe length	Detailed 3D BIM and energy simulation model with real length of pipes	Measured length of pipes from 2D-design drawings + onsite survey	Measured length of pipes from 2D-design drawings + onsite survey	
		A. Length of DHW and DHW circulation pipes		
Pipe lengths	Detailed simulation with measured pipe lengths	Generating of Equation with real pipe length	Validation of the performance of Equation with real pipe length	Calculated pipe length with generated Equations
		B. Heat loss of DHW pipes		
DHW and DHW circulation heat loss	Detailed simulation model, calibrated based on detailed field measurements	Calculated pipe heat loss with measured length, calculated length and assumed measured losses from earlier study	Calculated pipe heat loss with measured length, calculated length and assumed measured losses from earlier study	Measured DHW system energy losses
The influence of DHW system heat loss.	Calibrated model calculations with different renovation scenarios	Calculated DHW system unutilised heat loss	Calculated DHW system unutilised heat loss	Calculated DHW system heat loss comparison with measured consumption

Figure 1. Overview of the nZEB case building after the renovation.

The DHW consumption and heating energy consumption, together with DHW and DHW circulation heating, was measured from all apartments. In the case study building which we chose for calibrating our pipe heat loss model, we measured hourly data from every source (detailed information about DHW volumes and DHW heating energy per every hour and also circulation energy use) between the period June to November 2019. The indoor temperature in the main basement room was also measured during the same period.

2.3. Test Buildings and Reference Buildings

We selected test buildings from among the buildings where we have detailed information about pipe length and energy use (DHW, DHW circulation) in both basement and shafts. We included both new buildings and renovated buildings in the selection. Our goal was to involve as wide a range of buildings from the sector as possible. These buildings were constructed between 1970 and 2017 and the main construction method was concrete (large panels) or brick (Table 2). The average number of apartments was 50 apartments and floor gross area was 730 m^2. Table 2 presents the basic building parameters [26].

Table 2. Basic properties of studied buildings.

Code	Construction Material for Walls	Construction Year	Volume	Heating Area	Net Area	Building Gross Area	Length	Width	Apartments per Floor	No. Shafts	No. of Apartments	Perimeter	DHW Pipe Length in Basement	DHW Pipe Length in Shafts
			m^3	m^2	m^2	m^2	m	m				m	m	m
nZEB case building														
1.1	Concrete	1986	15757	4330	4330	887	57.5	16.2	16	16	80	147	120	224
Test buildings														
1.2	LWC block	1974	3283	998	1306	438	49.0	8.8	6	12	18	116	79	101
1.3	Concrete	1975	12017	2763	3378	727	65.7	11.7	11	11	55	155	86	154
1.4	Concrete	1966	10696	2968	3519	676	61.7	12.2	12	12	60	148	78	126
1.5	Brick	1983	14252	3393	4110	888	61.7	18.6	10	10	50	161	90	112
1.6	Concrete	1970	16114	4606	5030	593	46.8	13.4	8	8	72	121	46	151
1.7	Concrete	2017	15967	4112	4112	859	43.1	32.8	15	15	75	152	84	225
1.8	LWC block	1986	7944	1887	2415	762	72.0	12.0	8	8	24	168	87	67
1.9	Concrete	1981	35403	10840	10840	1323	101.0	13.2	16	24	144	228	166	605
1.10	Concrete	1979	18400	4567	5933	1167	109.9	12.2	18	26	90	244	171	364
1.11	Brick	1977	11143	2022	3211	728	51.9	14.3	10	10	50	132	72	140
1.12	Brick	1970	1844	498	498	234	23.4	10.5	4	4	8	68	33	23
1.13	Brick	1972	5495	1526	1172	520	57.7	18.1	6	12	18	152	73	101
1.14	LWC block	1979	5211	1426	1036	495	48.8	9.9	6	12	18	117	71	101
1.15	LWC block	1975	8945	2054	2448	634	49.2	11.2	9	9	45	121	69	129
Reference buildings														
2.1	Concrete	1977	3959	1291	1959	478	48.8	9.9	6	12	18	117	68	101
2.2	Concrete	1986	12763	3669	3669	859	62.3	13.1	12	20	60	151	91	280
2.3	Concrete	1964	13833	3501	4494	861	73.0	12.0	16	16	80	170	109	224
2.4	Concrete	1977	16412	4399	4399	993	75.9	12.7	12	18	60	177	115	252
2.5	Brick	1976	13341	3495	3495	786	62.3	13.6	9	21	45	152	99	294
2.6	Brick	1975	10484	2309	2868	657	33.2	32.0	8	16	40	130	73	224
2.7	LWC block	1987	5979	1508	1862	545	23.8	13.5	6	6	18	75	71	50

The data on DHW and DHW circulation heating energy use from 15 test buildings (coded 1.1 … 1.15) and 7 reference buildings (coded 2.1 … 2.7) was calculated from measured heating energy consumption. We also used data from 23 previously analysed buildings to compare the calculated energy use of our test and reference buildings with measured values [17–19].

2.4. Determining DHW Pipe Length

To come up with an appropriate method for determining DHW pipe length, we selected 15 buildings with basic data available (which are presented in (Table 2). We analysed the data (building volume, heating area, net area, floor gross area, total number of apartments, etc.) from 15 test buildings to find out which data could be used and how to formulate an equation to generate the length and energy use of the DHW systems. The buildings' perimeter and the number of DHW shafts were calculated and counted from the design drawings of these buildings.

We used R square to find the best parameter model with intercept and for the two parameter model we used a bootstrapping method [27] to find best frequency by randomly sampling 2 parameters 10,000 times. Our goal was to find a minimum pipe length difference from measured values. All measured pipe lengths in the buildings are presented in (Table 2). Measured DHW pipes and DHW circulation pipes were more or less the same (measured pipe length in test and reference buildings), which is why we decided to present, for measured pipe length, an average DHW and DHW circulation pipe length in each building.

These so-determined DHW and DHW circulation pipe lengths were compared with EN standard (EN-15316-3 [23]) calculated pipe lengths.

Pipe length of DHW (l_{DHW}) (1) and DHW circulation system ($l_{circ\cdot}$) (2) in the basement can be calculated by standard EN-15316-3 [23]. In the Equations, L_L is length and L_W is width of the building.

$$l_{DHWb} = L_L + 0.0625 \cdot L_L \cdot L_W, \qquad \text{(m)} \tag{1}$$

$$l_{circ \cdot b} = 2 \cdot L_L + 0.0125 \cdot L_L \cdot L_W, \qquad \text{(m)} \tag{2}$$

Pipe length of DHW (l_{DHWs}) ($l_{DHWs} = 0.038 \cdot L_L \cdot L_W \cdot N_{lev} \cdot H_{fl}$, (m)) and DHW circulation system ($l_{circ\cdot s}$) (4) in the shafts can be calculated by standard EN-15316-3 [23]. In Equations L_L is length, L_W is width, N_{lev} is number of floors and H_{fl} is height of floor of the building.

$$l_{DHWs} = 0.038 \cdot L_L \cdot L_W \cdot N_{lev} \cdot H_{fl}, \qquad \text{(m)} \tag{3}$$

$$l_{circ \cdot s} = 0.0752 \cdot L_L \cdot L_W \cdot N_{lev} \cdot, \qquad \text{(m)} \tag{4}$$

2.5. Indoor Climate and Energy Performance by nZEB Case Building Calibration

The indoor climate and energy performance model was built in the simulation program IDA ICE 4.8 [28,29]. This software allows the modelling of a multizone building, internal heat gains and external solar loads, outdoor climate, heating and ventilation systems and dynamic simulation of heat transfer and air flows. We were also able to model heat losses from the zones in which they occurred and represent uninsulated valves by using a 2 m uninsulated pipe length, which is more or less an average from calculated values [30].

To calibrate the model we built up a complex model using detailed DHW and DHW circulation drawings for the reference building and then simplified it to create our calculation model (Figure 2).

Building a simulation model that matched all losses with the zones where those losses were occurring was very complex. Therefore we simplified the basement to a one zone model (originally this was a multizone basement with 14 rooms, as we wanted to see how heat losses affected indoor temperatures in the basement in different thermal insulation cases (0, 20, 40 mm with and without valve insulation)) but calculated with the different EPC that we used in earlier studies of the same building [31].

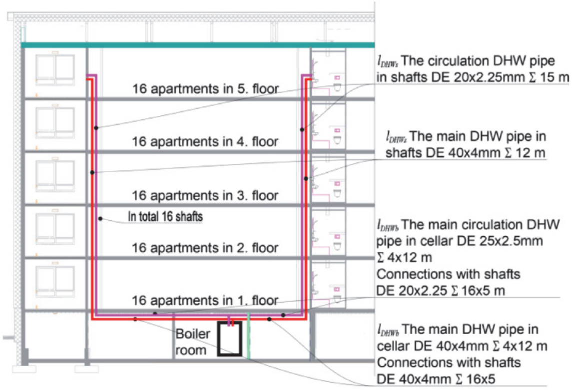

Figure 2. Simplified case building DHW and DHW circulation piping in basement and shafts.

The calculations can be repeated when the design of DHW and DHW circulation has been simplified by using a standard length for all main pipe lengths between shafts, and all pipe lengths and thermal insulation thicknesses have been described. The pipe model used is important, as is showing where pipes are located (in which zone). All pipes in the model must be hydraulically balanced, and inlet and outlet water temperature from the plant should be accurately represented.

Using measured pipe lengths in basement and shafts, we built up a dynamic simulation model with previously calibrated building heat losses. We measured indoor temperatures in the basement and used this for calibrating measured heat losses with calculated ones.

2.6. Heat Losses Calculations from DHW and DHW Circulation Pipes

Heat loss was calculated based on standard EN 15316-3 [23]. By this standard, pipe heat losses are calculated per length when the temperature difference is 1 Kelvin (Table 3). In this case, we can assume heat loss from pipes when we know the average basement or shaft temperature and pipe length in those places. However, indoor temperatures and how much these losses can be utilised as internal heat gain are both unknown.

Table 3. The dependence of pipe's heat loss on insulation thickness and pipe diameter.

Pipe's Outer Diameter, mm	**50**	**40**	**25**	**20**
Thermal pipe insulation thickness, mm	Pipe's linear thermal transmittance Ψ (W/m·K)			
40	0.25	0.22	0.17	0.15
20	0.37	0.32	0.23	0.21
0	1.22	0.98	0.62	0.50

2.7. The Influence of DHW and DHW Circulation Heat Loss on the Whole Building Energy Performance and Indoor Climate

The dependence of DHW heat loss on the energy performance of the building was analysed by using IDA ICE 4.8 dynamic simulation software. That is why we analysed the annual loss in the nZEB case building (Figure 1) with different thicknesses of thermal pipe insulation and with the different building envelope thermal insulations which are typically used in renovation scenarios in Estonia. Inputs for the simulation model are presented as the following:

Simulations were done in two different cases, with a heated basement and with an unheated basement. For this reason, we used two different heated areas 3562 m^2 (without basement) and 4324 m^2 (with basement). In the Figures, EPC classes are designated by class symbols (A, C, D, E and F).

Our goal was to find out, firstly, how much energy could be utilised from DHW system pipe losses in the basement and in shafts per calculated length and how large non-utilised losses per calculated length would be and, secondly, what the EPC class would be with and without pipe losses in the different cases.

3. Results

3.1. Measured and Calculated DHW Circulation Losses in Case Building

The DHW use in 2018 was 47.6 kWh/m^2·a, with energy consumption and DHW circulation losses having been measured in the nZEB case building at an hourly level. Two years' measurements of DHW circulation are shown in Figure 3b. In 2018 the total DHW circulation loss was 9.4 kWh/(m^2·a) (per heated area) and 11.4 kWh/(m^2·a) (per apartment area). In 2019, DHW circulation loss was even higher at 10.3 kWh/m^2·a (12.5 kWh/(m^2·a)), as was total DHW system energy use (49.2 kWh/(m^2·a)). In both years, the DHW circulation heating energy loss was approximately 20%. The DHW system energy loss in a typical reconstructed apartment building in Estonia is more or less the same [17].

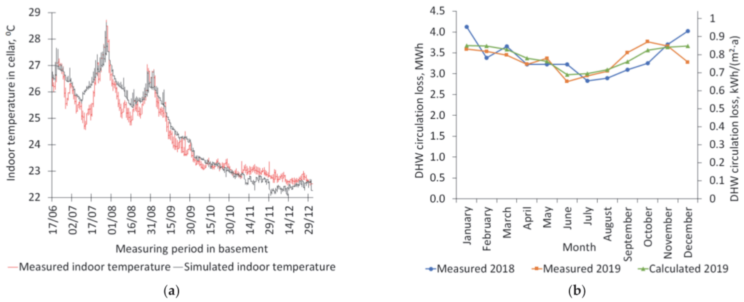

Figure 3. (**a**) Measured and calculated indoor temperature in basement; (**b**) measured and calculated DHW system heat loss in basement.

In Figure 3a, we can see that measured temperatures during the summer–autumn period in the basement were constantly more than 22 °C, which shows that pipe losses from DHW, DHW circulation and heating pipe connections with shafts were holding temperatures higher than the modelled heating set point temperature of 21 °C. In this case, we can see that indoor temperatures are more dependent on losses from piping lengths and thermal isolation than indoor setpoint temperatures.

3.2. Pipe Length Calculation

To go about finding a best equation for the DHW pipe length in the basements and shafts, we generated both one and two parameter equations. Table 4 presents the best results using our buildings' basic data (equations are made used test buildings' data). The best results (the smallest difference in pipe length difference) gained with the one parameter model equation for basement pipe length using building gross area, was a length difference between that measured and calculated in the test buildings of 17% and in reference buildings of 8%, which gave an average of 14%. Using a building perimeter calculated from the building design drawings gave slightly better results (15.6% with test buildings) but with reference buildings the average was the same.

Table 4. Case study building EPC classes with different building envelope thermal transmittances and ventilation strategy.

		Energy Performance of Building—Primary Energy (PE) Use and Energy Performance Certificate (EPC) Class				
		EPC "A *" and "B" PE ≤ 125 kWh/(m²·a)	**EPC "C" PE ≤ 150 kWh/(m²·a)**	**EPC "D" PE ≤ 180 kWh/(m²·a)**	**EPC "E" PE ≤ 220 kWh/(m²·a)**	**EPC "F" PE ≤ 280 kWh/(m²·a)**
Thermal transmittance of building envelope *U*, W/(m²·K)	External wall	0.13	0.17	0.22	0.22	1.0
	Basement wall	0.10	0.21	0.61	0.61	0.61
	Basement floor	0.23	0.38	0.39	0.39	0.39
	Roof	0.11	0.17	0.17	0.22	0.76
	Window	0.82	1.0	1.2	1.4	1.7
Ventilation strategy	Apartments	Mechanical ventilation 0.5 L/(s·m²), ventilation heat recovery (VHR) 0.8.			0.5 L/(s·m²) no VHR	0.35 L/(s·m²) no VHR
	Common rooms and heated basement	Mechanical ventilation 0.5 L/(s·m²), VHR 0.8.		No VHR 0.5 L/(s·m²)		
	In unheated room	0.15 L/(s·m²) without heat recovery				

* A is together with solar collectors and locally used PV panel electricity production (PE ≤ 105 kWh/(m²·a).

Pipe lengths in shafts was the best fit with the building heating area equation (pipe length difference from measured lengths were on average 28.3%).

Using for analyses also mean bias error or root mean square error, we can see (Table 5) that the equation selected in the first step fits well in both cases.

Table 5. Pipe length (in meters) equations, R-square values in test buildings, length difference from measured values, mean bias errors and root mean square errors in test and reference buildings.

Factor	Equation to Calculate the Pipe Length, m	R^2	Difference between Measured and Calculated, %			MBE (Mean Bias Error)			RMSE (Root Mean Square Error)		
		Test Buildings	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average
One parameter model					Pipe length in basement						
x = Volume	l = 0.0034·x + 46	0.56	23.8	9.2	19.2	−0.57	−5.8	−2.2	24.4	9.5	20.8
x = Heating area	l = 0.0109·x + 53	0.52	23.2	6.8	18.0	−0.04	−4.6	−1.5	25.4	9.2	21.6
x = Net area	l = 0.0112·x + 49	0.57	24.6	7.8	19.2	0.03	−4.5	−1.4	23.9	9.4	20.5
x = Gross area	**l = 0.1235·x − 2**	**0.82**	**17.1**	8.4	**14.4**	−0.01	0.2	**0.1**	15.7	7.7	**13.6**
x = Apartments per floor	l = 7.2845·x + 13	0.68	22.5	14.5	19.9	0.00	−4.6	−1.5	**1.0**	14.6	18.9
x = No. shafts	l = 6.1258·x + 11	**0.89**	**13.0**	28.7	18.0	0.00	17.1	5.4	12.3	28.4	18.9
x = Perimeter of building	l = 0.8015·x − 31	**0.85**	**15.6**	11.8	14.4	0.00	−8.9	−2.8	14.1	16.4	14.9
One parameter model					Pipe length in shafts						
x = Volume	l = 0.0163·x − 24	0.87	33.9	31.6	33.2	−0.1	−48.4	−15.5	50.7	65.2	55.7
x = Heating area	**l = 0.0538·x + 3**	**0.88**	26.8	31.6	28.3	0.1	−45.8	−14.5	**48.7**	65.0	**54.4**
x = Net area	l = 0.0522·x − 11	0.87	33.9	29.9	32.6	−0.1	−54.1	11.3	50.7	71.9	60.0
x = Gross area	l = 0.4471·x − 151	0.74	55.9	32.5	48.5	0.0	−23.8	**−7.6**	69.9	56.8	66.0
x = Apartments per floor	l = 25.768·x − 91	0.59	36.9	34.7	36.2	0.0	−41.1	−13.1	88.2	85.8	87.4
x = Tot apartments	l = 3.6964·x − 24	0.86	34.7	34.7	34.7	0.0	−58.2	−18.5	53.5	83.3	64.5
x = No shafts	l = 21.648·x − 98	0.77	36.5	25.1	32.8	0.0	35.5	11.3	66.1	44.4	60.0
x = Perimeter	l = 2.5985·x − 211	0.62	59.3	37.4	52.3	0.0	−54.1	−17.2	85.0	71.9	81.1

Table 5. *Cont.*

Factor	Equation to Calculate the Pipe Length, m	R^2	Difference between Measured and Calculated, %			MBE (Mean Bias Error)			RMSE (Root Mean Square Error)		
		Test Buildings	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average	Test Buildings	Reference Buildings	All Buildings Average
Two parameter model			Pipe length in basement								
x = Gross area and y = No. shafts	**l = 1.04236·x + 3.56701·y**	0.94	9.7	18.4	12.5	0.8	10.9	4.0	9.4	18.9	13.2
x = No. shafts and y = Perimeter	l = 3.02566·x + 0.44814·y − 16	0.96	10.3	18.4	12.9	0.5	4.1	1.7	9.7	18.2	13.0
EN 15316-3			42.6	30.6	38.8	33.3	20.6	29.3	36.8	27.9	34.2
Two parameter model			Pipe length in shafts								
x = no. shafts and y = heating area	l = 10.1399·x + 0.03717·y − 67	0.94	23.8	14.3	9.8	0.0	−5.7	−1.8	20.2	20.6	20.4
EN 15316-3			325.3	144.7	267.8	515.2	−94.6	321.2	610.3	114.3	508.0

For the two parameter equation we used a bootstrapping method. Best results for pipe lengths in basements when combining building gross area and number of DHW shafts (frequency from 1000 samples was 182) gave an average calculated length difference from measured length in the test buildings of 10%. However, we were unable to produce good results using any of the other basic building parameters which are known in the early design stages. The same lack of good results occurred when calculating pipes in shafts.

Figure 4a shows how well the floor gross area equation corelates with measured pipe lengths. Black points represent test buildings and blue points reference buildings. From this graph we can say that in buildings 1.2 and 1.6, the difference between measured pipe length and calculated pipe length was a little bit more than 30%. In the other test buildings, the calculated pipe length was on average 13% different from measured values (Figure 4b).

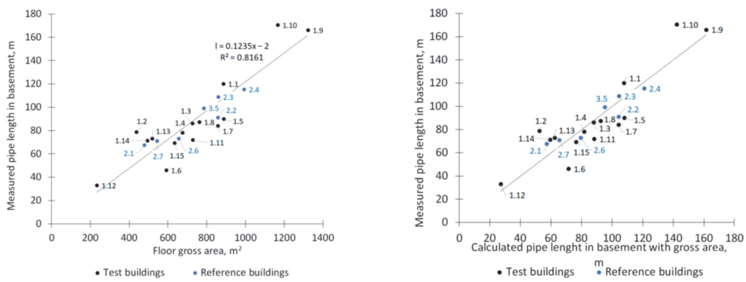

Figure 4. DWH pipe length in basement: (**a**) measured pipe length compared with floor gross area; (**b**) measured pipe length compared with calculated pipe lengths in basement.

DHW pipe lengths in shafts are detailed in Figure 5a,b. Our calculations showed that on average the pipe length difference from measured values was lowest when using this equation (in test buildings 35 m). The measured pipe length in six reference buildings was larger, which showed that by using this equation for calculations, we will probably get over-optimistic results compared to measured values in the future.

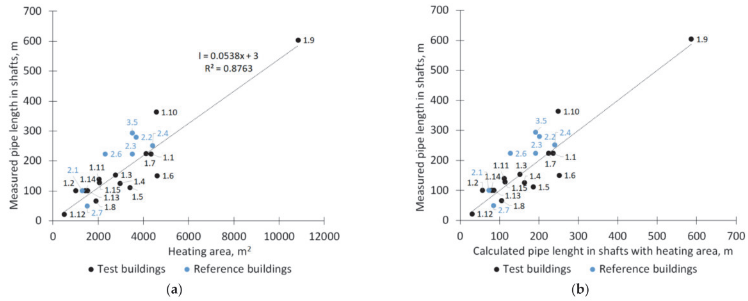

Figure 5. DHW pipe length in shaft: (**a**) measured pipe length compared with heating area; (**b**) measured pipe length compared with calculated pipe lengths in shafts.

Compared with the EN standard calculation method of using the heating area in the calculations, we can see large differences in the results for pipe lengths in shafts when compared to our equations. In test buildings, the average length difference using the EN standard equation was 258%. In comparison, our generated equation using the heated area gave an average length difference of 28%. In Figure 6a, we can see that the EN standard equation gave us results that were a little too pessimistic. The calculated pipe lengths in basements, when using the EN standard, was better than in shafts. The difference from measured length on average (test and reference buildings) was 39%, while the difference from calculated length, when using floor gross area, was 14% (Figure 6b).

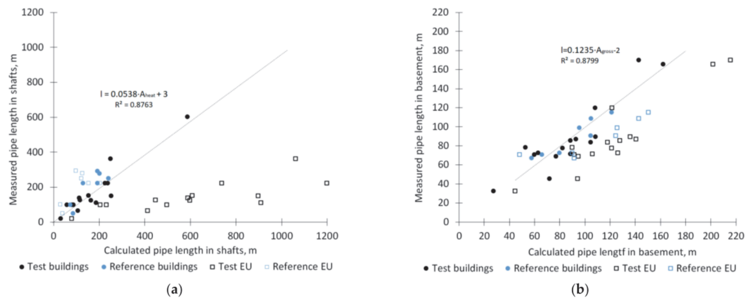

Figure 6. (**a**) Calculated pipe length in shafts with EN standard 15316-3 and using heating area; (**b**) calculated pipe length in basement with EN standard 15316-3 and using building gross area.

3.3. Parameters Influencing Heat Loss from DHW Circulation Piping

We investigated DHW pipe heat losses in the reference building:

- With different thickness of thermal insultation (0, 20 and 40 mm);
- With and without DHW circulation balancing valve insulation;
- Temperature in basement 21 °C or unheated;
- With different energy performance classes (EPC) (A, C, D, E, and F);
- Circulation pump working time.

To visualise how the various parameters influence energy loss from pipes, we decided to compare all EPC classes separately with different thicknesses of DHW thermal pipe insulation when the basement is both unheated and heated. In Figure 7a, we can see that with different EPC classes, unutilised DHW system losses varied between 48% to 81% in the unheated basement and this variance did not depend on the thickness of the pipes' thermal insulation. In the heated basement, unutilised heat loss from DHW pipes was between 24% to 71% (Figure 8b). Figure 7 shows the influence of thermal pipe insulation. When DHW system pipes are insulated with 20 mm of thermal insulation (EPC class A) than the total heat loss from pipes is 16 kWh/(m^2·a) but unutilised pipe losses are , which means that utilised pipe losses, as an internal gain, are 3 kWh/(m^2·a). The same situation was apparent in the heated basement with 12 kWh/(m^2·a) total loss, 8 kWh/(m^2·a) unutilised losses and a utilised pipe loss of 4 kWh/(m^2·a). We also analysed what occurs when the circulation pump is switched off during the night (22.00 until 6.00) and day-time (9.00 until 16.00), when DHW usage is low. We used for our calculations a measured usage profile and we found out that energy loss was decreased by only 0.5 kWh/(m^2·a) compared with constant circulation. As this effect was so low, we did not include this analysis in the figures.

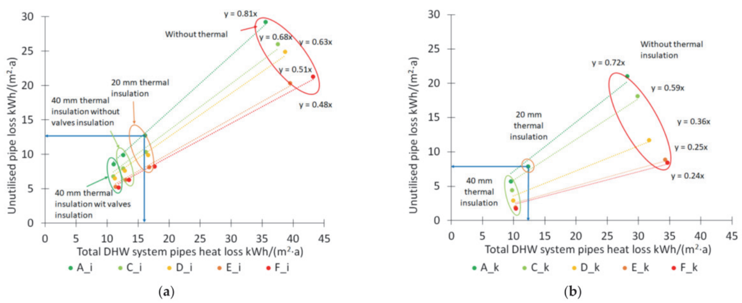

Figure 7. Total DHW pipe heat losses per heated area compared with unutilised pipe heat loss with different EPC classes and thermal pipe insulation: (**a**) when basement is not heated (i—unheated basement); (**b**) when basement is heated (k—heated basement).

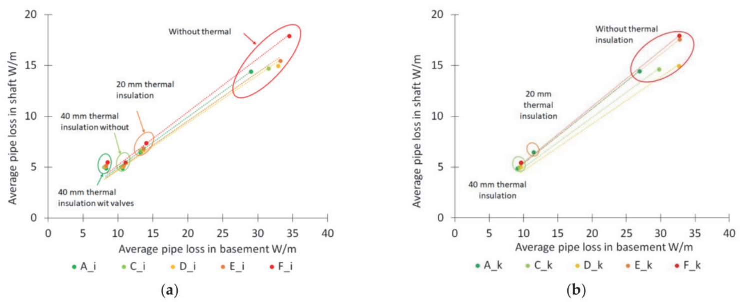

Figure 8. Pipe loss in basement and in shafts (W/m): (**a**) when basement is not heated (i—unheated basement); (**b**) when basement is heated (k—heated basement).

In cases where we have found the equation for pipe length separately in the basement and shafts, we wanted to see how large the pipe heat loss was, per length (W/m). We discovered that in all EPC classes, pipe losses from pipes covered with same thickness of thermal pipe insulation are almost the same (Figure 8a,b). With 40 mm of thermal pipe insulation, the pipe heat loss in an unheated basement averaged 11 W/m and in a heated basement 9.5 W/m. In shafts, the loss was more or less the same at 5 W/m. From Figure 7a,b, we can see how much of the entire losses are unutilised but we are not able to separate this between basements and shafts.

In Figure 9a, we can see that in unheated basements, the unutilised pipe losses in EPC classes C to F were more or less the same, between 58% and 70%. Only class A has unutilised losses of more than 80%. In Figure 10b, we can see a bigger gap between unutilised pipe losses in basements. In pipes with thermal insulation, the unutilised pipe losses in classes D, E and F are on average 18%, whereas for classes A and C these are over 60%. When the basement is heated, it is more realistic to assume that the basement envelopes are insulated and most of the pipe losses there are not utilised. Unutilised losses in shafts are, in classes E and F, on average 35% and in other classes from 55% to 80%.

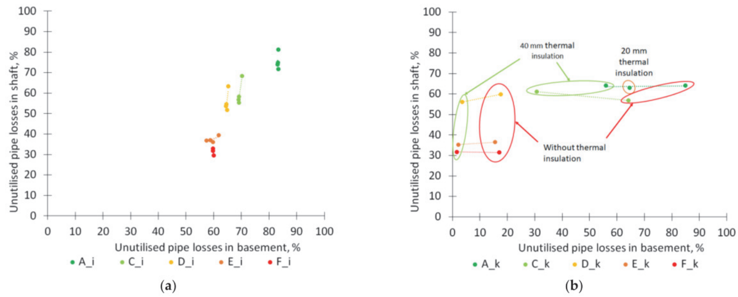

Figure 9. Unutilised pipe losses in basements and in shafts: (**a**) when basement is not heated (i—unheated basement); (**b**) when basement is heated (k—heated basement).

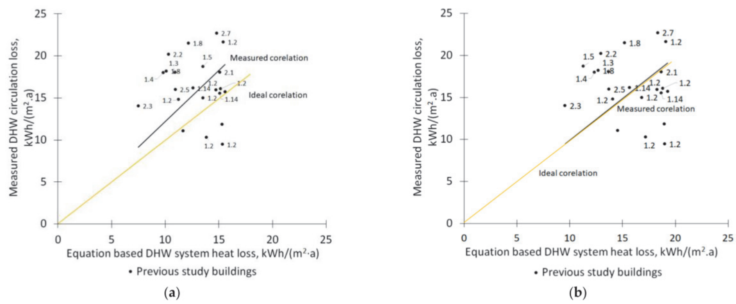

Figure 10. Measured and calculated DHW system pipe losses in buildings: (**a**) calculated as if in all buildings thermal pipe insulation is 40 mm and valves are not insulated; (**b**) calculated as if in all buildings thermal pipe insulation is 20 mm.

When comparing measured and calculated pipe lengths with the gross area equation ($l = 0.1235x - 1.6744$), then the difference between measured and calculated lengths in the basement is (DHW + DHW circulation pipes) 44 m (measured 260 and calculated 216 m) (10.1%) and in shafts using the calculation heating area equation ($l = 0.0538x + 2.7782$) the difference is 24 m (measured 448 m and calculated 472 m) (11.7%).

3.4. Heat Loss from DHW Piping in Earlier Studied Buildings

Based on nZEB case building DHW system heat loss analyses (Figures 7a, 8a and 9a), we compared earlier studied building measured heat losses with calculated values. We calculated all 23 buildings' pipe lengths in basement and in shaft using generated pipe length equations. EPC did not make a difference to DHW pipe heat losses in cases where the basement was not heated. We selected EPC class C for the DHW system heat loss calculations, in the first step with a pipe insulation of 40 mm (without circulation valve insulation) (Figure 10a), the total calculated loss in the basement was (10.5 W/m) 5.6 kWh/(m^2·a) with unutilised losses of 3.8 kWh/(m^2·a) (69% of total); and in shafts (5 W/m) 5.8 kWh/(m^2·a) with unutilised losses of 3.3 kWh/(m^2·a) (57% of total). Total unutilised pipe loss was 7.1 kWh/(m^2·a). In other buildings, the average calculated pipe loss was 12.9 kWh/(m^2·a) (Figure 10a) and average unutilised loss was 67% of this figure. Compared with the average measured loss of 16.3 kWh/(m^2·a) we can calculate a similar loss with a 20 mm thickness of thermal pipe insulation in Figure 10b.

If the average pipe loss in these buildings with 20 mm thermal pipe insulation is good then, building by building, we can see big differences from the measured loss. The mean absolute error from measured values is 4.2 kWh/(m^2·a).

3.5. Generating Heat Loss Equation from DHW Piping

While generating the equation from our nZEB case building, we noticed that, to a certain extent, pipe heat loss and DHW system loss utilisation as an internal heat gain depend on the EPC class and also on how much the DHW system pipes are insulated. Basement heat losses also depend on whether the basement is heated or not. We decided not to include EPC classes D, E and F with heated basements into the generated equation.

Our reference building showed that pipe losses per length were more or less the same across the different EPC classes.

From our research we generated an equation for DHW system heat loss from our case study loss analyses. In Table 6., pipe losses per length are presented with different thicknesses of thermal pipe insulation and also how much the pipe losses are unutilised as internal heat gain.

Table 6. Pipe losses per length with different thicknesses of thermal pipe insulation (qa) and how much of the losses are unutilised as internal heat gain (Qunut.).

	Insulation of Pipes	Basement is Unheated		
Basement losses		$q_{a \cdot \mathrm{basement}}$, W/m	$Q_{unut \cdot\ basement}$, % EPC "A"	$Q_{unut \cdot\ basement}$, % EPC "C"
	40 mm (insulated valves)	8.3	83	70
	40 mm (uninsulated valves)	10.8		
	20 mm	13.6		
		Basement is heated +21 °C		
		$q_{a \cdot \mathrm{basement}}$, W/m	$Q_{unut \cdot\ basement}$, %	
	40 mm (insulated valves)	7.0	56	48
	40 mm (uninsulated valves)	9.2		
	20	11.5		
Shaft losses		$q_{a \cdot \mathrm{shaft}}$, W/m	$Q_{unut \cdot\ shaft}$, %	
	40 mm	5.1	69	59
	20 mm	6.8		
	0 mm	15.5		

From this, we can generate a different heat loss equation for unutilised DHW system heat loss in the basement ($\Phi_{aDHW\ basement}$ Equation (5)) and in shafts ($\Phi_{aDHW\ shaft}$ Equation (6)):

$$\Phi_{aDHW\ basement} = l_{DHW\ cella} \cdot q_{a \cdot basement} \cdot Q_{unut \cdot\ basement} \cdot 8760 \cdot 10^{-3} / A_{heat}, \quad \mathrm{kWh/(m^2 \cdot a)} \quad (5)$$

$$\Phi_{aDHW\ shaft} = l_{DHW\ shaft} \cdot q_{a \cdot shaft} \cdot Q_{unut \cdot shaft} \cdot 8760 \cdot 10^{-3} / A_{heat} \quad \mathrm{kWh/(m^2 \cdot a)} \quad (6)$$

A_{heat} is building heating area (m^2)
l_{DHW} is calculated pipe length (l)
q_a is pipe heat loss per calculated length (W/m)
$Q_{unut \cdot}$ is unutilised pipe loss (%)
8760 is hours per year (h)

Using for our calculations the best equation to find the pipe length in basements (equation with floor gross area) and in shafts (equation with heating area), we then calculated, in all test and reference buildings with thermal pipe insulation of 40 mm (without thermal insulation on circulation pipe valves), the annual heat loss per heated area (basement is unheated). In Figure 10, we can see good correlation with the heating area. Buildings which have a larger heating area have lower pipe losses. The minimum unutilised pipe heat loss in a building is 5.5 kWh/(m^2·a) (total 7.6 kWh/(m^2·a)) even though the heated area is more than twice as large as the second biggest building. From this graph we can say that, for over 5000 m^2 of heated area, the pipe heat losses are the same. In smaller buildings however, there can be unutilised losses of up to 12.1 kWh/(m^2·a).

All buildings calculated average was 8.7 kWh/(m^2·a) and median 8.2 kWh/(m^2·a).

4. Discussion

In existing buildings where circulation losses are not measured separately, it is hard to separate the share of these losses from the entire building's energy use. In a previous study, we also analysed DHW circulation losses. In 23 buildings, the DHW circulation losses were not directly measured but were calculated from measured DHW consumption and the known total energy consumption for DHW. The graph Figure 11. presents all the buildings' DHW circulation heat loss against the heated area. In those buildings, DHW circulation heat loss was 16.3 kWh/(m^2·a) except in one outlier building, where it was extremely high (34 kWh/(m^2·a)). Earlier studies of other buildings' measured DHW system heat loss showed that, in similar buildings, it can vary considerably.

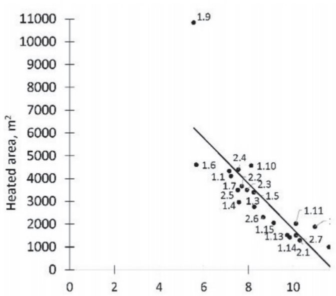

Figure 11. Test and reference building calculated unutilised DHW system pipe heat loss with 40 mm thermal pipe insulation without circulation valve thermal insulation and basement heating (EPC A).

From the Figure, we can see that across the same types of building (code 1.2), the measured DHW system energy loss can be from 9.5 to 34 kWh/(m^2·a) and the calculated loss (with 40 mm pipe insulation) 15.4 kWh/(m^2·a). In all seven of these buildings, the DHW and DHW circulation pipe lengths are very similar. The differences in heat loss came from the quality of the thermal pipe insulation installation work and the thickness of insulation. Basement heat losses in those buildings were also different.

In earlier studies we have noticed, when comparing volume-based measured DHW-calculated energy use with measured entire DHW energy consumption, that losses from pipes were on average 16.3 kWh/(m^2·a) [17–19]. From all the buildings' DHW energy need this was 27–62%, the average from 22 buildings was 44%. Very similar results were found in earlier studies. Bøhm and Danig showed, from the entire DHW heating energy need, a 65% loss [1] and later Bøhm specified it as 23–70% [2]. Similar losses have also been shown by Gassel [3] and Zhang et al. [5]. Horvath et al. [4] showed a slightly lower DHW system heat loss of between 5.7 and 9.9 kWh/(m^2·a). Our calculations showed that 5.5 kWh/(m^2·a) is the minimum loss in apartment buildings.

If DHW system pipe losses are not integrated into energy efficiency calculations we have shown that the predicted energy consumption is lower than the actual measured values taken in use. Furthermore, the expected EPC might be one class higher (C class improved to D class). One of our goals for finding an equation for DHW system pipe lengths was that, in the design phase, we would be able to make accurate predictions of the probable future energy consumption of apartment buildings.

In our research, we analysed different factors such as building volume, heating area, net area, floor gross area, total number of apartments. Our decision was not to analyse as per EN standard (EN 15316-3 [23]) with building lengths and DHW pipe lengths in the basement.

From our analysis, we decided to consider in our future calculation method for assuming DHW and DHW circulation pipe length, that for pipes located in basements, we would use the building gross area and for pipes located in shafts, the building heating area. Our analysis showed that the two parameter model quality is no better than the one parameter model, which is why we decided to only use the one parameter model for the length calculations.

As we had data from DHW system pipe losses from buildings studied earlier, we wanted to see how the calculated length correlated with measured pipe losses. As we had detailed the measured DHW losses in our reference building, we were able to analyse pipe losses in different EPC classes (A, C, D, E and F) with different thickness of thermal pipe insulation and with heated and without heated basements. From these analyses, we have found that in different EPC class buildings, pipe loss per heated area is more or less the same. The difference is in how these losses are utilised as an internal heat gain, and here there is a difference between heated and unheated basements. In an EPC class C building with an unheated basement, we can utilise, in the entire building, ca. 33% of pipe heat losses, but separately basement losses of 30% and shaft losses of 40%. If we focus on 40 mm of pipe insulation then heat loss per pipe length in the basement is 10.5 W/m and in shafts 5.0 W/m. From this we can calculate, for a similar building with calculated pipe length, the entire DHW system pipe losses. With a larger heated area, we have lower heat loss from pipes and our calculation showed in Figure 11 that, in buildings of over 5000 m^2 heated area, the unutilised loss cannot fall below 5.5 kWh/(m^2·a) (total 7.6 kWh/(m^2·a)) with 40 mm of thermal pipe insulation, when the basement is unheated. We have also shown that the maximum unutilised heat loss is 12.1 kWh/(m^2·a) (total 15.7 kWh/(m^2·a)). This shows that in smaller apartment buildings, the same piping heat loss from DHW systems is over 6 kWh/(m^2·a) greater. The EPC class in smaller buildings can be affected by the net DHW system loss of 12.1 kWh/(m^2·a) with a primary energy factor 0.65 (efficient district heating), 8.7 kWh/(m^2·a) (district heating efficiency 0.9) and with factor 1.0 (heating with gas) 12.7 kWh/(m^2·a) (gas boiler efficiency 0.95). To reach current EPC limits we should, in the future, also include in the calculations the DHW unutilised system losses.

Comparing the calculated length in all buildings (test and reference) then, on average, the pipe length in shafts is 0.11 m/m^2 (per heated area) with the Finnish method for calculating heat loss for EPC classes giving 0.2 m/m^2 [32]. According to this regulation, the loss from pipes in heated areas (depending on pipe insulation) is 6 or 10 W/m. Compare this to our calculation, which gave an average of 5 or 7 W/m. The Finnish regulation for calculated length in basements was not simplified. There is, however, a sentence in the regulation which states that pipe length in basements should be measured.

If volume-based DHW energy use by Estonian regulations [33] is 30 kWh/(m^2·a) and calculated unutilised circulation loss is between 5.5 kWh/(m^2·a) and 12.1 kWh/(m^2·a), then circulation loss is between 18% and 40%. This is more than Grasmanis at.al. [15] have found.

Himpe [34] concluded that simplified heat loss calculation methods can be significantly improved when the estimation of two influential parameters, that is the average temperature of the heat conducting medium and the working time of the system, reflects the actual design and operation of the systems. In their suggested equation, there is a simple question regarding the length of DHW and DHW circulation pipes. Our study showed that EN standard equations give us an overly pessimistic pipe length in basements and shafts and also that indoor temperatures in basements vary depending on the basement's thermal envelope properties.

5. Conclusions

Pipe heat losses in low-energy or nZEB apartment buildings can be more than 10% of the entire primary energy consumption. At this point in time, DHW and DHW circulation energy consumption heat losses are based on the volume of water consumption. Most apartment buildings have unheated basements where the main pipelines for DHW and DHW circulation are located.

Our work shows that:

- Pipe length is the most important value to use when assessing pipe heat losses in apartment buildings;
    - Pipe length with EN standard equation is not relevant for Estonian apartment buildings:
        - Length and width of buildings in the Estonian Registry of Buildings database is presented as a maximum and is not useful for nonrectangular shaped buildings;
        - Length according to EN 15316-3 standard for pipe gives over-long pipe lengths compared to Estonian apartment buildings;
    - Using floor gross area for calculating basement pipe length gave an average 14% difference from measured pipe length in all buildings;
    - Using the building heating area for calculating vertical shaft pipe lengths gave an average 28.3% difference from measured pipe length in all buildings;
    - With 40 mm thermal insulation on the pipes, heat losses from pipes in an EPC C class basement were 10.8 W/m and in shafts 5.1 W/m, and with 20 mm thermal insulation heat losses were 13.6 W/m in the basement and 6.5 W/m in the shafts.
- Pipe heat loss calculations in the reference building showed that the difference between thermal insulation levels on pipes did not affect how much heat loss from pipes can be utilised as internal heat gain;
    - For EPC class C buildings without basement heating, utilised pipe heat losses were in total 33%, and separately, in basements 30% and in shafts 40%.
- Heat loss from calculated lengths compared between the different thicknesses of thermal pipe insulation was more or less the same in buildings with different EPC classes and the actual value itself was more or less the same, which enables our equations to be used in all EPC classes of buildings.

Our study gives an alternative method for calculating heat losses from DHW systems in apartment buildings.

Author Contributions: A.H. carried out analyses of the measured data for the thesis. T.K. helped to develop the research principles of the study with the main author. A.M. helped build up the calibration model and T.-M.P. helped with equations. All authors have read and agreed to the published version of the manuscript.

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Improving the indoor climate and energy saving in renovated apartment buildings in Estonia

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Abstract. Energy saving is one of the driving forces in renovation of buildings. Ideally, energy savings should cover the cost of renovation. For purposes of cost efficiency, energy use before and after renovation should be known as accurately as possible. If the energy saving target is too ambitious, energy use after renovation could increase notably and, vice versa, if the target is too low, renovation may not be feasible.

In this study we analyze how well the energy saving targets are achieved in renovated apartment buildings in Estonia. The analysis is based on measurements and simulations of indoor climate and energy use in 20 comprehensively renovated apartment buildings. A professional designer and consultant have made an energy audit and design solution before the renovation. Our task was to check the energy audit and compare target and real energy use.

We found out that in most cases energy auditors have not assessed existing structures and ventilation correctly, and that basic energy audits should be more detailed in order to assess the existing buildings' energy consumption. Energy saving targets after renovation were also overoptimistic. Based on our research the Estonian energy renovation grant scheme was upgraded.

Keywords: energy saving, energy audit, renovation, apartment buildings.

1 Introduction

Energy use in buildings is the largest segment of energy use. Although the requirements for energy use of new buildings have been tightened since the energy crisis in 1970s, the energy use of existing buildings is still high [1] compared to what we expect from today's new buildings and from future near-zero energy buildings. Because the replacement rate of the existing building stock is only some percentages per year, the renovation and improvement of energy performance of existing building stock plays an important role in reaching national energy efficiency targets. Depending on the Member State, only 0.4-1.2% of the building stock is renovated each year [2]. Baek [3] showed that lack of awareness, information, and regulatory system as well economic reasons are the major barriers to improving the energy performance of existing residential buildings. Kuusk [4] showed that the apartment associations' investment capability is not sufficient to achieve the energy efficiency level of new buildings or low-energy buildings and subsides will increase investments of apartment associations into energy efficiency improvements.

Many studies have shown that investments in energy performance and comprehensive renovation of existing apartment buildings would be economically viable in longer terms [5–10]. In reality the cost effectiveness depends on how accurately energy saving targets are achieved. Branco et al. [11] showed after a 3-year experimental study that the real annual energy use was 268.3 kWh/m^2 instead of initially predicted 44.4 kWh/m^2 because the theoretical value does not take into account real conditions. Cali et al. [12] evaluated refurbished German dwellings and showed the average energy performance gap variation between 41% to 117% during different years. Majcen [13] analyzed Dutch social housing stock, renovated between 2010 and 2013, and showed that the energy performance gap is lower in more efficient buildings.

In Estonia the majority of the multistore apartment buildings were built during the period from 1960 to 1990, employing similar construction solutions. The priority of this dwelling programme was to build as quickly as possible and energy efficiency was not considered important during that period. Systematic renovation of residential buildings started in 2000s when also the energy performance regulation entered into force. During the period between 2010 and 2014 a total of 663 apartment buildings were renovated under the renovation grant scheme and supported by Ministry of Economic Affairs and Communications fund Kredex. To receive finance support, 3 levels for thermal energy saving were established (30, 40 and 50%). The government grant was 15, 25, or 35% from total cost, respectively. The total investment of apartment associations and the grant scheme amounted to 151 million euros, of which 38 million was in form of grants. In this study we analyze how the indoor climate and energy saving improved in these renovated apartment buildings.

2 Methods

In our case study we had analyzed 20 apartment building with different building types (CE: Prefabricated concrete element, AAC: lightweight concrete, Brick) and renovation solutions (Table 1). The heating system was renovated in all buildings. Renovation of ventilation system varied from system cleaning to installing fresh air inlets (FAI) or installation of a completely new ventilation system (SERU: supply-exhaust room units, EXHP: exhaust ventilation with heat pump heat recovery, AHU: central air handling unit).

Energy consumption data before and after reconstruction was collected by building managers. Energy balance contains use of electricity (including household electricity), heating and domestic hot water (DHW). We checked all energy audits made by consultants using the same method. In addition to the original energy balance, we separated energy for production and circulation of DHW. Because apartment buildings with district heating have only one heating meter that measures energy for room heating and DHW we calculated energy for DHW based on water use (DHW is 45% from whole water usage) and temperature rise (50 °C). This calculation based on measured values

[16]. The circulation heat loss is calculated based on difference of theoretical and measured energy use for DHW during summer months.
We measured indoor temperature, ventilation airflow and CO_2 concentration in all buildings in order to compare thermal energy use with the indoor climate situation. The table (see **Table 1**) shows building codes involved in government financial support. 15 means 15% financial support and 30% heating energy saving, 25 means 25% support and 40% heating energy saving and 35 means 35% support and 50% heating energy saving.

Table 1. Studied renovated buildings.

Code	Building type	Constr. year	Heating area (m^2)	Floors	Renovation works and additional insulation			
					Ex. wall	Roof	Windows	Vent
15.1	Brick	1970	3163	5	10cm			
15.2	CE	1973	1718	4	15-20cm		Partly	FAI
15.3	CE	1969	2959	5		23cm	-	
15.4	ACC	1984	1737	3	15cm	20cm	Partly	FAI
15.5	CE	1976	3075	5				
25.1	ACC	1975	777	2	15cm	25cm		FAI
25.2	Brick	1982	2623	5	15cmm	25cm		FAI
25.3	CE	1988	3519	5	15cm	20cm	Partly	FAI
25.4	Brick	1975	550	2	15cmm	25cm	Partly	
25.5	Brick	1971	1903	2	10-15cm	30cm	Partly	FAI
35.1	Brick	1978	1064	3	12cm	13cm	Partly	SERU
35.2	ACC	1979	1285	3	15cm	13cm	Partly	SERU
35.3	Brick/ACC	1982	1527	4	15cm	25cm	Partly	EXHP
35.4	Brick/ACC	1979	1041	3	15cm	23cm	Partly	EXHP
35.5	Brick/ACC	1979	1162	3	10cm	23cm	Partly	EXHP
35.6	Brick	1991	1151	5	15cm	8cm	Partly	EXHP
35.7	Brick/ACC	1972	1026	3	5-15cm	23cm	Partly	SERU
35.8	CE	1970	5030	9	15cm	23cm	Partly	EXHP
35.9	ACC	1981	940	2	15-20cm	20cm	Partly	SERU
35.10	Brick	1971	561	2	15cm	10cm		AHU

3 Results

Our check showed that there are various methodological errors in existing energy audits. That's why we decided to make new calculations for all existing buildings based on measured energy data by using the same methodology. Fig. 1 (left) shows the adjusted energy consumption in the pre-renovation situation. The graph shows energy consumption for heating, DHW, DHW circulation and electrical lighting and equipment. A comparison of adjusted energy consumption with auditor's values shows that the adjusted values are of the same magnitude or lower. Higher energy consumption in the pre-renovation situation (calculated by the auditor) also allows improved energy savings (Fig. 2). The main reasons why the energy consumption calculated by the auditor differed from our adjusted values are:

- Energy use that depends on outdoor temperature (heating, ventilation) must be based on the reference year. However, in some energy audits also the consumption of DHW was based on the reference year, although it does not depend on outdoor temperature.
- In some energy audits, the electricity consumption on heating, DHW, lighting and appliances was wrongly allocated. In some cases, the consumptions was calculated twice.
- Some audits had no electricity consumption at all and the auditor had for analysis used the estimated amount of energy for electricity.

When comparing the energy consumption before and after renovation (Fig. 1), we see that average energy saving in buildings is 37%. Energy consumption after renovation from total energy was in first group (energy saving target 30%, financial support 15%) in average 22%, in the second group it was 44 % (energy saving target 40%, financial support 25%), and in the last group it was 40% (energy saving target 50%, financial support 35%). When we compare total energy consumption after renovation the best results were shown by comprehensively renovated buildings with 35% financial support. In these buildings average delivered energy consumption per heated area is 119 kWh/(m^2· a). After renovation, in the buildings with 15% financial support it is in average 165 kWh/(m^2·a) which is more than 25% bigger than in comprehensively renovated buildings.

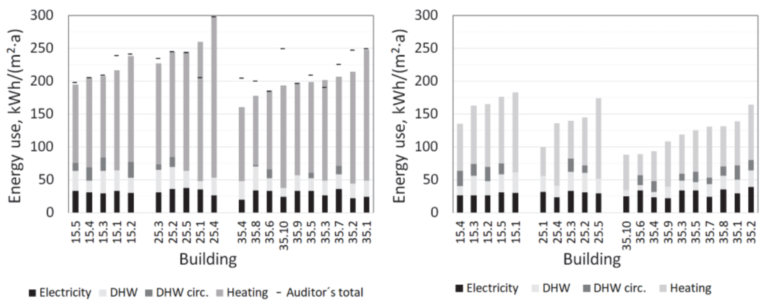

Fig. 1. Energy use before (left) and after (right).

The renovation grant scheme for buildings depends directly on energy savings achieved (heating, DHW). When comparing energy saving for room heating, DHW and DHW circulation, only half of the buildings fulfil the support criterion (Fig. 2). The reason why many buildings fail to meet the criterion is due to the differences in the calculation of energy saving. Energy use for 9 buildings (1.3; 1.5; 1.2; 2.2; 2.4; 3.8; 3.3; 3.7 and 3.10) was calculated correctly as required for the grant.

For the rest of the buildings, savings are calculated only on the heat energy used for space heating. For buildings where thermal heat consumption was calculated solely on the basis of thermal energy required for heating and ventilation air heating, the achievable energy savings (round dots) is below the level of thermal energy required under the financing requirements of the grant (Fig. 2).

In Fig.2, the round dots indicate the energy saving projected by the auditor and square dots indicate real savings. One of the reasons why the target savings were not achieved is related to errors in the calculation of thermal energy use before the renovation.

Fig. 2. Target and measured energy save compared with financial support target level (line).

Another reason why the target and real energy savings vary may be due to the difference between the calculated and actual temperature and different ventilation airflow. When analyzing indoor air temperature and ventilated airflow after renovation, we can see that they do not correlate with achievable energy savings (Fig. 3). Most buildings have higher temperatures than in the calculations and airflow is in average twice lower than the required level (0.35 $l/(s \cdot m^2)$). Only some buildings (35.2, 35.3, and 35.4) where indoor air temperature is near 22 degrees and airflow per heated area is 0.2 $l/s \cdot m^2$ can reach the target energy saving with energy efficiency by the fifth energy saving criterion. When we compare the target and real energy savings of various buildings with air temperature and airflow, then in buildings 15.1, 15.5, 25.5, and 35.7 there is no explicit correlation between the measured values. Therefore, we can say that the calculation of the thermal energy savings made by the auditor of these buildings was too optimistic. Looking at the energy savings achieved and comparing them with the measured airflow and indoor temperatures, we can say that in buildings 25.2, 25.4, 35.3, 35.5, 35.6, 35.7, 35.9, and 35.10 the thermal energy savings were achieved at the expense of indoor climate quality. If the airflow of these buildings is at the required level, achieving energy efficiency would be difficult (Fig. 3 right, Fig. 2). In buildings 35.3 and 35.5 the achievement of energy efficiency may be related to the low efficiency of the exhaust air heat pump and in buildings 35.7 and 35.9 with the low efficiency of space-based ventilation equipment.

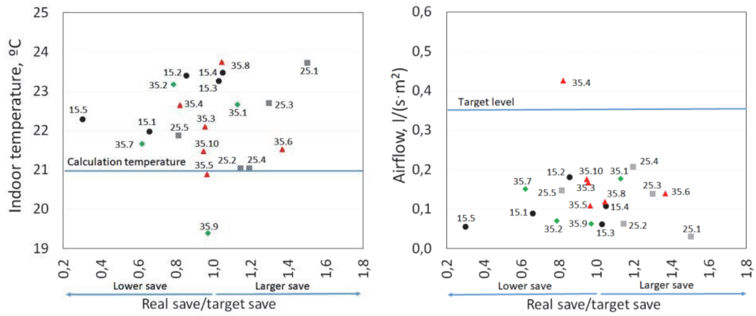

Fig. 3. The comparison of indoor temperature (left) and ventilation airflow with target energy saving for space heating (right).

4 Discussion

Half of the studied buildings achieved the target thermal energy savings. In several buildings, the real energy savings are higher than calculated. This is due to the lower ventilation airflow in buildings. This result is distressful, because energy savings cannot be achieved at the expense of worse indoor climate. The airflow was at the required level only in one building. As a result of our study, we can say that it is not possible to ensure proper airflow with natural ventilation. Of ventilation equipment, also room-based ventilation equipment proved problematic (noise, draft, efficiency, etc.). Therefore we no longer recommend to use these units for renovation of residential buildings in cold climate. That has been shown also by Simson [17].

We found a number of calculation errors in energy audits. Most of the errors were related to the reduction of heat energy use to the reference year and wrong allocation of electricity use for heating, DHW, lighting and appliances. In some cases, the energy auditor had also taken twice into account some energy use. This shows that there is a need for a common method of energy auditing. Better control would help to avoid such mistakes. In the future, there should be trained consultants who could check the most common errors.

There is no requirement to separate hot water circulation from domestic hot water supply in Estonian energy efficiency regulation. Heat losses from hot water circulation was a problem in houses that had a local electric boiler but after renovation are using district heating (35.2; 35.3; 35.4). In those buildings domestic hot water circulation losses after renovation were about 10 kWh/(m^2·a) and DHW and DHW circulation was after renovation that much bigger. This shows us that we also need a calculation method for hot water circulation.

In four apartment buildings (15.1, 15.5, 25.5, and 35.7) where measured indoor temperature was comparable to calculated temperature and real airflow was more than half lower than required, it was clear that energy saving calculations made by auditors contain mistakes. It is likely that auditors showed better energy saving target in order to secure financial support. This problem showed us that thermal energy saving is not a very good base point for financial support and one possibility is to show only target heating energy consumption after renovation which is also connected with Estonian energy labeling calculations.

The second possibility why auditors' energy saving targets were too high may have been that the existing energy auditing form for calculating heat losses is too simplified. Current form enables to take into account thermal conductivity heat losses through envelopes and envelop junctions. Comparing renovated buildings' energy consumption we can also analyse other parameters which should be differently taken into account [15]. This requires updating the energy auditing methodology.

A comparison of thermal energy efficiency levels between different renovation packages shows that there is almost statistical significance (p=0.07) between buildings with minor renovation (target level 30% and 15% financial support) and others. This shows that minor renovation do not guarantee energy savings and it would not be feasible for the state to support it. The importance to comprehensive renovation was showed also by Kuusk [4] and Majcen [13].

5 Conclusion

The energy saving target was achieved only in 40% of buildings with minor renovations (heat saving target: 30%), 40% in buildings with average renovations (heat saving target: 40%) and 50% in building with comprehensive energy renovation (heat saving target: 50%), all together in 11 buildings.

In the course of the study we found mistakes in calculated energy consumption by auditors. There were problems in analyzing existing energy consumption data. In the future it is important to improve control to avoid such mistakes. For this we should in addition to supplementary training of auditors we also need to train consultants to detect possible mistakes in audits. This requires updating the existing energy auditing form and methodology. The majority of studied buildings had problems with ventilation, indicating that energy saving comes partly at the expense of quality of indoor climate. Therefore, it is important to find better ventilation systems that guarantee required airflow since analysed systems mostly did not enable it.

From knowledge collected from this research it is important to ensure that in the future the renovation grant scheme is no longer linked to the energy saving target but with the final energy use that is also linked with Estonian energy label calculations.

Based on our research the Estonian energy renovation grant scheme was upgraded.

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University of Applied Sciences Tallinn	2007	Civil Engineering
Haapsalu Wiedeman Gymnasium	2003	Secondary education
Haapsalu Wiedeman Gymnasium	2000	Lower secondary education
Palivere Primary School	(1991–1999)	Lower secondary education

Language competence

Language	Level
Estonian	Native language
English	Average
German	Basic

Professional employment

Period	Organisation	Position
2020 − ...	University of Applied Sciences Tallinn	Leading Lecturer
2018 −...	Tallinn University of Technology	Expert
2012 − 2020	University of Applied Sciences Tallinn	Lecturer
2008 − 2012	University of Applied Sciences Tallinn	Teaching Assistant
2006 − 2007	University of Applied Sciences Tallinn	Project coordinator
2005 − 2006	Structural design office	Engineer
2004 − 2005	Engineering consulting office	Technician

Elulookirjeldus

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Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2011	Küte ja ventilatsioon, magister
Tallinna Tehnikakõrgkool	2007	Hoonete ehitus, rakenduskõrgharidus
Haapsalu Wiedemani Gümnaasium	2003	Keskharidus
Haapsalu Wiedemani Gümnaasium	2000	Põhiharidus
Palivere Põhikool	(1991–1999)	

Keelteoskus

Keel	Tase
Eesti	Emakeel
Inglise	Kesktase
Saksa	Baastase

Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2020 –	Tallinna Tehnikakõrgkool	Juhtivlektor
2018 –	Tallinna Tehnikaülikool	Ekspert
2012 – 2020	Tallinna Tehnikakõrgkool	Lektor
2008 – 2012	Tallinna Tehnikakõrgkool	Assistent
2006 – 2007	Tallinna Tehnikakõrgkool	Projekti koordinaator
2005 – 2006	Projekteerimisbüroo	Insener
2004 – 2005	Konsultatsiooni büroo	Tehnik

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