THESIS ON CIVIL ENGINEERING F56

Integrated Cost-Optimal Renovation of Apartment Buildings toward Nearly Zero-Energy Buildings

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TUT PRESS

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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 a doctoral or any equivalent academic degree elsewhere.

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Korterelamute kuluoptimaalne tervikrenoveerimine liginullenergiahooneks

KALLE KUUSK

TTÜ KIRJASTUS

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ABSTRACT

This study analyses the energy efficiency, economic viability and investment costs as well as supporting policy of energy renovation of apartment buildings. The real energy use of apartment buildings was measured to determine the current state before renovation. Individual energy saving measures and renovation packages were composed for reference buildings in order to analyse cost-optimal energy efficiency levels and investment costs.

From individual measures, insulating external walls has the highest effect (up to 30%) on the reduction of the primary energy consumption. Combination of individual measures in the energy renovation packages gave the best results. Additional thermal insulation on the building envelope with the replacement of windows and installation of a ventilation system with heat recovery will allow meeting the energy efficiency requirements for new apartment buildings. Depending on the building type, solar collectors for domestic hot water supply are needed in addition to the previous package to reach full technical energy savings potential (up to 70%) and fulfil the criteria of low-energy buildings.

Global cost calculations for different energy performance levels show that the cost-optimum level for the renovation of apartment buildings, depending on the building type, is close to the energy efficiency requirements of a new apartment building or close to the energy efficiency requirements of a low-energy building. Reductions of up to 70% in the energy consumption are both technically feasible and economically reasonable to apartment owners. However, as the total cost needed for cost-optimal renovation is around 200 €/m^2, the high investment cost is a major barrier to deep renovation.

Single energy efficiency measures financed from apartment owners' associations' own funds have not had a significant impact on the buildings energy use. Integrated deep energy renovation is needed in order to achieve the future energy efficiency goals. Although deep renovation would be economically viable in longer terms, the apartment owners' associations' investment capability is not sufficient to achieve the energy efficiency level of new buildings or low-energy buildings. Therefore financial assistance is necessary to execute cost-optimal renovation. Analysis showed that subsidies would increase apartment owners' associations' investments to improve building energy efficiency. Although some financial support is necessary for smaller apartment buildings to execute major renovation, the main target group of subsidies should be apartment buildings that perform renovation on a new building or low energy performance level.
Keywords: renovation; apartment buildings; energy savings; cost effectiveness; renovation cost; energy renovation policy.

Kuusk, K. (2015) **Korterelamute kuluoptimaalne tervikrenoveerimine liginullenergiahooneks.** Doktoritöö, Tallinna Tehnikaülikool.

KOKKUVÕTE

Käesolevas väitekirjas on analüüsitud korterelamute rekonstrueerimise energiatõhusustklasside saavutamist, kuluoptimaalsust, vajalike investeeringute mahtu ja võimaliku toetuse vajalikkust. Määramaks korterelamute praeguse olukorra energiakasutust, analüüsiti renoveerimata tellis- ja suurpaneel korterelamute mõõdetud energiakasutust. Referentshoonete näitel analüüsiti üksikute energiasäästu meetmete ja meetmete kogumite mõju eesmärgiga leida korterelamute rekonstrueerimise kuluoptimaalsuse tasemed ja hinnata selleks vajalike investeeringute mahtu.

Üksikutest energiasäästu meetmetest andis välisseinte soojustamine kõige suurema primaarenergia vajaduse vähenemise (kuni 30%). Kuid parima tulemuse annab siiski üksikute meetmete ühendamine energiasäästu pakettidesse. Hoone välispiirete soojustamine, akende vahetus ja soojustagastusega ventilatsioonisüsteemi rajamine võimaldab saavutada uuele korterelamule seatud energiatõhususe nõuded. Selleks, et saavutada madalenergia tase võib sõltuvalt hoone tüübist olla vajalik ka päikesekollektorite paigaldus sooja tarbevee soojendamiseks. Madalenergia hoone taseme saavutamine võimaldab jõuda tehnilise energiasäästupotentsiaalini (energiatarbe vähenemine kuni 70%).

Erinevate energiatõhususe tasemete kogukulude analüüs näitas, et korterelamute rekonstrueerimise kuluoptimaalne tase on sõltuvalt hoone tüübist, kas uue korterelamu energiatõhususe tase või madalenergia korterelamu energiatõhususe tase. Suurusjärgus 70% energiatarbimisest on võimalik vähendada, nii et korteriomanike 20 aasta kogukulud ei suurene. Kuluoptimaalse rekonstrueerimise kogumaksumus oli suurusjärgus 200 €/m^2, seega on suur investeeringu vajadus üks peamisi takistusi komplektse rekonstrueerimise läbiviimisel.

Korterelamute olemasoleva olukorra energiatarbimise analüüs näitas, et seni poolt läbi viidud väiksemad rekonstrueerimistööd ei ole oluliselt vähendanud korterelamute energiatarbimist. Riiklikult seatud energiasäästu eesmärkide täitmiseks on vajalik korterelamute kompleksne rekonstrueerimine. Kuigi kompleksne rekonstrueerimine oleks pikemas perspektiivis majanduslikult otstarbekas, siis ainult korteriomanike investeerimisvõimekusest ei piisa, et saavutada uue hoone või madalenergiahoone tase. Seetõttu on vajalik korterelamute rekonstrueerimise toetamine. Uuringu tulemused näitasid, et toetuse olemasolu tõstab oluliselt ka korteriomanike investeeringuid energiatõhusus parandamiseks. Toetuse peamiseks sihtrühmadeks peaksid olema korterelamud, mis saavutavad uue hoone või madalenergia taseme.

Märksõnad: korterelamute rekonstrueerimine; energiasääst; kuluoptimaalsus; rekonstrueerimise maksumus; energiarenoveerimise toetamine.

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Kalle Kuusk

May, 2015

CONTENTS

LIST OF PUBLICATIONS

This thesis is based mainly on data presented in the following publications in peer-reviewed journals:

I Kuusk, K., Kalamees, T., Maivel, M. Cost effectiveness of energy performance improvements in Estonian brick apartment buildings. Energy and Buildings 77 (2014) 313–322.

II Kuusk, K., Kalamees, T. The analysis of renovation cost effectiveness of apartment buildings. Building Research & Information 00 (Submitted 30.04.2015).

III Kuusk, K., Kalamees, T., Link, S., Ilomets, S., Mikola, A. Case-study analysis of concrete large-panel apartment building at pre- and post low-budget energy renovation. Journal of Civil Engineering and Management (2014) (Accepted for publication, 08.07.2014).

IV Kuusk, K., Kalamees, T. nZEB retrofit of a concrete large panel apartment building. Energy Procedia (2015) (Accepted for publication, 17.05.2015).

V Kurnitski, J., Kuusk, K., Tark, T., Uutar, A., Kalamees, K., Pikas, E. Energy and investment intensity of integrated renovation and 2030 cost optimal savings. Energy and Buildings 75 (2014) 51–59.

and in the following peer-reviewed conference publication:

VI Kuusk, K., Ilomets, S., Kalamees, K., Tuudak, S., Luman, A. Renovation vs. demolition of an old apartment building: energy use, economic and environmental analysis. NSB 2014 10th Nordic Symposium on Building Physics, 15−19 June 2014, Lund, Sweden.

These publications are referred to in the text by their Roman numbers.

AUTHOR'S CONTRIBUTION TO THE PUBLICATIONS

The author of the thesis is the principal author of publications I, II, III, IV, and VI. In V the author of the thesis is the responsible author of the part on apartment buildings.

In I, analysis of the measured data and the simulations were carried out by author. The research principles of the study were developed together with T. Kalamees. M. Maivel was involved in developing the simulation model of two reference buildings.

In II and IV simulations and calculations were done by author. The research principles of the study were developed in cooperation with the supervisor T. Kalamees. The results were discussed and conclusions were made by the author.

In III and VI, the analysis of the indoor climate and energy simulations, the analysis of renovation costs as well part of the fieldwork were made by author. Other authors were involved in fieldwork and discussion of results.

In V, the indoor climate and energy simulations and the evaluation of the renovation costs of apartment buildings were made by author.

NOTATIONS

Abbreviations

AOA	apartment owners association
AVG	average
BB	brick apartment building
CB	prefabricated concrete large-panel apartment building
COP	coefficient of performance
CO_2	carbon dioxide
DE	delivered energy
DHW	domestic hot water
ECC	energy certification class
EPBD	Energy Performance of Buildings Directive
EU	European Union
EPS	expanded polystyrene
GE-EPS	graphite-enhanced expanded polystyrene
HVAC	heating ventilation and air conditioning
IDA-ICE	IDA Indoor Climate and Energy
NPV	net present value
nZEB	nearly zero-energy building
PE	primary energy
PMV	predicted mean vote
PPD	predicted percentage of dissatisfaction
PV	photovoltaics
PVC	polyvinyl chloride
RH	relative humidity, %
SD	standard deviation
SNiP	Construction Codes and Regulations in Soviet Union (Stroitelnye Normy i Pravila)
TRY	test reference year
VAT	value added tax

Symbols

A	annual loan payment
A_{floor}	area, m^2
C_a	annual cost
C_g	global cost
C_i	initial cost
$f_{(pv)}$	present value factor
E	return on investment
e	escalation
E_n	decrease of delivered energy
m	duration in months
MB	initial loan

n	duration in years
q_{50}	air leakage rate
R	market interest rate
R_d	discount rate
R_r	real interest rate
S_i	cost of delivered energy
U	thermal transmittance, $W/(m^2 \cdot K)$
T	payback period
t	temperature, ^oC
Ψ	linear thermal transmittance, $W/(m \cdot K)$

TERMS

- **Cost-effective range**
  Energy performance level that can be achieved by energy-related renovation measures that are still cost effective, i.e. the life-cycle costs incurring are lower than the life-cycle costs of a maintenance renovation of the building. Maintenance renovation: renovation that restores the full functionality of the building but does not aim at improving the energy performance of the building such that the retrofitted building elements have the same life expectancy as the corresponding building elements of the energy-related renovation (the anyway renovation acts as reference for determining the additional costs and savings of the energy-related renovation option).

- **Cost-optimal level**
  The energy performance level that leads to the lowest cost during the estimated economic life cycle, where the lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building concerned, earnings from energy produced) and disposal costs, where applicable. The estimated economic life cycle is determined by each Member State.

- **Current state**
  The state of buildings where some minor energy saving measures have already been taken. In the simulations it was assumed that 2/3 of the windows had been replaced and the building's end walls had been insulated with a 50 mm thermal insulation. The insulation thickness 50 mm was chosen to represent the situation where half of the buildings have 100 mm of additional insulation on end walls.

- **Deep renovation**
  Renovation to energy efficiency level of new buildings or low-energy buildings. Generally this means a minimum of 50% energy savings.

- **Delivered energy, DE**
  Energy, expressed per energy carrier, supplied to the technical building systems through the system boundary, to satisfy the uses taken into account (e.g. heating, cooling, ventilation, domestic hot water, lighting, appliances etc.) or to produce electricity.

- **Energy efficiency measure**
  A change made to a building resulting in a reduction of the building's primary energy need.

- **Energy performance of a building, EP**
  The calculated or measured amount of energy needed to meet the energy demand associated with a 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).

- **Energy renovation package**
  A set of energy efficiency measures and/or measures based on renewable energy sources applied to a building.

- **Global cost**
  The sum of the present value of the initial investment costs plus the sum of running the costs (loan payments, energy) (referred to the starting year).

- **Major renovation, MR**
  The renovation of a building where the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25% of the value of the building (excluding the value of the land upon which the building is situated) or more than 25% of the surface of the building envelope undergoes renovation.

- **Nearly Zero-Energy Building, nZEB**
  A building that has a very high energy performance; the level of performance is defined by each Member State. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

- **Primary energy, PE**
  Energy 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. The Estonian regulation uses the following factors to calculate PE from delivered energy (DE): wood, wood-based fuels, and other biofuels: 0.75; district heating: 0.9; fossil fuels (gas, coal etc.): 1.0; electricity: 2.0.

1 INTRODUCTION

1.1 Background

It is estimated (Economidou et al., 2011) that there is 25 billion m^2 of useful floor space in the EU-27 (EU in 2007), Switzerland and Norway.Among the energy efficiency targets, the existing building stock and its energy performance improvements play a major role, because energy use in buildings has steadily increased and has exceeded the other major sectors: industry and transportation (Perez-Lombard et al., 2008) while the replacement rate of the existing stock is only 1−2% per year. Compared to 1994, energy use in buildings had increased by 2004 by a factor of 1.17, but stayed at about of 37% of the European Union (EU) total final energy consumption during this period (Perez-Lombard et al., 2008). In the last years, energy use in buildings has shown some decrease, although in 2010 it grew again substantially reaching the highest level of the last 20 years with the share of 39.9% (Bertoldi et al., 2012, Figure 1.1 left). In Estonia the share of buildings is significantly higher than the EU average of 50.2% (Figure 1.1 right) although in 2011 and 2012 it was slightly lower, about 48%. The Estonian final energy use was 33.0 TWh/a, total primary energy use 45.5 TWh/a (the share of buildings 55%) and non-renewable primary energy use 35.3 TWh/a (the share of buildings 47%). Energy use of buildings covers all building-related energy uses in residential and service sectors (electricity, fuels and district heating), but energy use in industrial buildings was calculated by sectors.

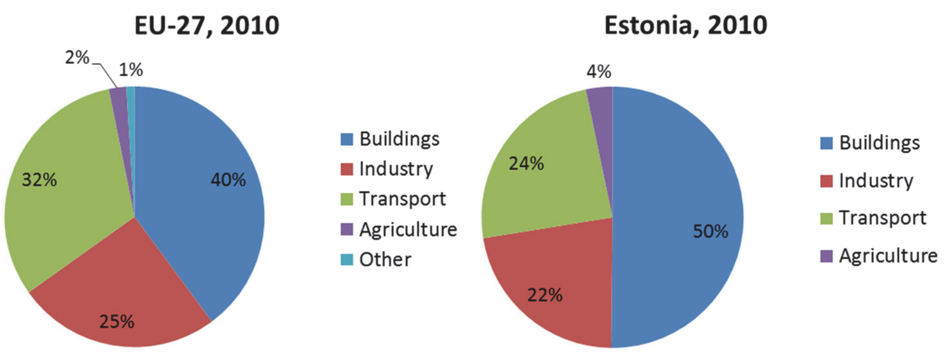


Figure 1.1 Final energy use in 2010 in EU-27 and in Estonia.

Residential buildings, which account for 75% of the total building stock and are estimated to represent roughly 17% of the total primary energy consumption and 25% of the final energy consumption in the EU, have been identified to have the greatest potential for cost-effective savings (EC, 2006). Energy use in buildings varies in Member States while annual energy consumption for residential buildings in the EU is around 200 kWh/m^2 (Lapillonne et al., 2012).

It has been found that countries have very different potentials for energy savings, depending on the size and condition of their housing stock. In total, by the year 2020 88 TWh of heating energy could be saved annually in single family houses and 58 TWh in apartment buildings, totalling 146 TWh of heating energy annually (Tuominen et al., 2012). Energy Roadmap 2050 (2011) states that decarbonization is possible and can be less costly than current policies in the long run. Better energy performance in existing buildings is the key factor in this future task as in terms of energy performance, the environmental impact of new residential buildings is negligible compared to the impact of the existing residential building stock in the EU (Nemry et al., 2010).

Energy Roadmap 2050 (2011) states that an analysis of more ambitious energy efficiency measures and cost-optimal policy is required. Cost-effective energy saving potential in 10 countries was calculated in (Tuominen et al. 2012) concluding that cost-effective saving of 10% of heating energy can be achieved by 2020 and 20% by 2030. Reported minimum and maximum costs of renovations show noteworthy variation between countries, minimum values ranging from 3 to 70 €/m^2 and maximum values from 5 to 200 €/m^2, allowing us to conclude that cost-optimal renovation options depend greatly on local conditions. Energy Roadmap 2050 (2011) concludes that electricity will have to play a much greater role than now (almost doubling its share in final energy demand to 36−39% by 2050), which shows the importance of electricity use also in buildings. Therefore, assessment of energy saving potential in buildings cannot be limited to heating energy, as is often done (Tuominen et al., 2012), but electricity use should be a consistent part of analyses as it affects both energy use and cost effectiveness. Roadmap 2050 (2011) sets out a cost-efficient pathway to reach the target of reducing domestic emissions by 80% by 2050. To get there, Europe's emissions should be 40% below 1990 levels by 2030, and the sector-specific target for residential and service sectors is 37% to 53% CO_2 reduction, which includes efficiency improvements together with increasing the share of low-carbon technologies in electricity mixup to 75−80% in 2030.

Estonia has set the goal of maintaining the final energy consumption at the same level as in 2010 (National Reform Programme ESTONIA 2020). However, this will require a decrease in energy use and an increase in energy efficiency. In order to evaluate the energy efficiency and economic viability of buildings energy renovation, information is needed from single energy renovation measures to large-scale assessment. The influence of reassured renovation measures can be tested by simulation and ideally by case studies.

In Estonia, as in most Eastern European countries, the majority of the apartment buildings were built during the period from 1960 to 1990, and similar construction solutions were used. A survey of apartment buildings in Moscow (Paiho et al., 2013) concluded that the analysis of buildings is simplified by the fact that there are only a few building types. On the other hand, in reality the used materials and their parameters can vary significantly also within the same building series. Nevertheless, as the energy performances of the different building types do not differ significantly, an adequate analysis can be made even by using only one building type. Therefore, Estonia is suitable as a research base because the Estonian apartment building stock contains many buildings of the same type, which allows conclusions to be drawn on the basis of the results from the reference buildings.

1.2 Objective and content of the study

The main objective of the study was to provide economically viable measures for deep renovation of apartment buildings in Estonia.

The specific objectives of this study were the following:

- to provide renovation measures for apartment buildings in order to achieve different energy efficiency levels;
- to determine the cost effectiveness, investment costs and possible need for financial support for deep renovation of apartment buildings;
- to test achievement of energy saving targets in a real renovation case;
- to determine cost-optimal energy savings for apartment buildings by 2030 as a part of Estonian energy roadmap preparation.

The thesis is based on five peer-reviewed journal articles and one conference paper (see page 9).

Cost-effective energy renovation measures for apartment buildings were analysed in articles I (brick buildings) and II (prefabricated concrete large-panel buildings) based on their energy use. Indoor climate and energy simulations were used to assess individual energy saving measures and renovation packages for seven reference buildings selected to represent the dominant types of apartment buildings in Estonia.

The investment cost of renovating apartment buildings and the economic viability of policies supporting renovation were studied in article II. Prefabricated concrete large-panel apartment buildings were used as reference. Results of this study are used in preparing a scheme of financial support for the renovation of apartment buildings in Estonia.

A possible solution for reducing energy consumption of buildings is demolition of an existing building and construction of a new building. Article VI analyses different renovation scenarios for a concrete element building type in order to find out how renovation, renovation with extensions and construction of a new building affect energy efficiency and economic viability.

Two case studies were conducted for the renovation of apartment buildings. The achievement of energy saving targets to the energy-efficiency level of new buildings was tested in a low-budget energy renovation by pre- and post-measurements and simulations in article III. Energy consumption, indoor climate, CO_2 concentration of indoor air, air leakage rate and thermal transmittance of thermal bridges were analysed before and after the renovation.

Another case study on energy renovation to nearly zero-energy building (nZEB) was analysed by simulation in article IV. The study analyses the energy consumption and economic viability with taking into account the expected increase in the rental income after the renovation of the apartment building. It is planned to complete the nZEB renovation of this building during 2016.

Article V focused on energy and investment intensity of integrated renovation variants in order to determine cost-optimal energy savings by 2030 as a part of the preparation of a new Estonian energy roadmap. For selected types of apartment buildings, 3−4 renovation scenarios with different energy efficiency targets were defined.

The newly acquired knowledge discussed in this thesis is related to

- reduction of the energy consumption of apartment buildings by implementing different energy efficiency measures and energy renovation packages;
- cost-effective levels for the renovation of apartment buildings;
- achievement of energy-saving targets in a real energy renovation case;
- cost-optimal energy savings for apartment buildings by 2030.

The practical applications of this thesis are

- energy renovation packages for apartment buildings can be used by consultants in order to achieve a certain Energy Certification Class;
- analysis of achievability and economic viability of different energy efficiency levels was used in the preparation of a new grant scheme for the renovation of apartment buildings in Estonia;
- analysis of cost-optimal energy savings for apartment buildings by 2030 was used in the preparation of a new Estonian energy roadmap.

2 ENERGY PERFORMANCE OF APARTMENT BUILDINGS

2.1 Assessment of energy performance

The Energy Performance of Buildings Directive recast (Directive 2010/31/EU, 2010) sets ambitious goals for the building sector to reduce energy use as well as emissions of greenhouse gases. Energy use of buildings covers all building-related energy uses (Figure 2.1):

- energy for providing a comfortable and healthy indoor climate
    - space heating (heat loss through the building envelope and infiltration);
    - space cooling (if appropriate, usually not topical in Estonian old apartment buildings);
    - heating (and cooling) of ventilation air;
    - air conditioning (if appropriate, usually not topical in Estonian old apartment buildings);
    - artificial lighting of rooms;
    - energy use of building service systems (pumps, fans etc.);
- energy for providing domestic hot water (DHW);
- electricity use of appliances and equipment by inhabitants;
- energy use of other systems and equipment in buildings that is not taken into account in energy performance calculations (elevator, kitchen appliances, heating of outdoor spaces etc.).

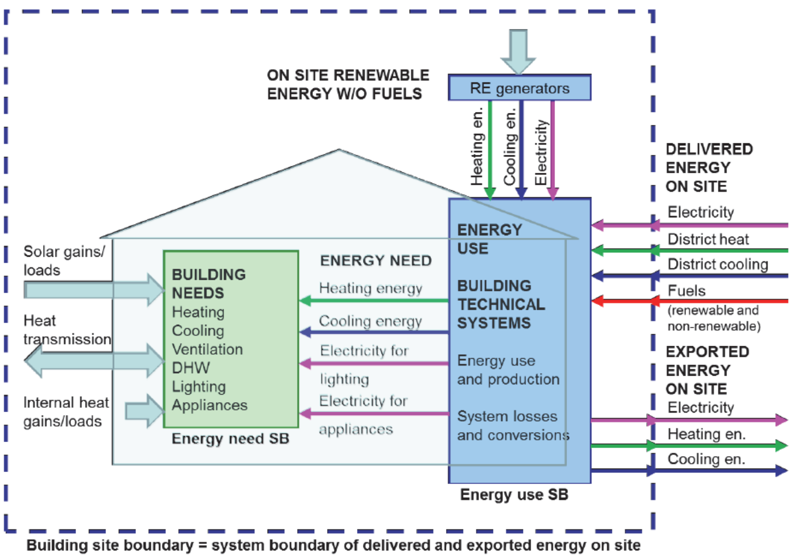


Figure 2.1 Energy boundary of net delivered energy and how it forms from energy need, energy use of technical building systems, on-site renewable energy production, delivered energy and exported energy (Kurnitski et al., 2011).

From country to country different energy usage components are taken into account in the building energy performance calculation procedure. Kurnitski (2008) made an overview of principles of energy performance requirements and calculation methods in EU Member States. Also the calculation principles differ country by country. During recent years some countries have developed their own calculation methods and have moved from simplified methods to detailed whole building primary energy simulation. For example in Finland, the new energy code D3 (2011) is one of the most advanced in the EU including simulation etc. (Kurnitski, 2012a). In most countries the energy performance of buildings is defined as (primary) energy use of the whole building (heating, cooling, ventilation, DHW, lighting, HVAC auxiliary, appliances), not as specific requirements for the building envelope or service systems (Kurnitski et al., 2014).

Because of different methods for assessing energy performance and different climates in EU countries, direct comparison of energy performance requirements is difficult. Figure 2.2 shows the maximum allowed delivered energy for heating, hot water and ventilation systems in six countries for new apartment buildings. Depending on the energy source, requirements are different. In Denmark the requirements are the strictest. For the renovation of apartment buildings requirements vary from the same requirements as set for new buildings like in Sweden (BFS2011) to the lower requirements like in Estonia (Minimum requirements for energy performance of buildings, 2012).

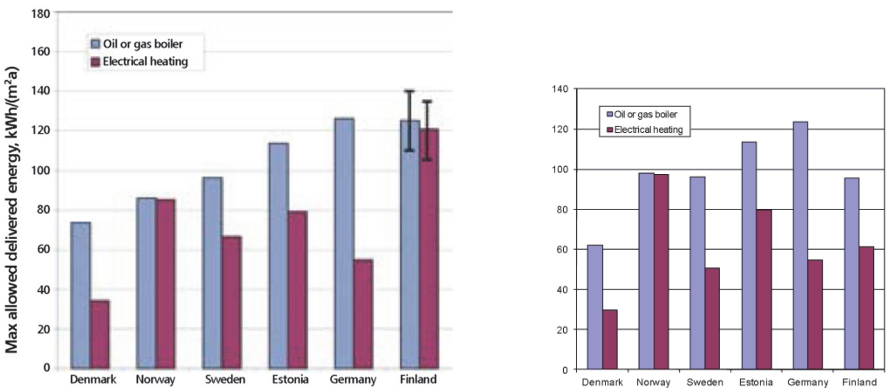


Figure 2.2 Maximum allowed delivered energy for heating, domestic hot water and ventilation systems in each country; degree-day corrected data for 2008, left (Kurnitski, 2008) and 2012, right (Kurnitski, 2012b).

The Energy Performance of Buildings Directive recast (Directive 2010/31/EU, 2010) defines nearly zero-energy building (nZEB) as a building that has a very high energy performance and requires the calculation of the primary energy indicator. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. According to the Directive the Member States shall ensure that by 31 December 2020, all new buildings are nZEB; and after 31 December 2018, new buildings occupied and owned by public authorities are nZEB. Recent studies (D'Agostino, 2015) have shown that Member States need to further strengthen and evaluate their policies and measures in order to successfully stimulate cost-effective deep renovation of existing buildings towards nZEBs and especially in view of building refurbishment, Member States should powerfully develop strategies able both to overcome barriers towards energy efficiency and to guide investment decisions in a forward-looking perspective.

2.2 Assessment of energy performance and indoor climate of apartment buildings in Estonia from the 1930s to today

2.2.1 Energy performance

In Estonia requirements have been set for the thermal transmittance of the building envelope or, more specifically, of the external walls since at least the 1930s. In the building regulations from 1932 and 1937 limits for the thermal transmittance of the external walls of the dwellings can be found: $U \leq 1.0$ kcal/(m^2·h·°C) or 1.17 W/(m^2·K) (RT 59 1932, art. 495) and $U \leq 0.9$ kcal/(m^2·h·°C) or 1.05 W/(m^2·K) (RT 43 – 1937, art. 386).

Thermal calculations made during the Soviet Union era for the construction of apartment buildings were based on SNiP II-3-79 (1979). As energy prices were very low, the thermal transmittance of the building envelope was high. The low quality of the construction works and the variations in the used materials and their parameters were also important factors for the high thermal transmittance of the building envelope. Thermal transmittance values of the external walls of the apartment buildings were the following:

- prefabricated large-panel wall $U \approx 0.8$–1.2 W/(m^2·K);
- brick wall (without insulation) $U \approx 1.6$–2.0 W/(m^2·K);
- brick wall (with 60 mm of insulation) $U \approx 0.8$–1.2 W/(m^2·K);
- autoclaved aerated concrete large-block wall $U \approx 0.6$–0.8 W/(m^2·K).

Typical wood-framed windows consisting of two-panes and tightened to the wall with a tow had $U \approx 2.5$–3.0 W/(m^2·K). Building structures at that time contained significant thermal bridges (Ilomets et al., 2014) (Figures 2.3−2.7), so actually the thermal transmittance of the building envelope as a whole is higher than the thermal transmittance of its single parts.

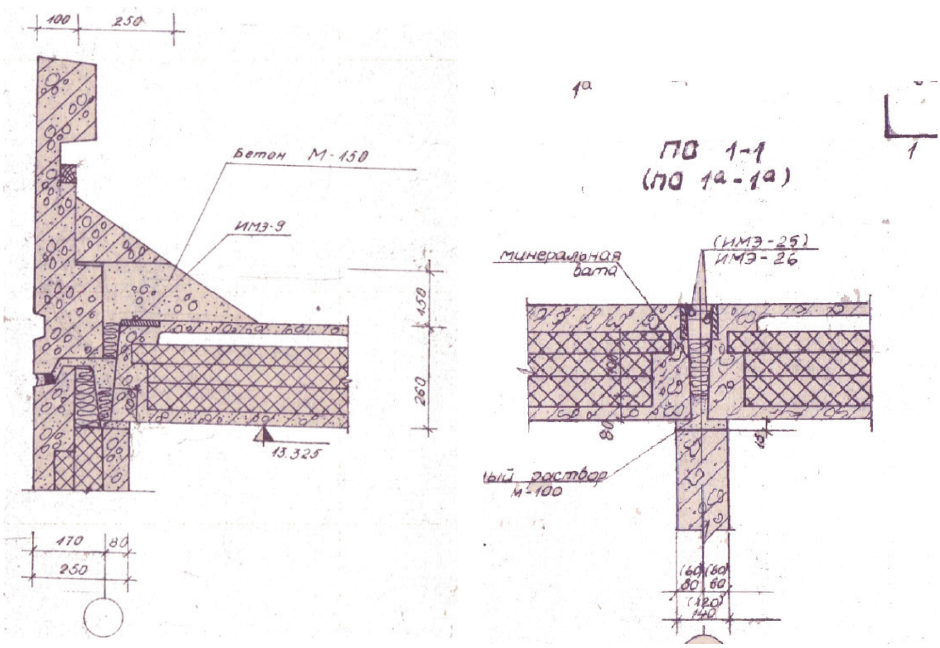


Figure 2.3 Example of the connection of the roof with an exterior wall (left) and a separating wall (right) of concrete large-panel apartment buildings (based on original drawings).

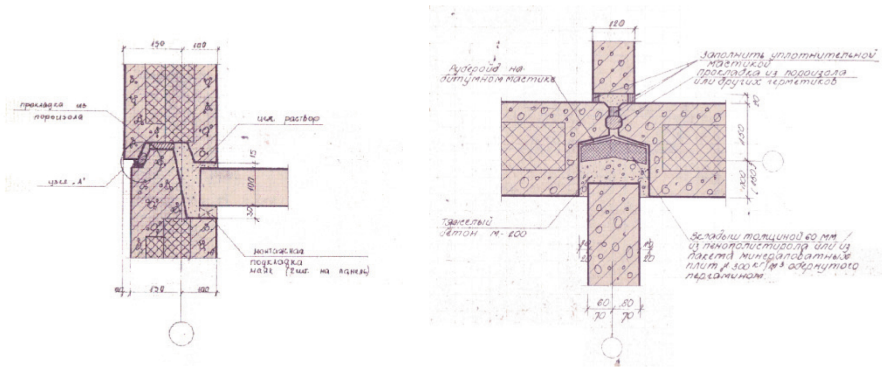


Figure 2.4 Example of the connection of an exterior wall with the floor (left) and a separating wall (right) of concrete large-panel apartment buildings (based on original drawings).

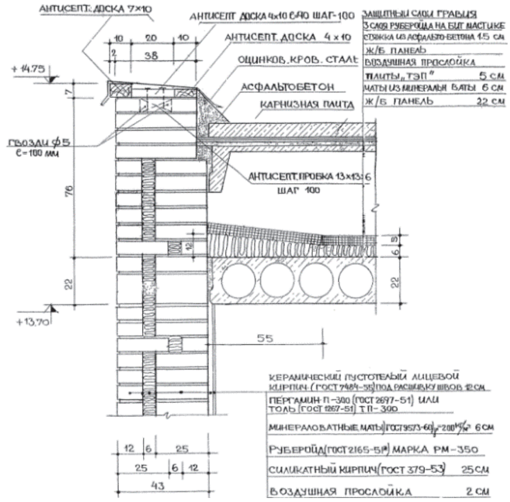


Figure 2.5 Example of the connection of the roof with an exterior wall of brick apartment buildings (based on original drawings).

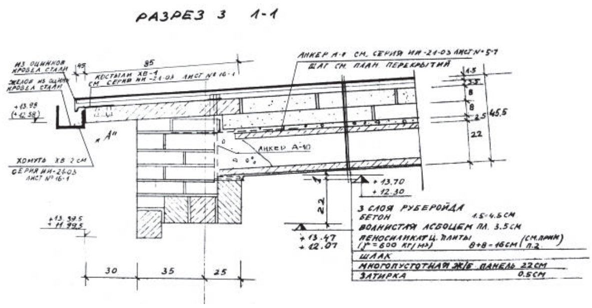


Figure 2.6 Example of the connection of the roof with an exterior wall of brick apartment buildings (based on original drawings).

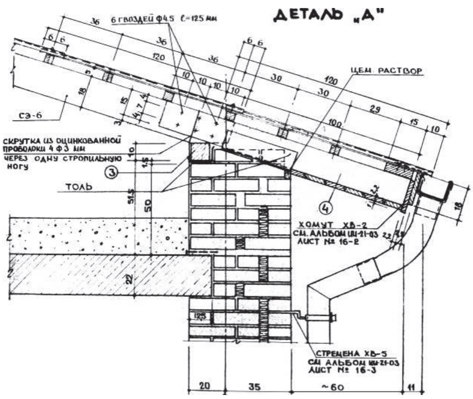


Figure 2.7 Example of the connection of the roof with an exterior wall of brick apartment buildings (based on original drawings).

The Ordinance "Thermal transmittance of the building envelope" (1991) of the Estonian Ministry of Construction enforced regulation of thermal transmittance of exterior walls for dwellings:

- external walls of detached houses 0.33 W/(m^2·K),
- external walls of multi-storey houses 0.45 W/(m^2·K),
- ceilings and roofs of upper floors 0.25 W/(m^2·K).

The Ordinance "Urgent measures to save energy in buildings" of the Estonian Ministry of Construction suggested that until the development of relevant energy efficiency standards

- energy use for space heating and ventilation in new and renovated dwellings, counted per heated area, should be limited as follows:
    - detached houses < 280 kWh/(m^2·a),
    - row houses < 265 kWh/(m^2·a),
    - other dwellings < 190 kWh/(m^2·a);
- technical measures for controlling room temperature and ventilation airflows should be included in design projects for new and renovated buildings.

Requirements for thermal transmittance of the building envelope (at indoor temperature 18ºC) set by the Estonian building code EPN 11.1 "Building envelope. Part 1. General regulations" (1995) and standard EVS 837-1:2003 "Building envelope. Part 1. General regulations" (based mostly on the Finnish building code (C3, 1985)) were used in the design of new buildings and major renovation between 1995 and 2008:

- basement wall 0.5 W/(m^2·K),
- external wall 0.28 W/(m^2·K),
- window 2.1 W/(m^2·K),
- ground floor 0.36 W/(m^2·K),
- roof 0.22 W/(m^2·K).

With the Estonian Government's Ordinance No. 258 "Minimum requirements for energy performance of buildings" (2007) the principle of assessing energy efficiency of buildings was changed drastically. Energy efficiency of the building was assessed as the energy use of the whole building not as the optimization of a single building element.

Since 2007, the energy performance of buildings in Estonia is evaluated according to the use of weighted delivered energy (DE). It is a similar value to primary energy (PE) and can be expressed as PE. PE takes into account the use of the delivered 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 relevant weighting factors. The Estonian regulation uses the following factors to calculate PE from DE:

- wood, wood-based fuels, and other biofuels: 0.75,
- district heating: 0.9,
- fossil fuels (gas, coal etc.): 1.0,
- electricity: 2.0.

Buildings belong to into Estonian Energy Certification Classes (ECC) according to the PE usage, see Table 2.1. The table also shows approximate DE in standard usage if district heating is used as the heat source and space heating need. Values for DE and space heating are given without renewable energy production. In case for ECC B (low-energy building,) solar collectors can be used for DHW and in case of ECC A (nZEB), in addition to solar collectors also photo voltaic (PV) solar panels can be used to produce electricity. In case of on-site renewable energy production, the space heating need may be higher.

Table 2.1 Energy use in different Energy Certification Classes of apartment buildings in Estonia, kWh/(m^2·a).

Energy class	A nZEB	B Low-energy	C New building	D Major renovation	E	F	G
Primary energy	≤ 100	101≤120	121≤150	151≤180	181≤220	221≤280	281≤340
Delivered energy	74	97	130	163	208	274	341
Space heating	14	37	70	103	148	214	281

2.2.2 Indoor climate

Indoor climate in apartment buildings depends on their architecture, building envelope, building service systems and users of the building service systems. The indoor climate in Estonian apartment buildings is mostly influenced by the performance of heating (thermal comfort) and ventilation (indoor air quality) systems.

Older apartment buildings were heated with stoves. Heating systems in apartment buildings built after World War II were based on the local conditions. In rural areas, common heating systems were stoves and building-based central boilers. In towns, the main solution was district heating with direct connection (without heat exchanger). With central boilers and district heating as a heat source, the distribution system was a one-pipe (later also two-pipe) hydronic radiator system (Figure 2.8, left). Piping of the distribution systems was often insufficiently insulated (Figure 2.8, right).

Figure 2.8 Example photo of the one-pipe heating system (left) and partial insulation of the heating system (right) (Kalamees et al., 2009).

Only very old dwellings could be built without a stack for ventilation. In buildings without a central heating system, the stove operated as a part of the ventilation system (extract air) because air is needed for burning wood. Window airing was the prevalent solution for the outdoor air intake in that case. Before 1991 almost all dwellings were built without mechanical ventilation systems (natural ventilation). Even if mechanical exhaust was designed, it was not used in practice, because it made a loud noise while working. Ventilation shafts were used for extract air. Lower apartment buildings (up to 5−6 floors) had a separate ventilation shaft for every apartment. Higher apartment buildings (more than 9 floors) had a separate ventilation shaft for only apartments in two upper floors. Ventilation shafts of apartments in lower floors were connected to the main ventilation shaft (Figure 2.9, left). Main building quality problems of the ventilation shafts were insufficient airtightness and rough inside surface (Figure 2.9, right). Supply air intake was designed from air leakages, mostly through the windows. Fresh air inlets were also sometimes used in apartment buildings (Mikola et al., 2013).

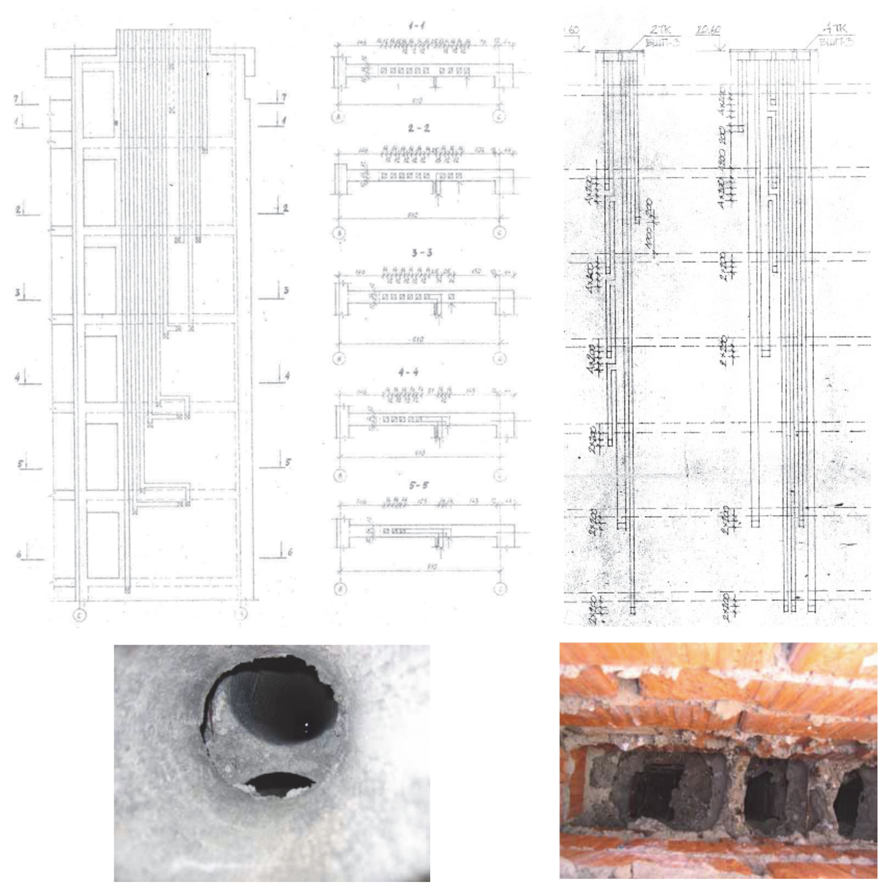


Figure 2.9 Principle schemes of the natural ventilation shafts (above) and example photos of poor building quality of the ventilation shafts (below) (Kalamees et al., 2009; Kalamees et al., 2010).

The ventilation systems of dwellings that were built before 1990 were designed according to SNiP II-3-71 (1972) (later SNiP 2.08.01-85, 1986).

Table 2.2 Ventilation airflows according to SNiP (1972, 1986).

	Supply air		Exhaust air		
Standard	Living room	Bedroom	Kitchen	Bathroom	WC
SNiP II-3-71	1 h^{-1} (earlier)	1 h^{-1} (earlier)	16 l/s	7 l/s	7 l/s
SNiP 2.08.01-85	0.8 l/(s·m^2)	0.8 l/(s·m^2)	(60 m^3/h)	(25 m^3/h)	(25 m^3/h)

At the beginning of the 1990s Finnish designing norms (D2) were used to design residential ventilation systems. The first Estonian standard for residential buildings, EVS 845-2:2004 in 2004, was also composed following Finnish standards. The European standard of indoor environmental input parameters (CR 1752, 1998) was taken into use in 2007. At present CEN/TR 14788 (2006) is also valid, but it is not widely used in practice. The indoor air CO_2 concentration is considered in the standard EN 15251:2007 of the indoor environmental input parameters and designing criteria CR 1752 (1998). The parameters are described in Table 2.3.

Table 2.3 Target values for indoor air quality in Estonia.

Indoor climate category	Expected percentage dissatisfied, %	CO_2 concentration at outdoor air level 350, ppm	Indoor air CO_2 concentration, ppm
I (A)	15	460	810
II (B)	20	660	1010
III (C)	30	1190	1540

Indoor climate category II (normal level of expectation, for new buildings and major renovations) is used in the assessment of new buildings and buildings undergoing major renovation while category III (acceptable, moderate level of expectation, for old buildings) is used in the assessment of the current situation before renovation. The general ventilation airflow in new apartment buildings and buildings undergoing major renovation (indoor climate category II) should be at least 0.42 l/(s·m^2) or 0.6 h^{-1}, and the airflows in living rooms and bedrooms should be at least 1.0 l/(s·m^2) or 7 l/(s·person). The general ventilation airflow in un-renovated apartment buildings (indoor climate category III) should be at least 0.35 l/(s·m2) or 0.5 h^{-1}, and airflows in living rooms and bedrooms should be at least 0.6 l/(s·m^2) or 4 l/(s·person).

Requirements for thermal comfort at legislative level are set in Estonian Government’s Ordinance No. 38. “Requirements for living spaces” (RT I 1999, 9, 38) and in standard EN 15251 (2007) (National appendix). The minimum temperature 18 ºC, set in Estonian Government’s Ordinance No. 38. is too low as inhabitants' expectancy is somewhere from 20 to 22 °C. Usually EVS 839 (2003) and EN 15251 (2007) (National appendix) have been used as reference in the assessment of indoor thermal comfort in apartment buildings in Estonia.

2.3 Energy use of apartment buildings

Apartment buildings in Northern Europe consume approximately 90–170 kWh/(m^2·a) energy for heating (Balaras et al., 2005; Engvall et al., 2014; Paiho et al., 2015).

Preliminary studies conducted in Estonia have shown that the total heat consumption for typical apartment buildings prior to retrofit was between 170 and 280 kWh/(m^2·a) (Martinot, 1997; Kõiv and Toode, 2001; Sasi and Hääl, 2002). These values are in the similar range as the results from other Eastern European countries (Matrosov, 2000; Juodis et al., 2003; Zavadskas et al., 2008; Blumberga et al., 2012; Paiho et al., 2012; Bumelytė and Galinienė, 2013).

The current high energy consumption numbers indicate that there is a large potential for energy savings and the residential sector has the biggest potential for cost-effective savings (EC, 2006). At the country level, the potential for energy savings is different because of the different size and condition of the building stock. For example, a study conducted in Germany (Galvin and Sunikka-Blank, 2013) showed that the total saving potential of renovating residential buildings to EnEV (2009) standard is 33% and the economically viable potential of renovation is around 25%. At the European level, over 40% of the energy savings could be obtained by the residential building stock applying a "standard" renovation and in some countries up to 86% applying an "advanced" renovation (Ballarini et al., 2014). To reduce the energy consumption of buildings, the European Commission has put forward an Energy Performance of Buildings Directive (Directive 2010/31/EU, 2010) which, among other items, states that under major renovations the energy performance of the building or the renovated part thereof is upgraded in order to meet minimum energy performance requirements in so far as this is technically, functionally and economically feasible. Studies (Uihlein and Eder, 2010) have also shown that it is reasonable to ensure that at refurbishment in any case the best energy efficiency level possible is installed, not only for major renovations, but also for individual building elements. This is even more important as the residential building stock shows high inertia due to the low stock turnover compared to other consumer goods such as household appliances or cars. One of the main priorities for renovation measures for apartment owners is a short payback period (Medineckienė and Björk, 2011), therefore it is difficult for apartment owners to make a decision for deep integrated renovation. Tuominen et al. (2012) studied nine EU countries and reported that common renovation barriers to the renovation are the low priority for energy efficiency improvements among the consumers and insufficient funding. These are major obstacles to achieving the maximum energy savings possible in retrofitting as the extent and selection of retrofitting measures depend mainly on the choices of inhabitants.

2.4 Indoor climate and energy renovation measures

One of the first steps to raise energy efficiency was measuring the consumption of energy. For example, in the former Soviet Union the DHW consumption in residential buildings was approximately 95 l/d per person (Borodkin and Dvoretskov, 1973). With the consumption metering in apartments and payment by real consumption, DHW consumption in Estonian apartment buildings decreased more than 3 times (Toode and Kõiv, 2005). Use of solar collectors for DHW and heat recovery from wastewater (Frijns et al., 2013; Cipolla and Maglionico, 2014) could be the next steps in the energy conservation of DWH. A large-scale energy-efficiency measure was the replacement or modernization of old heat substations. For example, during 2000 in Kaunas, 500 of 4000 heat substations in buildings were modernized (inefficient jet pumps at the input of heating systems were replaced by electric pumps, highly efficient compact heat exchangers and automatic regulation). This made it possible to regulate heat for space heating and hot water supply by lowering temperature during the night-time (Klevas and Zinevicius, 2000). Thermostatic valves have brought savings of up to 10% in the energy consumption (Monetti et al., 2015).

After renovation measures with lower cost, renovation measures with higher cost were executed (insulation of external walls, replacement of windows etc.). Krajčík and Petráš (2009) showed that for a panel apartment building in Slovakia the energy saving potential of mainly thermal insulation of building constructions is enormous: insulation of the roof, external walls and technical floor ceiling can save 37% energy. Energy-efficient renovation of Moscow apartment buildings and residential districts using different district modernization scenarios could give considerable energy savings: up to 34% of the electricity demand and up to 72% of the heating demand (Paiho et al., 2013). For Finnish apartment building the energy saving was estimated to be between 46% and 56% with exterior insulation of outside walls, renewal of windows, balcony doors and front doors, modernization of the district heating centre and the heat supply system, and installation of mechanical supply and exhaust ventilation systems with heat recovery in all apartments (Holopainen et al., 2007).

Renovation measures must also be cost effective. Nemry et al. (2010) modelled the building stock for the EU-25 and reported that additional roof and façade insulation as well as sealing of leakages are cost effective in houses while sealing of leakages appears to be the only cost-effective measure in multi-family and high-rise buildings. Verbeeck and Hens (2005) reported economically feasible hierarchy of energy-saving measures, based on five reference buildings in Belgium as follows: insulation of the roof; insulation of the floor, if easily accessible; new windows; more energy-efficient heating system and use of renewable energy systems. These measures are generally in line with those used in the current study with the exception of heat recovery ventilation, which is indispensable in a colder climate. A mechanical ventilation system is important in order not to compromise indoor climate and also for increased electricity usage.

In many cases existing apartment buildings are insufficiently heated and ventilated. This resulted in bad indoor climate and high indoor humidity loads (Kalamees et al., 2011a). Krajčík et al. (2010) showed that in old apartment buildings in addition to reducing energy consumption and saving money, also improvement of the indoor environment can be a strong motivation for renovation. Pustayová and Petráš (2013) noted that after the refurbishment of six blocks of residential buildings in Slovakia the difference between the thermal environment of the building before and after refurbishment can be obvious. Nevertheless, if energy reconstruction does not consider indoor environmental quality, it can adversely affect the indoor environment of the apartments (Földváry, 2014). Therefore it is extremely important that together with the improvement of energy performance also indoor climate (thermal comfort and indoor air quality) is under consideration during the design and realization of the renovation solution.

The design of renovation raises the question of the extent and economic viability of renovation. Frequent discussions also address the demolition of an existing building and the construction of a new building. Gaspar and Santos (2015) compared the two design strategies and three “scenarios”: (a) the original construction, (b) demolition of the original construction and building a new house and (c) partial demolition of the original construction and a major refurbishment operation. They concluded that refurbishment was a more sustainable strategy than new construction as it represented less matter and embodied energy consumption and less demolition waste.

Dutch experience shows that the transformation of the existing housing stock is a much more environmentally efficient way to achieve the same result than demolition and rebuilding (Itard and Klunder, 2007). Power (2008, 2010) argues that large-scale and accelerated demolition would neither help with meeting energy and climate change targets, nor would it address social needs. Thomsen and Van Der Flier (2009) concluded their research stating that, from a sustainable perspective, life cycle extension appears preferable instead of demolition followed by replacement with a new construction.

In Estonia where apartments are mainly owned and not rented, demolition is particularly difficult. The condition of the existing building structures cannot be the reason for demolition or for low renovation volumes. Results of research covering the current technical condition of Estonian old concrete-element housing stock refer to a satisfactory condition in terms of load-bearing but to insufficient energy performance, indoor climate and hygrothermal performance of the building envelope (Kalamees, 2011b). Nevertheless, the agenda of Tallinn Vision Council contains a target to demolish 103 of the oldest prefabricated concrete large-panel apartment buildings in Tallinn (Sarv, 2013). The concept targeted to demolishing existing buildings introduces new economic and environmental challenges. Kährik and Tammaru (2010) showed that prefabricated panel housing areas have maintained a relatively good image and social mix to the present day and that there are no straightforward signs of their socio-economic downgrading or becoming ethnic minority ghettos. Therefore there is no need to demolish buildings also for socio-urban reasons.

2.5 Energy renovation policy measures

Retrofitting existing buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions (Ma et al., 2012). Nevertheless, for the final users of apartments deep renovation is expensive and has a relatively long payback period (especially for older inhabitants). If the building is originally underheated and underventilated, the improvement of indoor climate needs energy that may be surprising for inhabitants. Often inhabitants have difficulties to understand and pay for a better indoor climate.

Despite the large energy saving potential, earlier studies (Wesselink et al., 2010) have found that the European Union 2020 energy saving target will not be achieved. The same study concluded that closing the gap between planned targets and realized energy savings requires a threefold increase in policy impact compared to energy savings policies adopted since the 2006 Energy Efficiency Action Plan. Galvin and Sunikka-Blank (2013) showed that policy-makers should emphasize also other reasons than only reduction of CO_2 emissions and consider a more systematic approach to inhabitants' behaviour change in order to promote renovation to economically viable levels. Joelsson and Gustavsson (2008) found that when choosing an energy-renovation measure, the house owners give higher priority to economic aspects than to environmental ones. This indicates that the use of economic instruments would be an efficient way to promote energy-renovation measures that are in line with the future environmental goals. A study conducted in Wales (Jones et al., 2013) concluded that the cost of deep integrated renovation is a major barrier to large-scale renovation of existing buildings. Tuominen et al. (2012) studied nine EU countries and reported that a common renovation barrier is the low priority for energy efficiency improvements among the consumers and insufficient funding.

One of the common public policy measures to overcome renovation barriers has been partial public funding of energy efficiency retrofits. The lack of money and the low investment capacity are particularly serious problems in the owner-occupied sector (Meijer et al., 2009). Setting up the correct requirements for the energy-renovation measures is essential and regulations must be flexible and consider local conditions as a ''one size fits all'' set of regulations would often be unjustified (Brecha et al., 2011). Galvin (2014) stated that whenever policy-makers set mandatory standards for upgrades, this often entails people paying large sums of money and therefore policy-makers need to be very sure they are doing these residents a good turn and not forcing them to pay for aims and goals these residents might not even share. Weiss et al. (2012) concluded that different support programmes with different goals are needed: one funding programme for building owners willing to invest to a higher levels of energy efficiency and another programme, which considers also social criteria, for energy-renovation measures meeting lower standards.

In Estonia, the common practice of managing an apartment building is the apartment owners' association (AOA), which is a non-profit association established by apartment owners for the purpose of shared management of the legal shares of the buildings and representation of the shared interests of its members. During 2009–2010, AOAs could apply for a renovation loan without a grant that provided a more favourable interest rate than a commercial loan. During 2010–2014 over 600 apartment buildings were renovated in Estonia with the support scheme of the Fund KredEx financed from the CO_2 emissions trading and governmental budget. The amount of the grant was 15%, 25% or 35% of the total project cost depending on the energy efficiency level to be achieved. The new grant scheme was under development during 2014. The strategy for supporting policy, its economic viability and investment cost of energy renovation of apartment buildings require thorough analysis before introducing the grant scheme.

2.6 Assessment of the energy-saving potential of dwellings

In recent years the research on possible energy consumption reduction and/or associated CO_2 emissions in the building stocks has been growing. Mata et al.

(2013) showed that depending on the energy saving measure the potential to reduce the final energy demand of the Swedish residential sector is 53%. The measures that provide the greatest savings are those that involve heat recovery systems and reduction of the indoor temperature, giving energy savings of 22% and 14%, respectively. Upgrading the thermal transmittance of the building envelope and windows would each provide annual energy savings of 7%. A study conducted in Finland (Tuominen et al., 2013) showed that the investments to energy-efficient buildings are an economically sound and effective way to save energy. The required investments carry manageable costs. A rather modest increase resulting in a few percent rise in the annual construction and renovation investments can decrease the total primary energy consumption 3.8–5.3% by 2020 and 4.7–6.8% by 2050 compared to the business as usual scenario. Kragh and Wittchen (2014) composed average design building models for the Danish residential building stock and showed that the suggested typology and the corresponding space heating balance model are suitable for making strategic political scenario analyses of how to plan the work of coming years concerning upgrading the energy performance of the building stock in the most suitable and efficient way. Blumberga et al. (2014) validated a system dynamics model by a case study using historical data from a subsidy scheme and accompanying policy measures and showed that Latvian national energy efficiency goals cannot be met by 2016 and the absence of major consumer-oriented policy tools will slow down the diffusion process of energy-efficiency projects.

Countries have very different potentials for energy savings, depending on the size and condition of their housing stock (Tuominen et al., 2012). Therefore national assessment is needed in each country with the type and conditions of buildings, national practice, energy sources etc. taken into account.

3 METHODS

3.1 Studied dwellings

The methodology used in this study was oriented to detailed description of renovation alternatives that will most probably be used in the majority of buildings to be renovated in Estonia. This was a somewhat different approach compared to the energy modelling of the building stock, where sufficiently detailed distributions of age and building types play an important role, for example, 300 categories have been used in the modelling of the Swedish building stock (Mata et al., 2013). In the current study, the accuracy of the energy modelling in the building stock was intentionally compromised, so that a very limited number of reference buildings were used considered enough for the estimation of the technical energy saving potential. Major effort was put to detailed energy and cost simulations of such integrated renovation variants that would be directly applicable in practice.

The current study focuses on the energy performance of apartment buildings, as they form the largest part of buildings with controlled indoor climate in Estonia (Table 3.1). There are 264 000 dwellings in Estonia with a total net area of 66 691 $\times 10^3$ m^2, see Figure 3.1. Apartment buildings account for 51% (34 282 $\times 10^3$ m^2) of the total net area of dwellings. The second large group of dwellings is detached houses with 41% (26 447 $\times 10^3$ m^2) of the total net area of dwellings.

Table 3.1 Size and distribution of Estonian buildings with controlled indoor climate (National Register of Construction Works, 2010).

Building type	Floor area, m$^2\times10^3$	Floor area, %
Apartment building	34 282	31
Detached house	26 447	24
Other residential	5 962	5
Industrial (w/o process)	16 658	15
Office buildings	8 269	8
Retail	6 487	6
Educational	4 133	4
Hotels	1 741	2
Hospitals, clinics	1 840	2
Other	4 419	4
Total	**110 242**	**100**

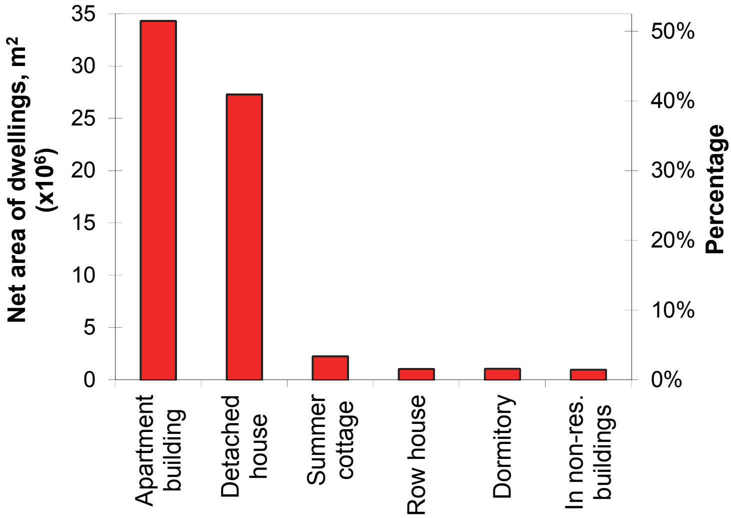


Figure 3.1 Net area of dwellings in Estonia (National Register of Construction Works, 2010).

Brick apartment buildings (BB) and prefabricated concrete large-panels apartment buildings (CB) were selected for the study because these construction materials are dominant in Estonia, see Figure 3.2. This means that the results can be generalized to a large number of apartment buildings.

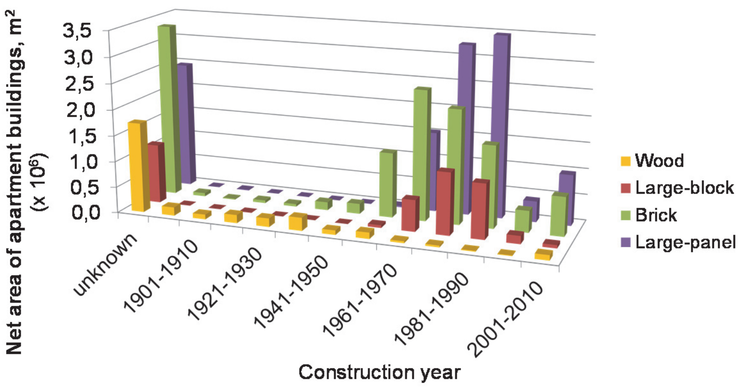


Figure 3.2 Distribution of apartment buildings by the net area and by the construction types in Estonia.

For further investigation of indoor climate and energy performance, 30 brick apartment buildings and 105 apartment buildings made of concrete large panels were randomly selected, based on their age, number of floors, size and structures. The BB, analysed in this study, were constructed between 1940 and 1990 and the CB were constructed between 1962 and 1992. All the buildings studied were in private ownership as is the predominant (≈95%) solution in Estonia.

The studied dwellings had natural passive stack ventilation. In some apartments, kitchens were supplied with a hood. In all of the dwellings, windows could be opened for airing purposes. Buildings were heated mainly with district heating and one-pipe hydronic radiator heating systems as was the typical original solution. As a rule, radiators were not equipped with thermostats; therefore, individual control of the room temperature was impossible. Room temperature for the whole building was regulated in heat substations depending on outdoor temperatures.

Original drawings and energy audits of the buildings were analysed to determine the thermal properties of the building envelope. The thermal transmittances of the building envelope of the BB and CB were in similar range:

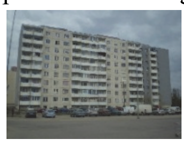
- external walls: $U_{\mathrm{wall}} \approx 0.8–1.2\ \mathrm{W/(m^2 \cdot K)}$;
- roof–ceilings: $U_{\mathrm{roof}} \approx 0.7–1.1\ \mathrm{W/(m^2 \cdot K)}$;
- windows: $U_{\mathrm{window}} \approx 2.9\ \mathrm{W/\ (m^2 \cdot K)}$.

The energy renovation measures that had been taken for CB were analysed more deeply, and buildings with different renovation extent were included into the study. For example, the window replacement rate ranged from 15% to 90% with an average of 65%. In 2/3 of the studied buildings additional insulation had been installed to some parts of the building envelope (either on end walls or on the roof or on end walls and the roof). Only 10% of the buildings had new or renovated heating systems with thermostats, allowing individual control of the room temperature. Ventilation had typically not been renovated at all.

Based on the typology, age, size and number of floors of the building, four building types of BB and three building types of CB were selected as reference buildings from different construction periods (Table 3.2) for indoor climate and energy simulations and economic calculations. To take into account that some minor energy saving measures had already been implemented for the current state of buildings it was assumed that 2/3 of the windows had been replaced ($U_{\mathrm{window\ (glass/frame)}}$ 1.8/2.0 $\mathrm{W/(m^2 \cdot K)}$) and the building end walls had been insulated with a 50 mm thermal insulation ($U_{\mathrm{end\ walls,}}$ 0.45 $\mathrm{W/(m^2 \cdot K)}$). The insulation thickness of 50 mm was chosen to represent the situation where half of the buildings have 100 mm of additional insulation on end walls.

Table 3.2 Characterization of reference buildings “as built” based on calculations from drawings and energy audits.

Brick apartment buildings				
				
	Ref.”A” /AP2	Ref. “B” / AP4	Ref. “C” / AP5	Ref. “D” / AP10
Used in article	I, V	I, V	I, V	I, V
Construction period	<1961	1961–70	1971–80	1981–90
Number of floors	2	4	5	10
Net area, m^2	508	1383	3147	11 374
Heated area, m^2	388	1154	2623	10 781
Compactness, m^2 / m^3, m^{-1}	0.60	0.44	0.47	0.32
Number of apartments	8	32	40	162
Thermal transmittance, W/(m^2·K)				
U_{wall}	1.1	1.0	0.8	0.8
U_{roof}	1.1	1.1	0.9	0.7
U_{window}	2.9/2.0	2.9/2.0	2.9/2.0	2.9/2.0

Prefabricated concrete large-panel apartment buildings				
				
	Ref. “A”	Ref. “B”	Ref. “C”	
Used in article	II, III, VI	II	II	IV
Construction period	<1970	1971–80	1981–90	
Number of floors	5	5	9	5
Net area, m^2	3 519	5 484	10 421	3824
Heated area, m^2	2 968	4 481	8 262	3306
Compactness, m^2 / m^3, m^{-1}	0.35	0.35	0.29	0.33
Number of apartments	60	75	144	80
Thermal transmittance, W/(m^2·K)				
U_{wall}	1.1	1.0	0.8	1.1
U_{roof}	1.1	1.1	0.9	1.0
U_{window}	2.9/2.0	2.9/2.0	2.9/2.0	2.9/2.0

All reference buildings had unheated basements except Ref. “D” of BB, which had no basement.

The reference buildings were selected to represent the whole distribution by age, size and number of floors of the Estonian building stock (Figure 3.3; Figure 3.4).

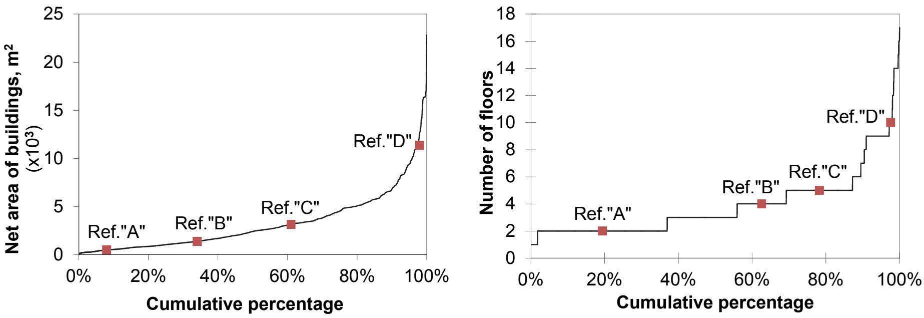


Figure 3.3 Net area (left) and number of floors (right) and percentage from the whole building stock of reference brick apartment buildings.

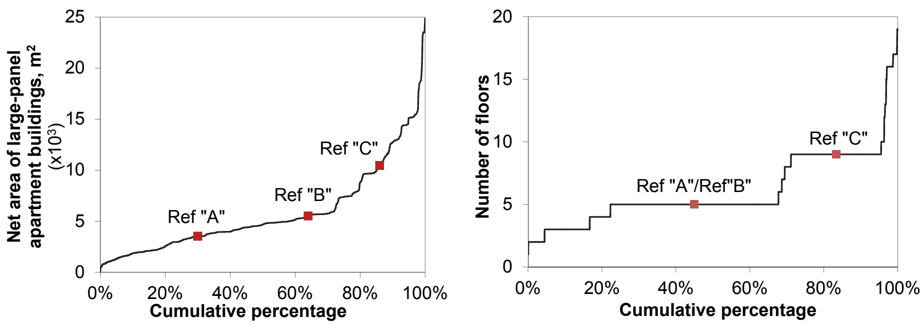


Figure 3.4 Net area (left) and number of floors (right) and percentage from the whole building stock of concrete large-panel apartment buildings.

3.2 Measurements of energy consumption and indoor climate

The actual use of energy was determined for a building as a whole and differences between the apartments were not distinguished. The data on energy use were retrieved from energy companies, apartment owners and energy audits. Our analysis includes measurements over a 3-year period of

- electricity (lighting, appliances and equipment, and in BB sometimes also DHW);
- gas (cooking and in BB sometimes DHW and heating);
- water (cold and hot water together);
- domestic hot water (DHW);
- heating (space heating and heating of ventilation air).

Indoor climate measurements in this study concentrated on comparison of the indoor climate before and after the renovation. Indoor climate was assessed based on measurements of

- temperature and RH indoors with data loggers (Onset Hobo U12-013; measurement range from –30 °C to +70 °C; 5% to 95% RH, accuracy ±0.35 °C; ±2.5% RH) in the bedroom at one-hour measuring intervals;
- indoor CO_2 concentration in the bedrooms at 10-minute measuring intervals during 2 to 3 weeks using Telaire CO_2 monitors with data loggers (Telaire 7001; measurement range 0−4000 ppm, accuracy of ±5% of reading or 50 ppm).
- a questionnaire was conducted for each building to obtain information about the occupants' habits, typical complaints and symptoms related to indoor air quality;
- air leakage of the apartments' fabric was measured using "Minneapolis Blower Door Model 4" equipment with an automated performance testing system (flow range at 50 Pa 25 –7800 m^3/h, accuracy ±3 %) according to standardized fan pressurization method (EN 13829).

Measurements and questionnaires were conducted within the research project "Technical condition and service life of the Estonian brick apartment buildings" (Kalamees et al., 2010) where the author of this thesis was involved in the analysis of energy consumption and the simulation of energy renovation measures. Knowledge gained within this research project about the condition of load bearing structures, thermal bridges and indoor climate as well as information obtained from occupants' questionnaires are used as background information for energy-renovation measures, but not presented in this thesis. Results of research project "Technical condition and service life of the Estonian prefabricated concrete large panel apartment buildings" (Kalamees et al., 2009) are also used as background information for energy-renovation measures.

3.3 Calculations

3.3.1 Energy and indoor climate simulations

The energy performance of the reference buildings was simulated by the energy and indoor climate simulation program IDA Indoor Climate and Energy 4.6 (IDA ICE). This software has been validated, for example by Achermann (2000), Kropf and Zweifel (2001), Travesi et al. (2001) and Loutzenhiser et al. (2007).

According to Björsell et al. (1999), IDA ICE may be used for most building types for the calculation of

- the full zone heat and moisture balance, including specific contributions from sun, occupants, equipment, lighting, ventilation, heating and cooling devices, surface transmissions, air leakage, cold bridges and furniture;

- the solar influx through windows with a full 3D account of the local shading devices and those of surrounding buildings and other objects;
- air and surface temperatures;
- the operating temperature at multiple arbitrary occupant locations, e.g. in the proximity of hot or cold surfaces;
- the directed operating temperature for the estimation of asymmetric comfort conditions;
- comfort indices, PPD and PMV, at multiple arbitrary occupant locations;
- the daylight level at an arbitrary room location;
- the air CO_2 and moisture levels, which both can be used for controlling the system air flow of variable air volume;
- the air temperature stratification in displacement ventilation systems;
- wind and buoyancy driven airflows through leaks and openings via a fully integrated airflow network model. This enables to study temporarily open windows or doors between rooms;
- the airflow, temperature, moisture, CO_2 and pressure at arbitrary locations of the air-handling and distribution systems;
- the power levels for primary and secondary system components;
- the total energy cost based on time-dependent prices.

The Estonian Test Reference Year TRY (Kalamees and Kurnitski, 2006) was used for simulating outdoor climate conditions (annual heating degree days at t_i 17ºC: 4160 ºC·d).

The simulation models were calibrated based on the measured energy use of the reference buildings. To calibrate in the building model the real use of electricity, the factor 0.7 for heat emission of appliances was used. The use of internal blinds to limit solar heat gain varied between 0.25 and 0.5. Comparison of the simulated (ideal heater) and the measured (radiators without thermostats) space heating consumption showed that the simulated consumption was higher due to the efficiency of using internal heat gains and control of the real heating system. All the reference buildings had district heating for heat source and water radiators for the distribution system. The generation and distribution efficiencies were as follow:

- generation efficiency of district heating substation 1.0;
- distribution efficiency of radiators without thermostats 0.87;
- distribution efficiency of radiators with thermostats 0.97.

After calibration of the simulation model, the energy renovation measures were calculated according to a unified calculation methodology and with a standard usage (Methodology for calculating the energy performance of buildings, 2012 and Minimum requirements for energy performance of buildings, 2012) because our aim was to analyse the energy consumption of the building type during standard use and not the energy consumption of a specific building.

The zoning of the simulation model is shown on the example of the CB reference building "A". The model of buildings was divided into different zones according to the apartment's layout (Figure 3.5), and the third-floor zones were multiplied by 3 to represent also the second and the fourth floor.

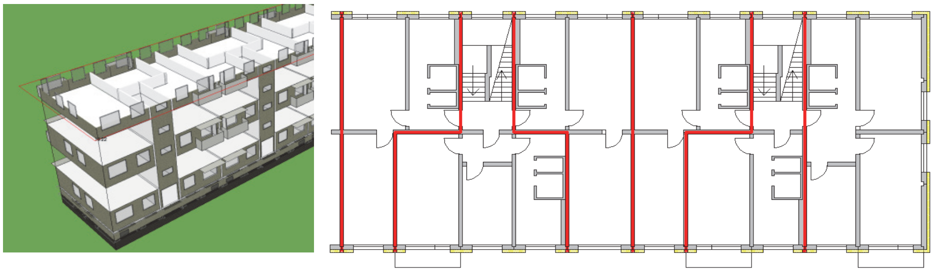


Figure 3.5 Simulation model (left) and floor plan (right) of the large-panel apartment buildings reference building "A". Red walls show the distribution of the zones in the simulation model.

Internal heat gains in the simulation were as follows:

- occupants: 3 W/m^2. The usage rate was 0.6 (15.8 kWh/(m^2·a)), Figure 3.6 top;
- appliances, equipment: 3 W/m^2. The usage rate was 0.6 (15.8 kWh/(m^2·a)) , Figure 3.6 middle. The heat gains of equipment were divided by 0.7 to calculate DE;
- lighting: 8 W/m^2. The usage rate was 0.1 (7.0 kWh/(m^2·a)) Figure 3.6 bottom.

Detailed profiles of internal heat gains are shown in Figure 3.6.

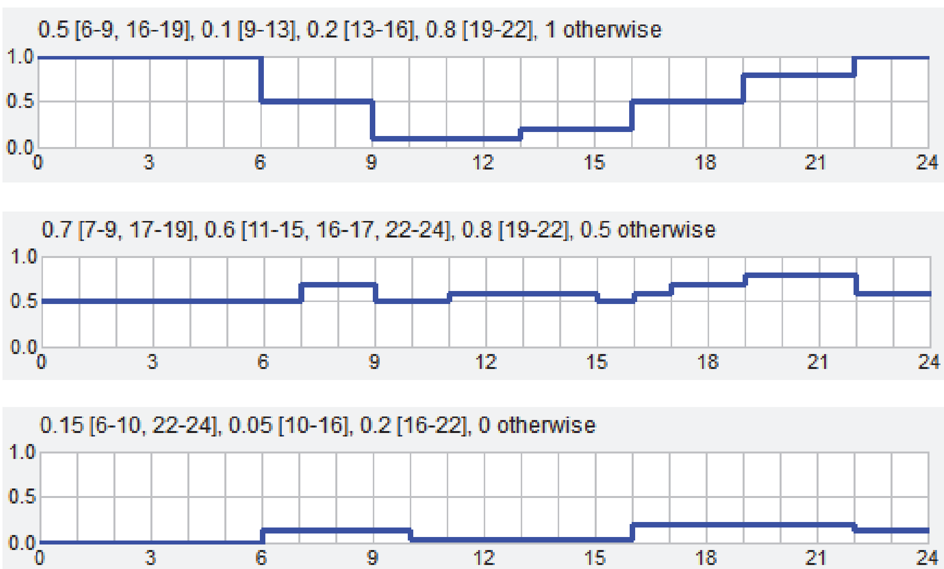


Figure 3.6 Detailed profiles of internal heat gains of occupants (top), equipment (middle) and lighting (bottom).

The ventilation airflow counted per heated area was 0.35 l/(s·m^2) for a non-renovated case representing indoor climate category III (EN 15251, 2007) and 0.42 l/(s·m^2) for renovation packages representing indoor climate category II. The infiltration airflow in a non-renovated case for CB was calculated with the average measured value (q_{50}=4.3 m^3/(h·m^2)) (Kalamees et al., 2011b) and for BB with the measured value (q_{50}=4.4 m^3/(h·m^2)). In the renovated case a slight improvement in the airtightness of the buildings (q_{50}=4.0 m^3/(h·m^2)) was assumed for both building types. The energy need for DHW was 520 l/(m^2·a), that is 30 kWh/(m^2·a), which makes approximately 35−45 l/(pers.·day) depending on the apartment occupation density.

For ventilation heat recovery mainly two technical solutions were used: apartment-based air handling units with heat recovery and mechanical exhaust ventilation with a heat pump for heat recovery. The principle of the latter is that the supply air enters through fresh air radiators and is filtered and heated at the same time. The extract air moves through ventilation shafts to an air handling unit cooling coil where heat is transferred with a brine loop of water to water heat pump. The heat pump provides heat to the DHW and the space heating system. The Coefficient of Performance (COP) of the exhaust air ventilation heat pump was 3.5 during the heating period and 3.0 during summer. The lower COP in summer results from the use of the heat pump only for DHW, which has a higher temperature (55 °C) (Kõiv et al., 2012).

Only district heating as the heat source and radiators for the distribution system were used in the simulations. It was expected that the renovated heating system with thermostats would maintain a constant internal temperature of at least 21 °C.

3.3.2 Economic calculations

The global cost (EN 15459, 2007; Equation 1) calculations were used to assess the cost effectiveness of the renovation measures and renovation packages relative to the current state of the reference buildings. Based on the current practice, the cost of the renovation was calculated considering 85% loan financing and 15% self-financing. A discount period of 20 years was selected because the maximum period for renovation loans for apartment owners' associations in Estonia is 20 years.

$$C_{\mathrm{g}}(\tau)=\frac{C_{\mathrm{i}}+\sum_{\mathrm{i}=1}^{20}(C_{\mathrm{ai}}(j)\cdot R_{\mathrm{d}}(i))}{A_{\mathrm{floor}}}-\frac{C_{\mathrm{g}}^{\mathrm{ref}}}{A_{\mathrm{floor}}} \tag{1}$$

where $C_{\mathrm{g}}(\tau)$ is the global cost (referred to the starting year), €/m^2; C_{i} is the initial investment cost (self-financing of a renovation loan), €; $C_{\mathrm{a,i}}(j)$ is the annual cost of year i for the component j (energy cost and loan payback cost), €; $R_{\mathrm{d}}(i)$ is the discount rate for year i; $C^{\mathrm{ref}}_{\mathrm{g}}$ is the global cost of the reference building, €; A_{floor} is the net floor area, m^2.

In Article I, the payback period (Equation 2) was calculated using return on investment (Equation 3) and total loan payment with interest (Equation 4):

$$T = \frac{100\%}{E} \tag{2}$$

where T is the payback period in years; E is the return on investment, %.

Return on investment was calculated for each year of the loan considering the escalation of the energy prices:

$$E = \frac{\sum(En_i \cdot S_i)}{A} \cdot 100\% \tag{3}$$

where En_i is the delivered energy decrease for year i , MWh/a; S_i is the delivered energy cost for year i , €/MWh. Payback period was calculated using the median return on investment.

The total loan payment with interest was calculated:

$$A = MB \cdot \left[\frac{i \cdot (1+i)^m}{\left(1+i)^m - 1\right)} \right] \cdot 12 \cdot n \tag{4}$$

where A is the total loan payments with interest, €; MB is the initial loan, €; i is the monthly interest (annual interest/12), %; m is the loan duration in months; n is the loan period in years.

In Article V, where renovation scenarios for the entire building stock were analysed, two methods were used. The first one was simple unit cost approach (invested € per MW capacity) often used for comparison of energy generation plants. To be suitable for energy savings assessment, unit cost in euros per annual energy saving of 1 MWh was calculated. This approach has evident limitations, but the use was motivated by easy inter-comparison of any energy-saving measures in different sectors (transport, industry, energy generation etc.). The other method used was an investment calculation with net present value method with Equations 5 to 7.

The following input data were used:

- calculation period 20 years;
- real interest rate 4%;
- escalation of the energy prices 3% (inflation reduced from actual price increase);
- heating energy (district heat) price 0.075 €/kWh (VAT included);
- pellets 0.054, gas 0.055 and wood chips 0.031 €/kWh for heating of detached houses (VAT included);

- electricity price in residential buildings 0.14 €/kWh (VAT included);
- the present value factor (Equation 7) $f_{pv}(n) = 18.05$;
- all costs include VAT of 20%.

Cost effectiveness of the renovation variants was assessed with financial calculation of the net present value (NPV) according to principles set in the European Commission's cost optimality methodology (Commission regulation No 244/2012) developed for the assessment of cost-optimal energy performance levels. The NPV was calculated as global cost consisting of construction cost and discounted energy costs according to EN 15459 (2007):

$$C_g = \frac{C_I + C_a \cdot f_{pv}(n)}{A_{floor}} \tag{5}$$

where C_g is global cost, NPV, €/m^2; C_I is construction cost of the renovation variant, €; C_a is annual energy cost during the starting year, €; $f_{pv}(n)$ is present value factor for the calculation period of n years; A_{floor} is heated net floor area, m^2.

To calculate the present value factor $f_{pv}(n)$, real interest rate R_R depending on the market interest rate R and on the inflation rate R_i (all in per cents) was calculated (EN 15459, 2007):

$$R_R = \frac{R - R_i}{1 + R_i/100} \tag{6}$$

The present value factor $f_{pv}(n)$ for the calculation period of n years was calculated (EN 15459, 2007):

$$f_{pv}(n) = \frac{1 - \left(1 + (R_R - e)/100\right)^{-n}}{(R_R - e)/100} \tag{7}$$

where R_R is the real interest rate, %; e is escalation of the energy prices, % (inflation reduced from actual price increase); n is the number of years considered, i.e. the length of the calculation period.

The calculations of the global cost and payback period were made with a typical interest rate 4%. Escalation rate was in most cases 3%. To show sensitivity to the escalation rate, additional escalation rate scenarios were considered in Article I (1% and 5% escalation) and in Article VI (1%, 5%, 7% and 9% escalation).

The construction costs used in Article I and Article III (Table 3.3) were calculated on the basis of the real costs and estimations made by the construction companies. Construction cost of renovation variants was calculated as full cost (i.e. not only energy performance related costs) where all costs of construction works and installations were taken into account. For example, in the case of roof insulation, all construction works of roof repair were included. The renovation variants did not include interior remodelling, but internal finishing was taken into account in the case of window replacement and heating and ventilation installations. The construction costs used in Article VI were calculated on the basis of estimations made by construction companies.

The energy price levels used were (including VAT of 20%):

- 0.14 €/kWh for electricity,
- 0.075 €/kWh for district heating.

Table 3.3 Construction costs of renovation measures (2012, including VAT 20%).

Energy renovation measure	Cost
Additional insulation for external walls, €/m^2	
+ 100 mm	65
+ 150 mm	68
+ 200 mm	70
+ 300 mm	80
+ 400 mm	100
Additional insulation for flat roof, €/m^2	
+ 200 mm	60
+ 300 mm	65
+ 400 mm	75
+ 500 mm	90
Additional insulation for attic floor, €/m^2 (includes replacement of roof construction)	
+ 200 mm	100
+ 300 mm	102
+ 400 mm	105
+ 500 mm	110
Additional insulation for basement ceiling, €/m^2	
+ 100 mm	25
+ 150 mm	27
+ 200 mm	30
Replacement of windows, €/m^2	
U –1.4 W/(m^2·K)	110−140*
U –1.1 W/(m^2.K)	140−160*
U –0.6 W/(m^2·K)	240
Renovation of heating system, €/m^2 (net area)	
Renovation of current 1-pipe system	10
New 2-pipe system	20−30*
Renovation of ventilation system, €/m^2 (net area)	
Exhaust ventilation without heat recovery	5
Exhaust air heat pump	25−30*
Room-based ventilation with heat recovery	35
Apartment-based ventilation with heat recovery	45−55*
Renewable energy systems, €/MWh	
Solar collectors	1200−1500*
Solar panels (PV)	2800

*In case of the cost range, the cost of the system depended on the size of the system.

3.4 Energy-efficiency measures

Energy simulations were made for the following individual renovation measures:

- additional insulation on external walls: +100 to +400 mm;
- additional insulation on roof: +200 to +500 mm;
- additional insulation on basement ceiling: +100 to +200 mm;
- replacement of windows: U –0.6 to –1.4 W/(m^2·K);
- renovation of the heating system: mainly installation of a new 2-pipe heating system;
- renovation of the ventilation system:
    - exhaust ventilation without heat recovery,
    - exhaust ventilation with exhaust air heat pump for heat recovery,
    - room-based balanced ventilation units with heat recovery,
    - apartment-based balanced ventilation with heat recovery;
- renewable energy systems:
    - solar collectors;
    - solar panels.

Annual production of DHW from solar panels was calculated with 400 kWh of produced heat energy per m^2 of solar panel. It was estimated that due to other building service systems on the roof, 75% of the roof area could be used for the installation of solar panels (in case of nZEB). According to the methodology ("Methodology for calculating the energy performance of buildings", 2012), the maximum amount of heat energy from solar panels taken into account in energy calculations can be 50% of the annual energy use for DHW.

Individual renovation measures were combined into renovation packages. One renovation package for each Energy Certification Class for each reference building was simulated in Article I. In Article II, simulated changes of energy efficiency and global cost of individual renovation measures were combined in order to create a larger number of different energy renovation packages. Random comparison of simulated energy packages showed that the results were within the same range.

Simulation results are presented as weighted average of reference buildings simulation results based on the proportion of the net area of the reference building type in the total net area of CB.

The realization of energy-renovation measures was tested in a case study (Figure 3.7) in Article III. A CB was renovated during the pilot energy-renovation project "Healthy and Economical Home", which began in 2010 with the following targets:

- to select renovation solutions that offer maximum repeatability;
- to achieve the same energy efficiency as are the requirements for new apartment buildings: PE ≤ 150 kWh/(m^2·a);

- to decrease heating energy use by >50%;
- to reach indoor climate category II (EN 15251, 2007);
- cost of renovation works ≤160 €/heated m^2;
- air leakage rate q_{50} < 3 m^3/(h·m^2);
- to extend the service life of the building after the renovation by 50 years;
- to receive apartment owners' association's approval of the designed renovation solutions.

Figure 3.7 Photo of the building used in the case study before (left) and after (right) the renovation.

The selected building type is widespread in Estonia, accounting for 48% of the total surface area of the CB and 17% of the total surface area of all apartment buildings. Thermal transmittance of the building envelope and the linear thermal transmittance of thermal bridges before and after renovation are shown in Table 3.4.

Table 3.4 Thermal properties of the building envelope in the case study building before and after the renovation

Thermal transmittance of building envelope		Before renovation	After renovation
U, W/(m^2·K)	walls U_{wall}	0.90	0.17
	roof U_{roof}	0.70	0.11
	windows U_{window}	1.85	1.40
Linear thermal transmittance of thermal bridges Ψ, W/(m·K)			
external wall/external wall		0.70	0.15
external wall/internal wall		0.30	0.01
external wall/internal floor		0.50	0.01
external wall/basement ceiling		0.50	0.06
external wall/roof		0.55	0.20
external wall/window		0.13	0.20
external wall/balcony floor		0.20	0.45
Air leakage rate q_{50}, m^3/(h·m^2)		5.1	4.9

The procedure of selecting energy-efficiency measures and renovation scenarios for the nZEB case study in Article IV were the following. First, the current state of the building (insufficiently ventilated and without room-based temperature control) was aligned with the indoor climate requirements. For that, the heating system was balanced and equipped with thermostatic valves and a mechanical exhaust ventilation system without heat recovery was installed. This state was the base case for comparing energy-efficiency measures. Energy-efficiency measures were combined in order to achieve different energy efficiency levels. For ECC D (energy-efficiency requirement for major renovation), the building envelope was insulated, windows were replaced and a new 2-pipe heating system was installed. For ECC C (energy-efficiency requirement for new building), apartment-based ventilation units (heat recovery efficiency 70%, specific fan power 1.5) were installed in addition to the previous renovation package. For ECC B (energy-efficiency requirement for low-energy building), solar collectors were installed in addition to the previous renovation package. For ECC A (energy-efficiency requirement for nZEB), PV panels were installed in addition to the previous renovation package.

The area of solar collectors was calculated using a simplified method (Walker, 2013). The calculated solar collector area was 180 m^2. In order to meet nZEB energy-efficiency requirements, the remaining roof area was used to install PV panels. The maximum area of PV panels that could be installed was estimated to be 150 m^2.

The building studied is used as a dormitory. In addition to the energy renovation, its apartments need modernization. To analyse the economic viability from an apartment owner's perspective when no apartment modernization is needed, the calculations excluded the investment need of apartment modernization.

Energy simulations in Paper VI were made for different stages of the building:

- original building without any renovation measures with real use for validation;
- original building without any renovation measures with standard use;
- major renovation;
- renovation on a low-energy building level;
- renovation on a low-energy building level with extensions of the building.

Extensions were attached to kitchens and staircases in the simulations of low-energy buildings with extensions. Additional space was used to accommodate the ventilation air handling units and to increase the small floor area of the existing kitchen. Solar collectors were installed for producing DHW to compensate for the increased heat loss caused by the additional constructions.

4 RESULTS

4.1 Energy use at the current state of buildings

4.1.1 Electricity

Annual and monthly use of electricity in brick apartment buildings (BB) are shown in Figure 4.1. The average annual use of electricity (lighting, household electricity and space heating in some cases) was 35 kWh/(m^2·a) (22–49 kWh/(m^2·a)). Similar results were found also in prefabricated concrete large-panel apartment buildings (CB) where average electricity use was 32 kWh/(m^2·a) (SD 6 kWh/(m^2·a)). The use of electricity in apartments made up 80–90% of the total use of electricity. It varied from +15% to –28% of the annual average, mainly due to the lower use of lighting.

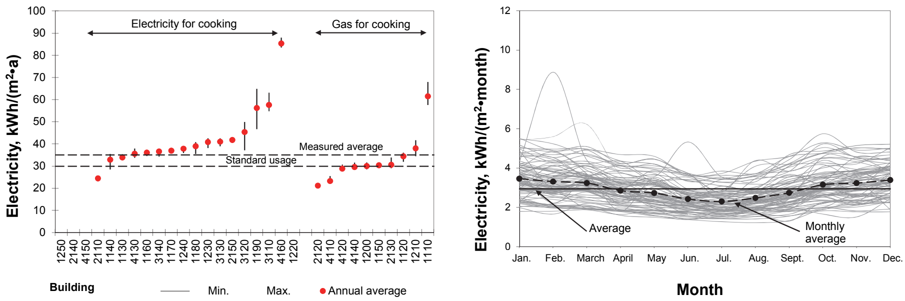


Figure 4.1 Average annual (left) and monthly (right) use of electricity in brick apartment buildings.

4.1.2 Gas

The annual average use of gas for cooking in the BB was 5 kWh/(m^2·a) (SD 3 kWh/(m^2·a)) and for cooking and DHW 29 kWh/(m^2·a) (SD 9 kWh/(m^2·a)). In the CB, gas was only used for cooking; the average use was 8 kWh/(m^2·a) (SD 2 kWh/(m^2·a)).

4.1.3 Tap water

The annual average daily hot water use in BB was 1.3 l/(m^2·d) (SD 0.3 l/ (m^2·d)) and energy use for DHW was 27 kWh/(m^2·a) (SD 6 kWh/(m^2·a)), see Figure 4.2. The average energy use for DHW in CB was 39 kWh/(m^2·a) (SD 12 kWh/(m^2·a)). The annual average daily overall (hot and cold) water use was 3 l/(m^2·d) (SD 0.6 l/(m^2·d)) and 202 l/ (apartm.·d) (SD 64 l/ (apartm. ·d)). On average DHW accounted for 40% of the overall water use. The use of DHW was 35 l/person (SD 10 l/person).

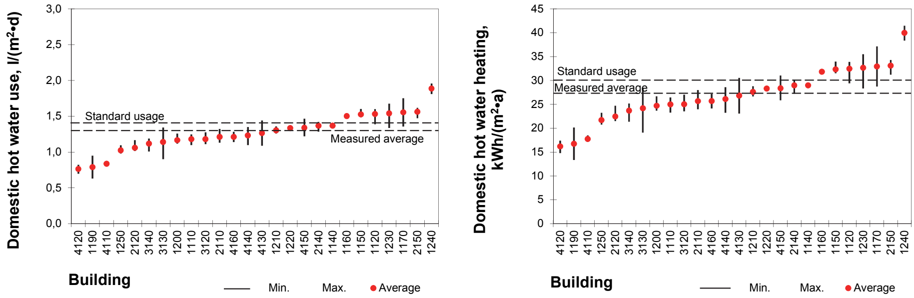


Figure 4.2 Daily average hot water use (left) and energy use for producing domestic hot water (right).

Energy for space heating and ventilation in the studied apartment buildings covered the following heat losses:

- through the building envelope;
- through the thermal bridges;
- due to infiltration;
- due to natural ventilation.

The average energy use for space heating in the BB was 150 kWh/(m^2·a) (SD 41 kWh/(m^2·a)), see Figure 4.3 left. The energy use for heating was higher in buildings with a one-pipe heat distribution system (complicated balance and temperature regulation) and in buildings with larger compactness, see Figure 4.3 right. The highest energy usage for space heating per m^2 is typical of buildings with a small net area but with a relatively large building envelope area. In the CB the average energy use for space heating was 136 kWh/(m^2·a) (SD 25 kWh/(m^2·a)).

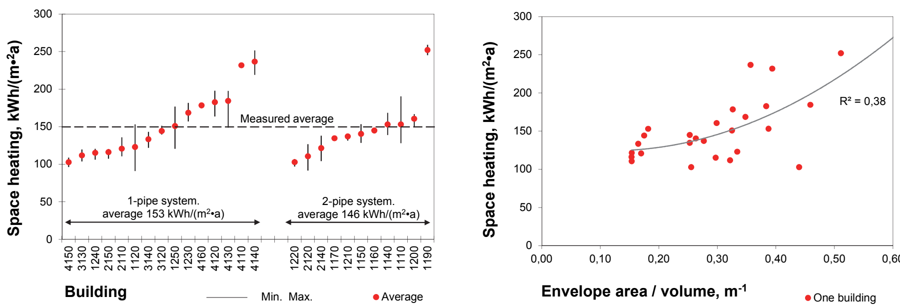


Figure 4.3 Energy use for space heating in brick apartment buildings depending on the heat distribution system (left) and compactness of the building (right).

4.1.4 Total primary energy consumption

Delivered energy (DE) usage of BB (Figure 4.4 left) was added to show the difference between the DE and the primary energy (PE). The average use of PE in BB was 263 kWh/(m^2·a) (SD 58 kWh/(m^2·a)), see Figure 4.4 right. Only one measured building was found to meet the requirements for major renovation of apartment buildings.

The distribution of the PE usage in the BB without gas was as follows: 57% was used for space heating, 12% for DHW and 31% for electricity.

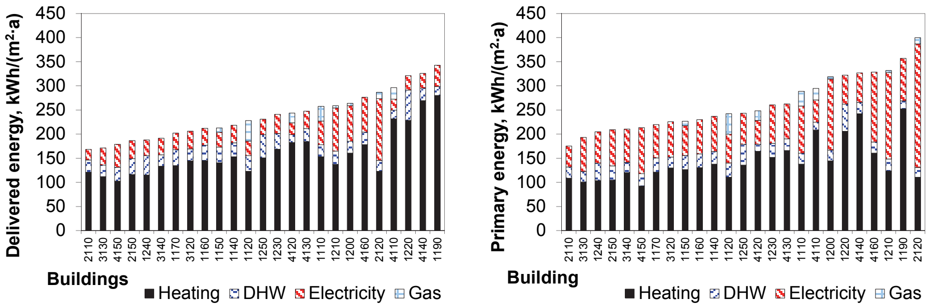


Figure 4.4 Delivered energy use (left) and primary energy use (right) of brick apartment buildings.

The average use of PE in the CB was 224 kWh/(m^2·a) (SD 25 kWh/(m^2·a)), see Figure 4.5. Three studied buildings met the energy-efficiency requirement of major renovation (ECC D). The distribution of PE use in the buildings without gas was as follows: 55% for space heating, 15% for DHW and 30% for electricity.

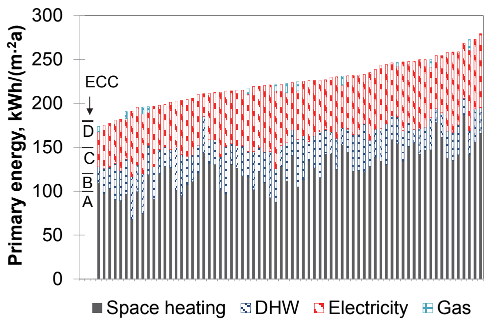


Figure 4.5 Use of primary energy in the studied concrete large-panel apartment buildings.

For deeper analysis of energy use in CB the buildings were divided into different groups according to the introduced renovation measures. Analysis of energy use for space heating showed that single energy saving measures (additional insulation on roofs or on end walls, new heating system) had no significant impact on energy use for space heating, see Figure 4.6. However, according to Student's *t*-test, there was statistical difference in energy consumption for space heating between buildings without any renovation and with some renovation measures taken: buildings with additionally insulated end walls (50−150 mm) and roofs (150−300 mm) − *p*-value 0.02, buildings with additional insulation of end walls and a renovated heating system − *p*-value 0.01 and buildings with additional insulation of end walls, side walls and the roof − *p*-value 0.0001.

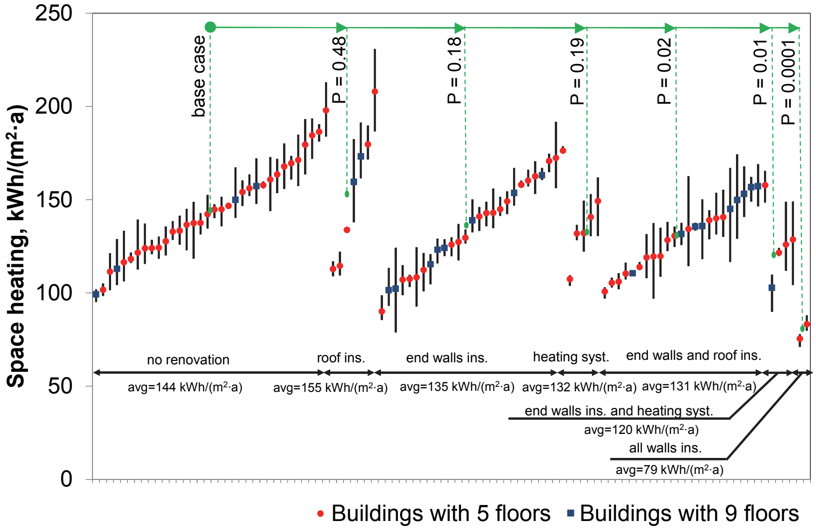


Figure 4.6 Energy use for space heating in the studied concrete large-panel apartment buildings.

4.2 Cost effectiveness of energy renovations

4.2.1 Individual renovation measures

The change of the global cost and energy performance was selected to assess the cost effectiveness of individual energy-renovation measures. The results for BB are shown in Figure 4.7.

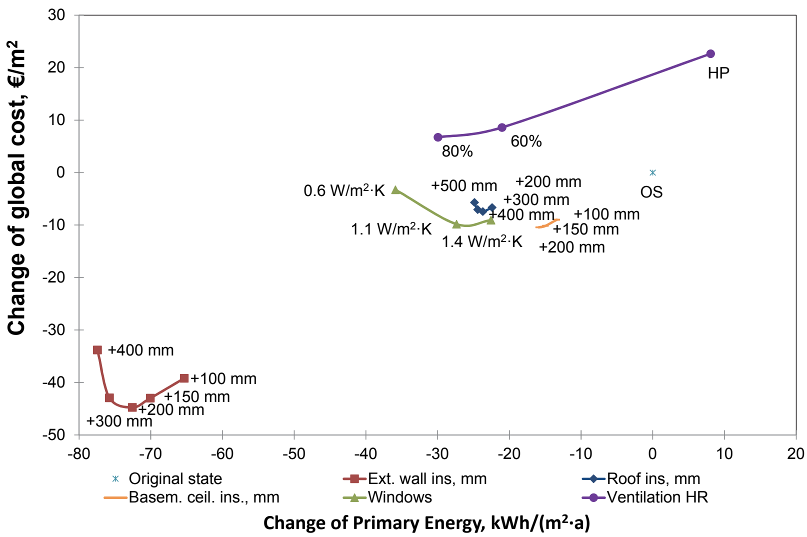


Figure 4.7 Change of energy performance and global cost at different individual renovation measures in brick apartment buildings.

Insulating the exterior of the external walls showed the highest energy saving effect. Depending on the building compactness and the ratio of the window area to the facade area, the insulation of external walls reduces the PE use by 20–30%. The effect of increasing the insulation layer thickness over 200–300 mm on the reduction of PE or DE was small. The influence of insulating the roof and floors depends strongly on the number of floors: the higher the building, the smaller the effect (5 to 9 floors – the PE decreases 3%, 2 to 4 floors – 6–7%, 1 to 2 floors – 14%). As an individual measure, additional roof insulation over 300 mm showed no impact on the PE or the amount of DE. Replacement of windows reduced the PE in all cases because of the high thermal transmittance of the existing windows. Due to the current higher costs (low market demand) of modern windows with the lowest thermal transmittance $U \approx 0.6$ W/(m^2·K) (triple glazing with two low emissivity coating layers and insulated frames), the most reasonable window in terms of economy is with the thermal transmittance 1.1 W/(m^2·K) (double glazing with a low-emissivity coating).

Installing a ventilation system with heat recovery increases the global cost due to the improved ventilation airflow and electricity use. The best ventilation system from the energy efficiency point of view is a balanced ventilation system with an apartment-based air handling unit with heat recovery. Ventilation systems with heat recovery mainly used in renovation of apartment buildings in recent years in Estonia were room-based air handling units and exhaust air heat pumps. Reductions of DE are similar in both systems, ca 10–15%, but as a heat pump uses considerably more electricity, the reduction of the PE is smaller.

The changes of the global cost and energy performance as a result of individual renovation measures for CB are shown in Figure 4.8.

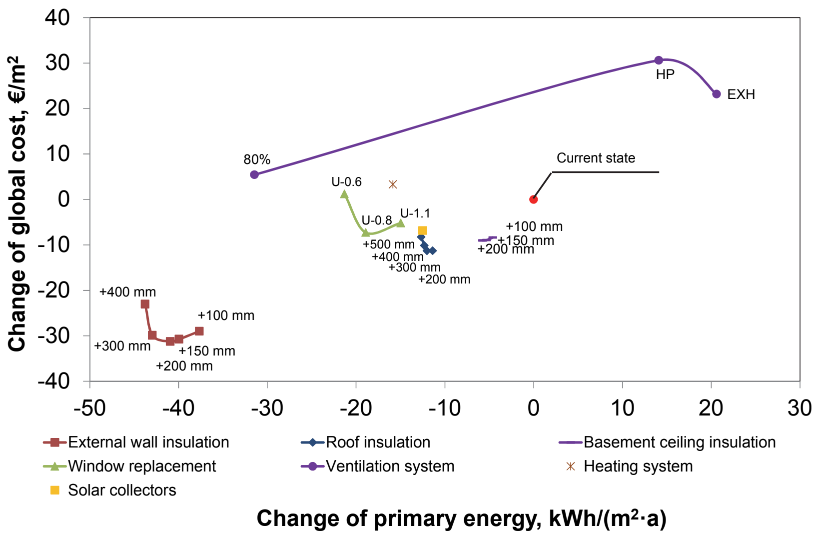


Figure 4.8 Change of energy performance and global cost of different individual renovation measures of concrete large-panel apartment buildings.

Also for CB, insulation of external walls leads to the greatest reduction in the global cost and primary energy use. Insulation thicknesses of 200 mm or 300 mm are most reasonable with PE reduction of 17% and 18%, respectively. The insulation thickness of the roof and basement ceiling has a small effect on the global cost and PE consumption because of their small share of the total envelope area. Roof insulation decreases PE by 5% and basement ceiling insulation by 2% with all modelled insulation thicknesses.

The most reasonable window is with the thermal transmittance of 0.8 W/(m^2·K) (triple glazing with two low emissivity coating layers) as it had the same range of global cost reduction but a higher decrease of PE use than *U* 1.1 W/(m^2·K). Windows with *U* 1.1 W/(m^2·K) decreased PE by 6% and with *U* 0.8 W/(m^2·K) decreased PE by 8%. The window with the lowest thermal transmittance 0.6 W/(m^2·K) increases the global cost due to its presently higher cost.

Renovation of the ventilation system with installing an exhaust air heat pump for heat recovery increases the global cost and PE consumption due to the improved ventilation airflow and higher electricity use. Apartment-based air handling units with the heat exchanger efficiency of 80% decrease PE consumption by 13%. Due to the large electricity consumption, the heat pump of the exhaust air ventilation has the highest global cost. The ventilation system with an exhaust air heat pump decreases the DE use by 7%.

4.2.2 Cost effectiveness of energy renovation packages

In all the packages, a 150 mm additional insulation of basement ceilings was installed to improve the thermal comfort of the ground floor occupants. The global costs of renovation packages with room-based and with apartment-based air handling units are in the same range. Packages with an exhaust air heat pump are not included in the calculation of the cost-optimal range for BB as their global costs are noticeably higher than those of other renovation packages. Economically the optimum of energy renovation measures is close to the PE use of 150 kWh/(m^2·a), which corresponds to the requirements for new apartment buildings, see Figure 4.9. The performance level of a low-energy building is achievable without increasing the current state of global costs.

All economic calculations were made with an interest rate of 4% and an escalation rate of 3%. To show sensitivity to the changes of the escalation rate, global costs and payback periods were also calculated with the escalation rates of 1% and 5%. At an escalation rate of 1%, renovation packages are not economically viable. At an escalation rate of 5%, renovation packages are all viable.

Analysis showed that renovation of the ventilation system affects energy consumption significantly. Therefore renovation packages are treated by different renovation solutions of ventilation systems. The weighted average use of the PE in the current state was 241 kWh/(m^2·a). The economical optimum of energy renovation measures is around the PE level of 120 kWh/(m^2·a), which corresponds to the requirements for low-energy apartment buildings, see Figure 4.9. Therefore, it is possible to reduce PE consumption by 50% without increasing the current state of global costs. Reduction of energy use relative to the current state of apartment buildings is shown in Table 4.1.

Table 4.1 Reduction of energy usage relative to the current state of buildings in case of standard use, %.

Criterion		Primary Energy	Delivered Energy
Minor renovation	(ECC E)	9%	12%
Major renovation	(ECC D)	25%	32%
New building	(ECC C)	38%	46%
Low-energy building	(ECC B)	50%	61%
nZEB	(ECC A)	59%	70%

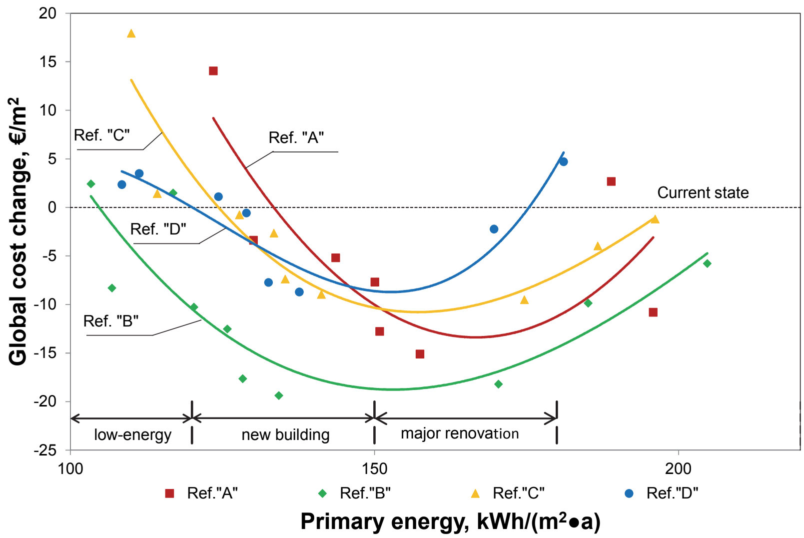


Figure 4.9 Change of global cost and energy performance relative to the current state of reference brick apartment buildings.

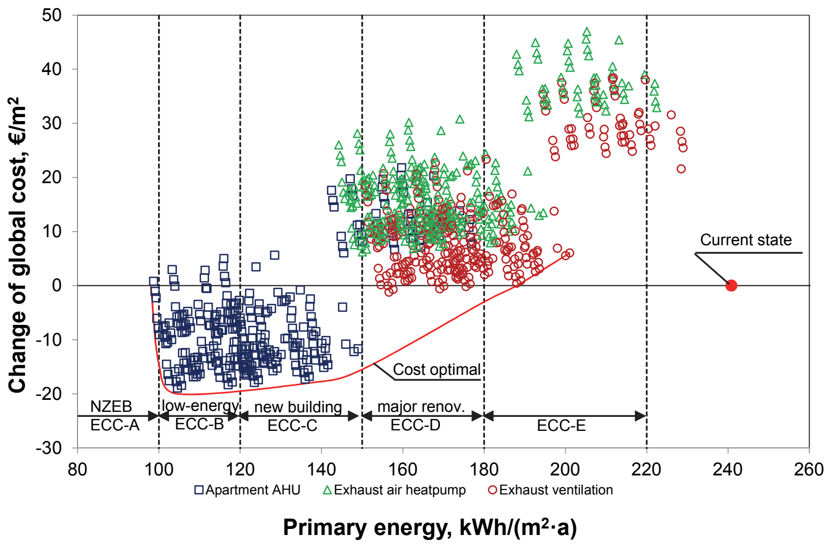


Figure 4.10 Change of global cost and energy performance relative to the current state of weighed average of the reference concrete large-panel apartment buildings.

Payback periods for cost effectiveness are similar to the global cost method, see Figure 4.11. Payback periods for large building packages (Ref. "D") with major renovations are significantly longer, thus energy renovations resulting in small reductions (current state PE 215 kWh/(m^2·a)) in the PE consumption are not economically viable. An economically optimum range of the payback period is at the PE 150 kWh/(m^2·a), with the payback period of 19–21 years.

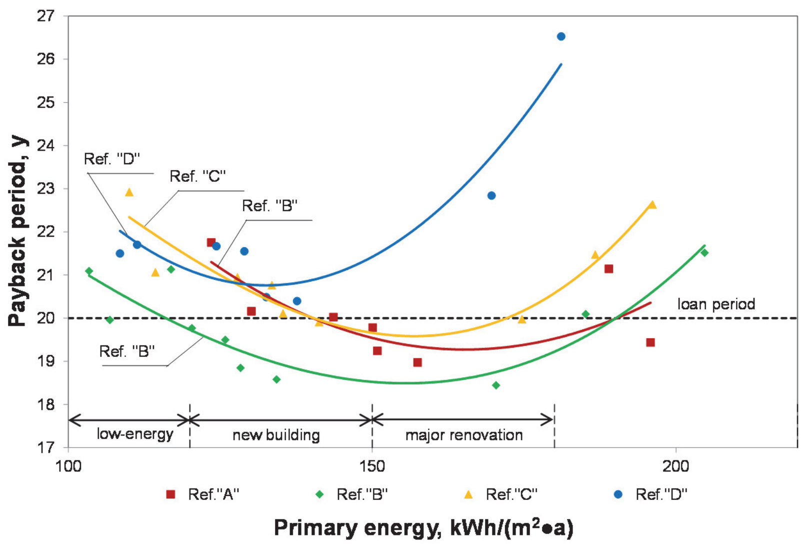


Figure 4.11 Payback periods of renovation packages for brick apartment buildings.

Major renovation of brick apartment buildings

The major renovation requirement was satisfied by using additional thermal insulation for the whole building envelope and by replacing windows. From the energy saving point of view, there is not much need to insulate the basement ceiling, but it is included to avoid cold floors in the ground floor apartments. To renovate 1-pipe heating systems in case of a ventilation system without heat recovery thermostats must be installed. However, with an exhaust air heat pump new 2-pipe heating systems thermostats are required to achieve the maximum usage of lower heat carrier temperatures produced by a heat pump. For smaller BB with a net area of ca 500 m^2 (Ref. “A”), either room-based air handling units (heat recovery 60%) or apartment-based air handling units (heat recovery 80%) are needed to achieve the required PE use of major renovation.

Renovation of brick apartment buildings to the same energy efficiency as new building

To achieve the energy performance levels required for new buildings, it is necessary to insulate the building envelope at major renovation, and to install the ventilation systems with heat recovery and a new 2-pipe heating system with thermostats. As an exhaust air heat pump uses a considerable amount of electricity, apartment-based air handling units are used in the renovation packages. It is not feasible to meet PE requirements of new apartment buildings at the current common renovation practice (150 mm additional insulation for external walls, 300 mm additional roof insulation and replacement only original wooden-framed windows) by installing a heat pump for ventilation heat recovery. Solar collectors for DHW are needed to achieve the level of new building PE for smaller brick apartment buildings (Ref. “A”).

Renovation of brick apartment buildings to low-energy buildings

Energy renovation packages for low-energy buildings differ from the packages of new apartment buildings with a need for solar collectors for DHW. A low-energy level is not achievable for smaller brick apartment buildings (Ref. “A”). To show a minimum PE use for every reference building, one renovation package consisted of maximum insulation of the building envelope, maximum heat recovery and solar collectors for DHW. The low-energy level gave the best result. A PE level of the nZEB is mostly infeasible in BB without on-site electricity production from renewable energy sources.

4.2.3 The need for investment and financial support

Analysis of needed investments showed a relatively linear correlation between the energy efficiency level and the renovation cost (Figure 4.12). Energy-saving-related renovation investments necessary for major renovation are between 90 and 110 €/m^2. Larger savings require larger investments: renovation to energy performance of new buildings is 130−150 €/m^2, for low-energy level 150−170 €/m^2 and nZEB close to 200 €/m^2. The final renovation cost may be larger because of non-energy-saving-related, but inevitable, renovation costs. These investments could be high for apartment owners, especially for elderly inhabitants.

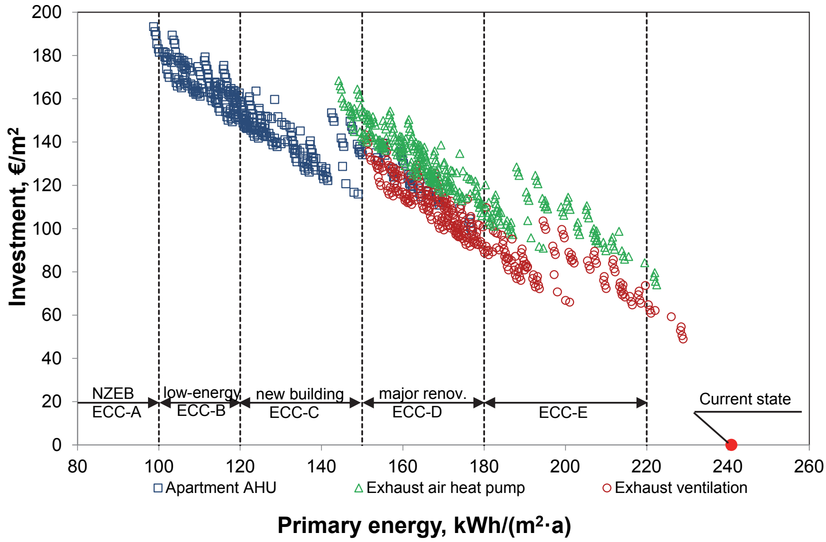


Figure 4.12 Change of energy performance and investment need.

Investment capability is usually the limitation for renovation to the low-energy or nearly zero-energy level. The influence of financial support on the renovation extent and the achieved energy efficiency was analysed by an inventory of the already made renovation of a selection of large apartment buildings in Estonia. The influence of the grant support scheme on investments is shown in Figure 4.13. The average investment for apartment buildings with an area of 3000 m^2 that achieved ECC E (minor renovation) was 36 €/m^2, of which the apartment owners association's share was 31 €/m^2. To achieve ECC D (major renovation) the average investment was 71 €/m^2, of which the apartment owners association's share was 53 €/m^2. For achieving ECC C (requirement for new buildings) the average investment was 120 €/m^2, of which the apartment owners association's share was 78 €/m^2. Comparison of investments made only with a loan without grant support to improve energy efficiency showed that a grant support scheme has raised apartment owner's contribution to energy renovation. With the grant support of 25%, apartment owners have invested on average 20 €/m^2 more their own funds to the energy efficiency-measures than without any support. For example, in case of reference building “A” with a net area of 3500 m^2, this means 70 000 € more funds to improve the building's energy efficiency. In the case of a grant support of 35%, apartment owners have invested on average 45 €/m^2 more into energy-efficiency measures than without any support. Again, using the example of reference building “A” with a net area of 3500 m^2, this means 158 000 € more funds to improve energy efficiency. Considering the fact that without the grant support, the average investment for improving the energy efficiency of the apartment building was approximately 30 €/m^2, the grant support for achieving the energy-efficiency level of new apartment buildings has more than doubled apartment owners' association's investments to energy-efficiency measures.

Comparison of investment needs and investments made only by apartment owners' associations shows that without a grant, apartment owners' associations are not able to make the necessary investments to significantly improve the energy efficiency of buildings.

In order to make renovation more affordable for the apartment owners' associations the new renovation scheme in Estonia, which started in April 2015, proposes a higher grant share (Requirements for applying apartment buildings renovation grant, 2015). The financial support for the highest energy-efficiency level was proposed to increase from 35% to 40%. Renovation grant of 40% will lower renovation costs needed to achieve the new building energy-efficiency level to around 80 €/m^2, which is affordable for apartment owners' associations (Figure 4.14). Renovation of a building to ECC C level is economically much more attractive and hopefully will help to decrease the overall energy use of buildings and to achieve the national energy saving targets.

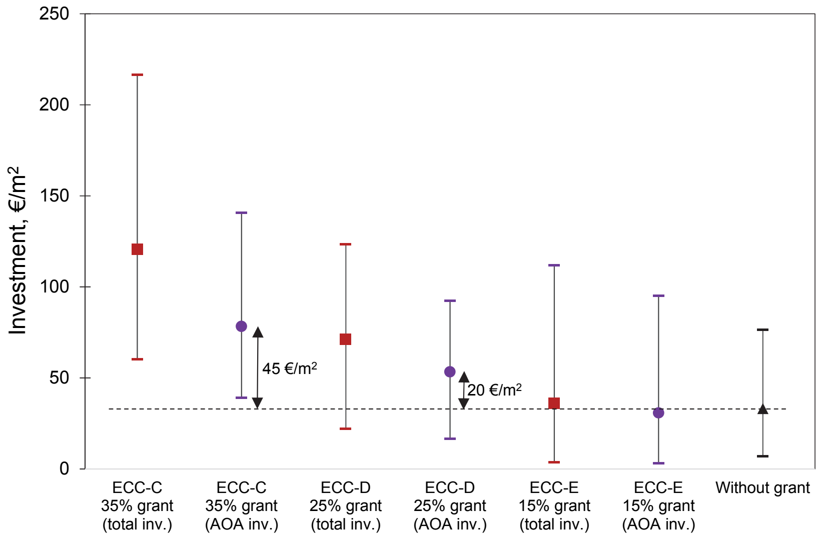


Figure 4.13 Real investments for the renovation of concrete large-panel apartment buildings in order to achieve different energy certificate classes. The dotted horizontal line represents renovation without grant that is selected for comparison. AOA inv. – investments made by the apartment owners' associations (= total investment minus the grant support).

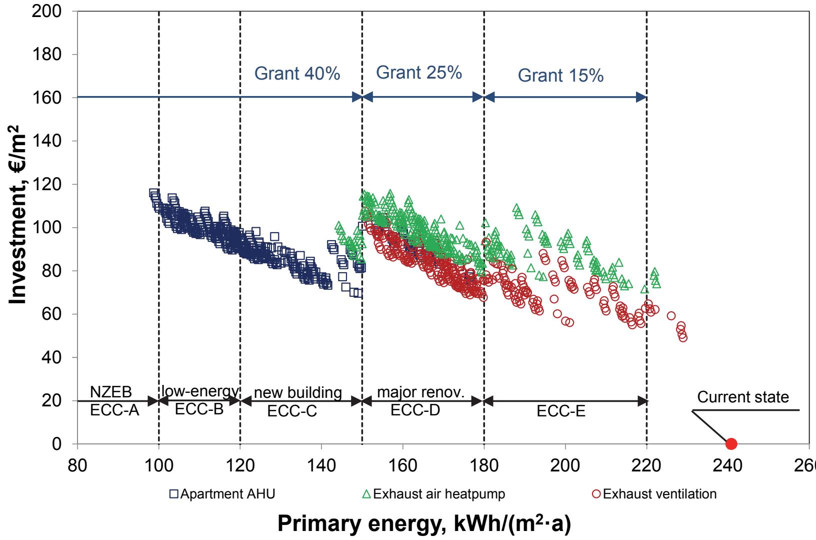
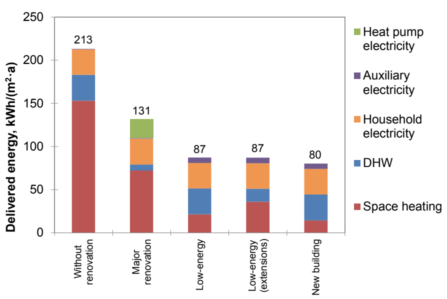


Figure 4.14 Investment need with renovation grants.

4.2.4 Cost effectiveness of demolition and reconstruction

Calculations showed that the use of the delivered space heating energy can be decreased from 153 kWh/(m^2·a) to 15 kWh/(m^2·a) (Figure 4.15 left). Due to decreased compactness and additional linear thermal bridges of buildings with extensions the low-energy renovation scenario with extensions has a higher space heating energy need (32 kWh/(m^2·a)) than the low-energy scenario with the current building body shape (19 kWh/(m^2·a)). Distribution of the PE at the standard usage is shown in Figure 4.15 right. Electricity accounts for the largest share of the PE consumption in different renovation scenarios. For further reduction of the PE, it is necessary to reduce the electricity demand. Comparison of the energy use for low-energy renovation and for a new building shows no substantial differences. Thus, existing buildings can be renovated to meet the same energy-efficiency levels as required for new buildings.



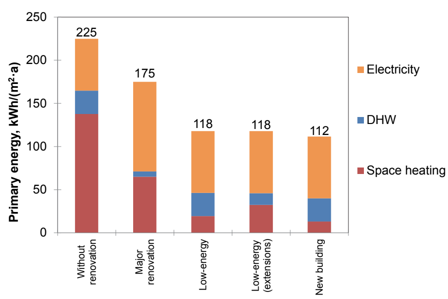


Figure 4.15 Delivered energy use (left) and primary energy use (right) of different renovation strategies.

Global cost was selected to assess the cost effectiveness of renovation strategies (Table 4.2). Before the renovation stage, the global cost is lower than in all renovation scenarios because the calculations do not take into account the maintenance costs. If the pre-renovation stage is taken as the reference point, the escalation should be 9% for the global cost to decrease in the renovation scenarios. The implemented low-budget major renovation has the lowest global cost values in the renovation strategies. The low-energy renovation with building extensions has a ca 15% higher global cost than the low-energy renovation without additional extensions. Demolishing an existing building and building a new one means a ca four times higher global cost than the low-energy renovation and the low-energy renovation with extensions.

Table 4.2 Global incremental cost values at different escalation percentages.

Scenario	Global cost, €/net m^2				
	1%	3%	5%	7%	9%
Without renovation	218	264	326	410	524
Major renovation	290	325	370	432	517
Low-energy	330	353	383	425	481
Low-energy (extensions)	388	412	443	485	543
New building	1463	1484	1513	1552	1605

4.3 Achievement of energy saving targets

4.3.1 Selection of the renovation solutions

The achievement of energy saving targets was tested in a CB in Tallinn. The analysed renovation packages with their energy use and renovation cost are shown in Table 4.3. All packages are calculated with the renovation of the heating system (new 2-pipe system with thermostats) and ventilation system (central exhaust system with heat recovery with an exhaust air heat pump).

Table 4.3 Analysed renovation packages (grey shading shows realized renovation packages).

Renovation measure: Roof		Exterior wall			Windows		Basement	PE, kWh/(m²·a)	Total cost, €	Cost, €/m²
R_1: 40 cm fill insulation inside the roof structure: $U_{roof} = 0.23$ W/(m²·K)	R_2: 30 cm EPS above the roof $U_{roof} = 0.11$ W/(m²·K),	E_1: 15 cm EPS $U_{wall} = 0.21$ W/(m²·K)	E_2: 15 cm GE-EPS $U_{wall} = 0.17$	E_3: 20 cm EPS $U_{wall} = 0.16$ W/(m²·K)	W_1: replacing old windows $U_{old\ window}$=1.8–1.1 W/(m²·K)	W_2: replacing all windows: $U_{new\ window} = 0.9$ W/(m²·K)	10 cm EPS $U_{basement}$ wall = 0.36 W/(m²·K).			
								155	334 000	113
								154	338 000	114
								153	340 000	115
								148	437 000	147
								147	441 000	149
								146	443 000	149
								153	350 000	118
								151	354 000	119
								151	355 000	120
								145	453 000	153
								144	457 000	154
								144	459 000	155

All proposed renovation measures meet the renovation cost criterion (cost < 160 €/heated m²). The decision was made considering PE use. Only packages containing the replacement of all windows met the set criterion PE ≤ 150 kWh/(m²·a). The selected package was $R_2E_2W_1$ (30 cm EPS above the roof, 15 cm GE-EPS on the external wall and replacing only old windows). As before the renovation already 75% of the windows had been replaced, it was decided to change only the remaining 25%. The solution was selected because it is more comfortable from the point of view of inhabitants' living conditions during the renovation (less work inside the apartment) and it prevented opposition by apartment owners who were against replacing the already changed windows. Later analysis showed that this decision was a mistake. The PE usage criterion was planned to be achieved with the installation of a heat pump with a higher COP than 3.0 which was used in the preliminary energy performance calculations.

The thermal transmittance of the external walls and of the roof was significantly reduced. Because the renovation was done on a low budget, thicker layers of additional insulation on the external walls and the roof were not used. The largest unused potential for the reduction of thermal transmittance of the building envelope is in the replacement of windows. The full potential was not realized because not all the windows were replaced. Stairwell doors were not replaced during the renovation. Given a very small share of the total building envelope area, not changing the existing stairwell doors is not relevant in terms of the overall energy demand.

The linear thermal transmittance of thermal bridges in the external wall/internal wall and the external wall/internal floor junctions was practically removed. The linear thermal transmittance of thermal bridges in the external wall/external wall and the external wall/roof junctions was significantly reduced. Problem areas are the external wall/balcony floor junctions and the external wall/window junctions where the linear thermal transmittance of thermal bridges increased after the renovation because windows stayed in their original place and were not moved into the insulation layer.

4.3.2 Energy performance

The usage of PE decreased by 20%: before the renovation it was 212 kWh/(m^2·a) and after the renovation 168 kWh/(m^2·a). Figure 4.16 shows the measured DE usage before the renovation (216 kWh/(m^2·a)), calculated expected DE usage after the renovation (103 kWh/(m^2·a)) and measured DE usage after the renovation (132 kWh/(m^2·a)). A minus sign indicates the heat pump heating energy production.

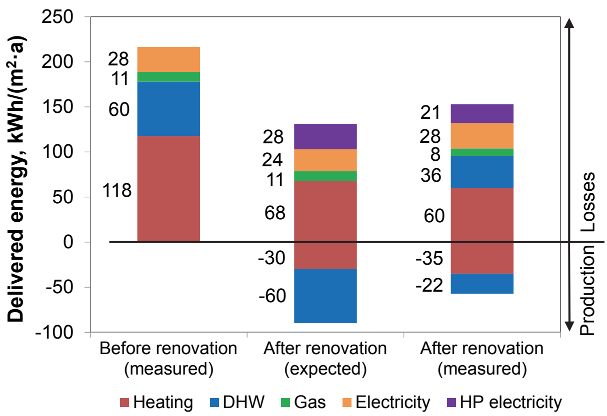


Figure 4.16 Energy performance before and after the renovation (DHW − domestic hot water, HP – heat pump).

Space heating decreased by 49% and DE need for DHW decreased by 40%. The main reason for failure to achieve the calculated energy performance was the low heat production of the exhaust air heat pump. It was estimated that the heat pump would produce 260 MWh annually and cover the total energy need for

DHW. The actual production was 170 MWh, which covered 40% of the energy need for DHW.

4.3.3 Indoor climate

There was a significant difference in the room temperature before and after the renovation during the cold period (>−10 °C). Indoor temperature measurement results in accordance with indoor climate categories (EN 15251, 2007) are shown in Figure 4.17. Before the renovation apartments were overheated, especially during cold periods. There was no significant difference in the RH or moisture excess before and after the renovation. The RH correlated with the outdoor air temperature and dropped below 20% during the coldest period.

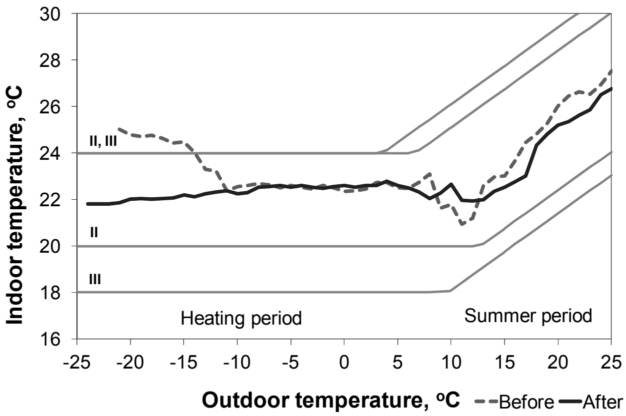


Figure 4.17 Measurement results of indoor air temperature depending on the outdoor air temperature before and after the renovation.

The concentration of CO_2 was measured in three apartments during a two-week period. The results are shown for night-time (23:00−07:00) before and after the renovation, see Figure 4.18. Results indicate that the CO_2 levels in the bedrooms decreased but the indoor climate criterion set before the renovation was not achieved. Before the renovation, the bedroom indoor air CO_2 concentration met the indoor climate class II requirements 20% of the time and the class III requirements 53% of the time. After the renovation, the CO_2 concentration met the class II requirements 66% of the time and the class III requirements 97% of the time.

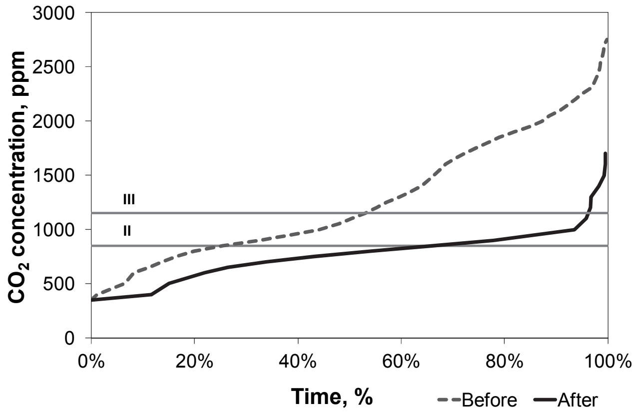


Figure 4.18 Measurement results of indoor CO_2 concentration before and after the renovation.

Airtightness of the building envelope before and after the renovation was measured in eight apartments. Before the renovation three apartments had old 2-pane wooden-framed windows that were a part of the passive stack ventilation system. During the renovation all old windows were replaced with new 3-pane windows with a single PVC frame. The results of airtightness measurements are shown in Figure 4.19. Airtightness of the building envelope improved only in the apartments where the windows were replaced during the renovation. The average air leakage rate decreased by 26%. With the existing PVC windows, the average air leakage rate increased by 18%. Only one apartment out of the measured eight met the set post-renovation airtightness criterion of air leakage rate $q_{50} < 3$ m^3/(h·m^2).

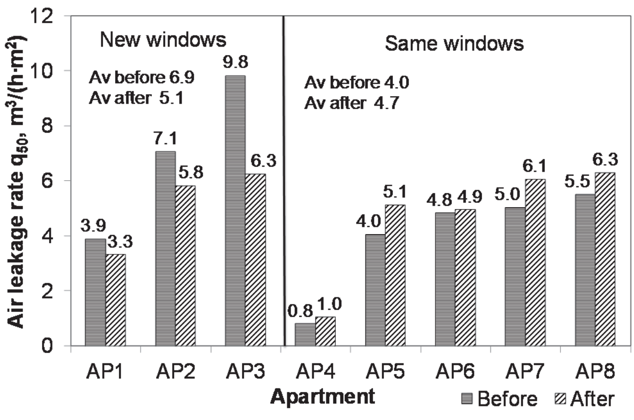


Figure 4.19 Airtightness before and after renovation with two-pane wooden-framed windows replaced (left) and the existing PVC windows (right).

4.3.4 Renovation costs

The total cost of renovation works met the criterion set before the renovation (≤160 €/heated m^2), but the actual costs were 28% higher than planned.

According to estimates, the renovation cost would be 119 €/heated m^2, the actual costs were 152 €/heated m^2 (Table 4.4 and Figure 4.20)

Table 4.4 Expected and actual renovation costs.

Renovation measure	Expected cost		Actual cost	
	€	€/heated m^2	€	€/heated m^2
Insulation of roof	32 000	11	40 700	14
Insulation of external walls (with foundation walls)	83 000	28	132 500	45
Replacement of old windows	21 000	7	16 500	6
Removing the concrete layer around the windows	7000	2	-	-
Renovation of balconies	32 000	11	48 300	16
Renovation of heating system	96 000	32	100 000	34
Renovation of ventilation system	83 000	28	100 000	34
Installation of individual heating measuring system	-	-	12 000	4
Total	354 000	119	450 000	152

Annual costs per apartment m^2 without renovation and with renovation are shown in Figure 4.20. Costs are calculated as average for the loan period (20 years) and with the energy price escalation. The current pilot project with grants was economically reasonable for inhabitants, and annual total costs per apartment m^2 were 3.4 € lower than without renovation. If the same renovation works were made without grants, the annual costs per apartment m^2 would be 4.1 € higher than without renovation. Therefore, financial assistance to apartment owners' associations is required to perform major renovation.

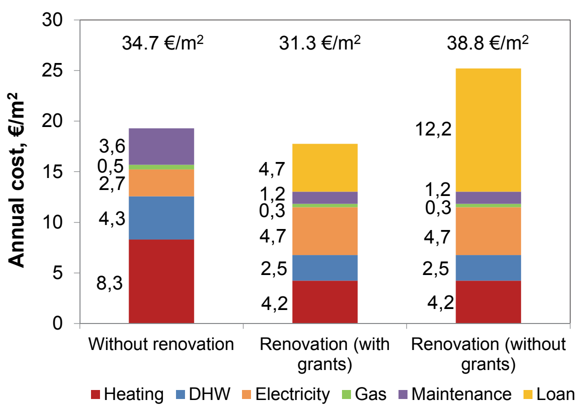


Figure 4.20 Annual costs per apartment m^2 without renovation and with renovation.

4.4 Realization of nZEB renovation

Energy use and investment costs of different renovation scenarios are shown in Table 4.5. The need of DE is reduced by 70% and that of PE by 60% with nZEB renovation. Therefore annual reduction of energy costs is also 70%, which gives a possibility of increasing the annual income from the lease.

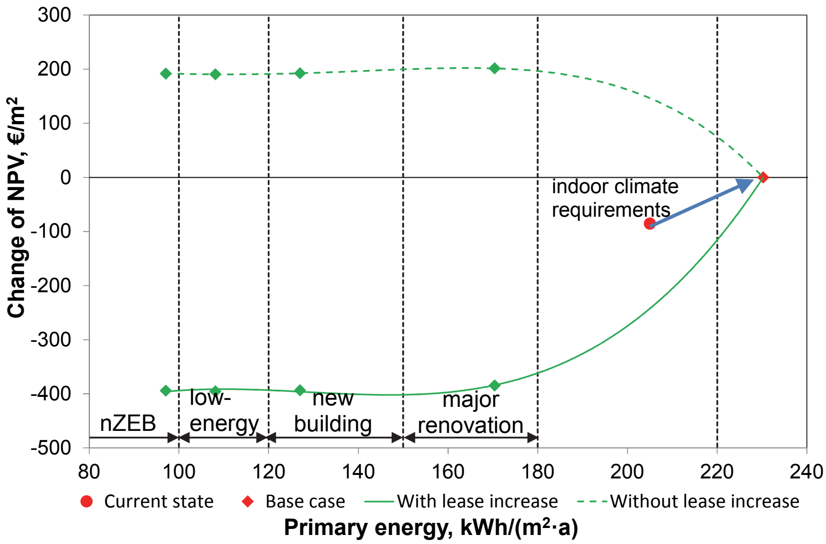
NPV calculation results of renovation packages are shown in Figure 4.21.

The first renovation package that fulfils the indoor climate requirements was set as a base case for renovation packages; this investment is required to ensure a healthy living environment. An increase in the ventilation airflows raises the primary energy usage. Therefore, the NPV of the base case is higher than that of the current state. All the other renovation scenarios decreased the NPV due to the lower energy consumption and increased the annual lease income. Results on the graph show a relatively straight line from the major renovation level to the nZEB level. Renovation to the nZEB level has the same global incremental cost as renovation to a new building or a low-energy building level although investment costs for the nZEB renovation have a 25% higher construction cost than the investment cost of major renovation. Higher energy efficiency compensates for the higher initial investment costs. Without the higher income from the lease, all renovation scenarios increased the NPV. Therefore, the increased income from the lease is the main factor that makes the nZEB renovation profitable.

Excluding the investment costs for apartment modernization reduces the NPV even with no changes in the annual lease income. The results of the NPV calculation are relatively close to zero, which means that at higher renovation costs, the nZEB renovation may increase the NPV when the annual lease income is excluded. Because increase of lease without the modernization of apartments may not be possible, this scenario has not been taken into account in the final conclusions.

Table 4.5 Energy use and investment costs of renovation scenarios.

	nZEB	Low-energy building	New building	Major renovation	Current state with indoor climate	Current state
Thermal transmittance, W/(m^2·K)						
Exterior wall	0.15	0.15	0.15	0.15	1.1	1.1
Roof	0.08	0.08	0.08	0.08	1.0	1.0
Window	0.8	0.8	0.8	0.8	1.6	1.6
Air leakage rate, q_{50}	4.0	4.0	4.0	4.0	4.4	4.4
Delivered energy (energy use of technical systems with system losses), kWh/(m^2·a)						
Space heating	15	15	15	12	79	131
Ventilation	7.6	7.6	7.6	70	70	in space heating
Domestic hot water	30	30	30	30	30	30
Appliances, lighting	29.5	29.5	29.5	29.5	29.5	29.5
Fans, pumps	6.2	6.2	6.2	5.4	5.4	0.5
Total	62	67	88	147	214	191
Produced energy on site, kWh/(m^2·a)						
Solar collectors (heat)	21	21	-	-	-	-
PV panels (electricity)	5.5	-	-	-	-	-
Primary energy use, kWh/(m^2·a)						
Energy performance value	97	108	127	170	230	205
Investment costs of renovation works, €/m^2						
With modernization of apartments	413	400	376	324	-	-
Without modernization of apartments	203	190	166	114	21	-



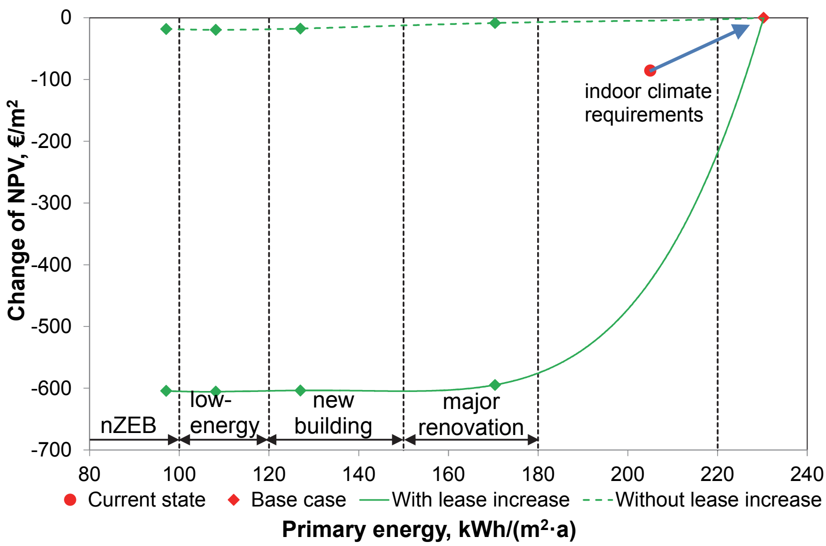


Figure 4.21 Change of NPV of renovation with investment costs of modernization of apartments (above) and without investment costs of modernization of apartments (below).

Calculation results for the payback period show (Figure 4.21) the same principle. When the indoor climate requirements are fulfilled, the annual energy consumption increases. It is shown on the graph as an increase of the primary energy usage. All the other renovation packages have similar payback periods of around eight years with the investment costs for apartment modernization taken into account and payback periods of around four years without the investment costs for apartment modernization. Payback periods of different renovation scenarios show larger differences when the annual lease income is not considered.

This means that changes in the annual lease income have a higher impact on the NPV calculation than the annual reduction of energy costs.

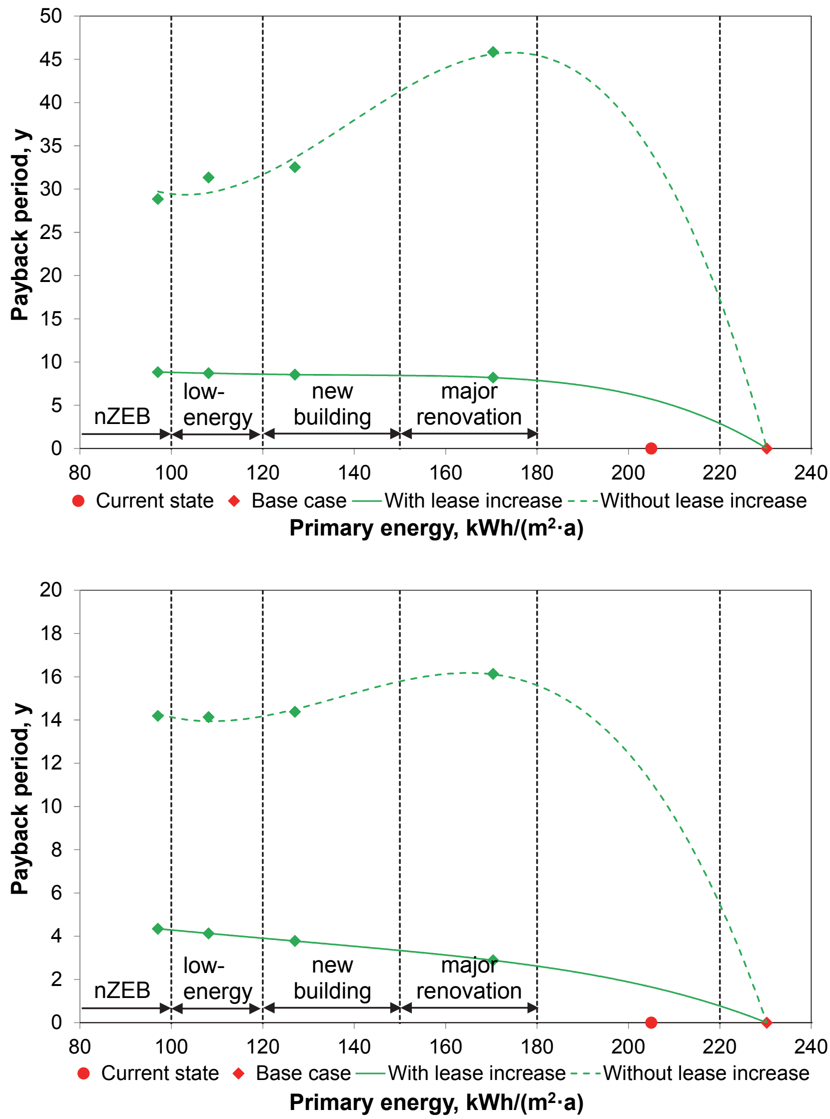


Figure 4.21 Payback period of renovation with investment costs of modernization of apartments (above) and without investment costs of modernization of apartments (below).

4.5 2030 Renovation Strategy for cost-optimal savings

4.5.1 Energy and investment intensity of integrated renovation variants

For all reference buildings, the problem of ventilation rate was faced, which had to be solved before it was possible to start simulation of renovation alternatives. If the energy use of the existing situation was simulated with minimum outdoor airflow rate requirements of "Minimum requirements for energy performance of buildings" (2012) following category II of EN 15251 (2007), the simulated energy use was much greater than the statistical average. Therefore, energy use with two ventilation rates was calculated:

- ventilation rate of 20−40% of minimum requirements resulting in the statistical average energy use;
- standard ventilation rate equal to minimum requirements resulting in a higher energy use.

The energy use calculated with the lower ventilation rate describes the situation in the existing building stock with a poor indoor climate. This value is relevant for the assessment of average energy use in the building stock, which is needed for scenario calculations, because any scenario should be compared with the existing situation. For the assessment of integrated renovation variants the higher energy use value with the ventilation rate equal to minimum requirements was used. The higher value corresponds to the situation where ventilation will be improved. This option was considered also as the relevant baseline, because otherwise deteriorated indoor climate could cause major public health expenses, which are to be quantified as one cost component of energy savings.

In the following figures, delivered heating energy and electricity of simulated variants are plotted as a function of investment cost of renovation. Simulated energy uses are shown with both ventilation rates and occupancy considerations for the existing situation.

In apartment buildings the difference between the average existing and standard energy use was caused by ventilation and partly by some electrical heating in the existing stock. The delivered electricity of the existing stock was reduced from 35 to 24 kWh/m^2 in the reference buildings with standard use and district heating (Figure 4.22). Therefore the difference of electrical heating of 9kWh/m^2 decreases the actual difference of delivered heat, 140 vs. 178 kWh/m^2. All renovation variants were with district heating, but the results apply reasonably well for gas boilers for the cases where district heating is not available. Results show solid heating energy saving, but electricity use was slightly increased because of mechanical ventilation and exhaust air pump in the second renovation variant (ECC D).

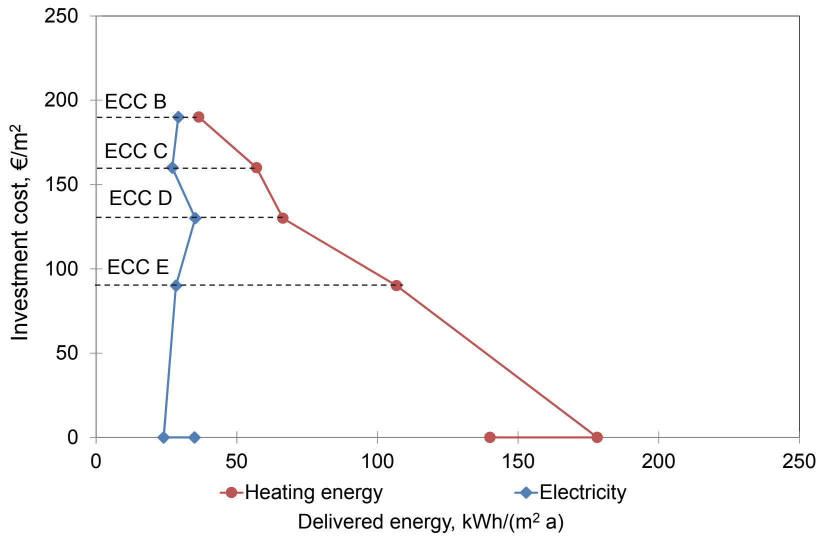


Figure 4.22 Integrated renovation variants in reference apartment buildings. First points on the delivered energy axis (investment cost 0 €/m^2) correspond to the average statistical energy use and to the existing situation with standard ventilation. Next points correspond to renovation variants (ECC E−ECC B).

4.5.2 Cost-optimal integrated renovation variants

To assess the cost effectiveness of integrated renovation variants studied, two methods were used. One was a simple unit cost approach (invested € per MW capacity) often used for comparison of energy production plants. The other method used was an investment calculation with the NPV method. The unit costs were between 400 and 1500 €/MWh/a for the majority of cases (Figure 4.23). According to these results, it is not possible to assess cost effectiveness of renovation variants with this indicator because heat and electricity are summed. The calculation period is not taken into account and comparison with the existing situation is not provided.

The NPV results are free of limitations of the unit cost approach, and show cost-optimal variants with the lowest NPV value (Figure 4.24). The variants studied were sound, as for all building types integrated renovation variants existed that have a lower NPV relative to the existing situation. The number of variants was also sufficient, because the last ones with deeper and more expensive renovation measures showed an increase in the NPV. The results allow concluding that investments slightly below or higher than 200 €/m^2 were cost optimal.

Figure 4.23 Unit costs of energy savings. The points from left to right correspond to renovation variants of each building type (ECC E−ECC B).

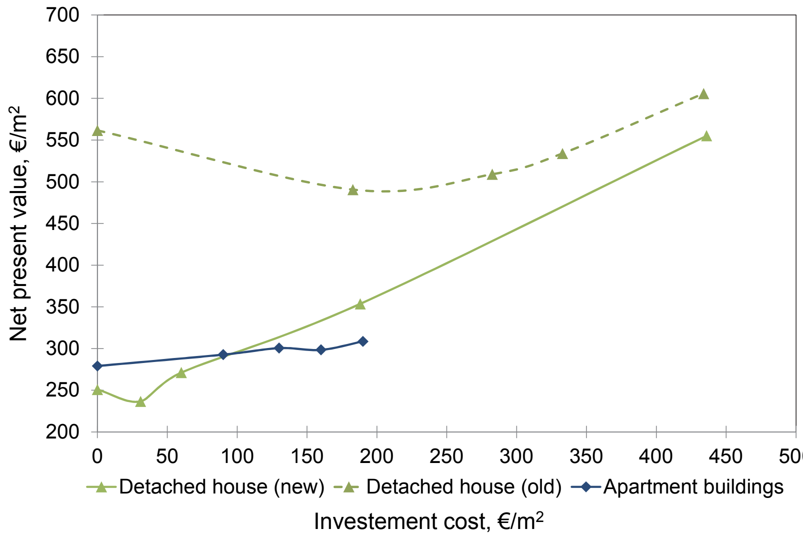


Figure 4.24 Net present value of integrated renovation variants. The first points on the left (0 €/m^2) correspond to the existing situation with standard ventilation and occupancy. Other points from left to right correspond to renovation variants of each building type (ECC E−ECC B).

The variants in Figure 4.24, which are cost-optimal or cost-effective, were selected as realistically achievable in practice with proper regulation and direct renovation funding grants and loans, requiring cost-optimal or just next to cost-optimal deep renovation measures.

Selection of cost-effective variants with a slightly higher cost than that of cost-optimal ones is justified because of the used renovation full cost calculation method (building quality and real estate value are increased but not valuated), relatively low escalation values of energy prices and calculation period of 20 years, which is for residential buildings shorter than 30 years given in cost-optimal regulation (Commission regulation No 244, 2012). Such selection does not change the nature of comprehensive renovation, but instead of cost-optimal technical solutions, slightly more effective and expensive ones are used in order to maximize cost-effective energy savings.

5 DISCUSSION

Cost effectiveness of energy renovations

Until recent years, under renovations primarily small-scale construction works, such as replacement of windows by apartment owners and replacement of the old heat supply substation, were done. External walls of some apartment buildings have been insulated, but the thickness of the additional insulation layer is generally only 100−150 mm. Those minor renovation works have not significantly reduced the energy use of apartment buildings. Average PE use of the studied CB was 224 kWh/(m^2·a) and of the BB 263 kWh/(m^2·a), these values correspond to the ECC F. The results of this study indicate that the global cost optimum for CB renovations is close to PE consumption 120 kWh/(m^2·a), which is the energy efficiency requirement for low-energy apartment buildings, and for BB renovations close to 150 kWh/(m^2·a), which meets the energy efficiency requirement for new apartment buildings. The differences in the results are caused by the difference between the reference buildings used for analysis. In the cost-optimal analysis for BB also smaller apartment buildings (net area < 1000 m^2) were used as reference buildings. For smaller buildings, global cost optimum resulted in a higher PE consumption, which is close to the criteria for the major renovation PE of 180 kWh/m^2·a. As CB are larger, their cost-optimal energy performance level is lower.

One of the most difficult tasks in the renovation of apartment buildings concerns the ventilation system. The economic calculations of individual renovation measures showed that a ventilation system with heat recovery is the only group measured that increases global costs relative to a building's original state. This is partly due to the low air change rate in apartments, high costs of ventilation investments and finishing works, and also due to increased ventilation airflows and electricity use of mechanical supply–exhaust ventilation systems. The current natural ventilation systems are not regulated and apartments are mostly under-ventilated. Ensuring that ventilation airflows meet indoor climate standard requirements increases global costs, but energy savings cannot be achieved through lower indoor air quality as indoor air pollutants affect inhabitants' health (Jones, 1999). Our results showed that global cost values and payback periods for renovation packages with heat recovery are in the same range as solutions without heat recovery, but ensure a lower PE need. Therefore, ventilation systems with heat recovery are reasonable as better energy performance is achieved over the same payback period.

In this study, the energy renovation measures were chosen from measures that are used in building renovation and therefore could be indicated as suitable measures. For example, the thickness of the insulation layer was simulated with 50 mm and 100 mm steps. Ascione et al. (2015) stated that empirical selection of renovation measures cannot guarantee the same accuracy and feasibility of the multi-objective optimization, because all the possible solutions are not explored. In this study, the intention was not to explore all possible solutions, but to use renovation measures for which accurate cost data were available. Accurate cost data are essential in order to perform reliable cost-optimality calculations.

Analysis of renovation vs. demolition showed that the energy performance of existing low-energy buildings and low-energy buildings with extensions is close to that of a new building; however, the construction cost of a new building is about four times higher. Also, the environmental impact of a new building as a renovation scenario is the highest. Our result that demolition and constructing a new building has a higher environmental impact is in principle similar to conclusions found in previous studies (Ireland, 2008; Yates, 2006), which report that equivalent refurbishment can be as "green" as new buildings but the difference is rather small and depends on the case and the chosen time period. Since all renovation scenarios have lower total environmental impact compared by status quo (without renovation), we have proven the need for renovation of the older housing stock from the environmental aspect. It should be noted that some of the additional factors related to a new building (transportation, HVAC systems, construction waste management) were excluded in our analysis, otherwise, the difference between renovation vs new building would even have been larger.

Tallinn Vision Council has pointed out that the floor planning of these old dwellings is unsuitable for families (Sarv, 2013) because bathrooms and kitchens are small. In addition, in the five-storey buildings, narrow staircases and absence of elevators restrict movement of families with small children and elderly or disabled people. Demolition is a plausible solution when some region is intended to be thoroughly renewed. At higher volumes, the construction costs would be lower and a larger macro-economic impact would be also an important factor, but here further detailed analysis is required. On a single building level, renovation is substantially cheaper than building a new dwelling. The number of old concrete-element buildings reveals a potential solution in favour of renovation due to enormous construction capacity. Power (2008) stated that even with the highest feasible level of demolition, the existing stock would remain the dominant energy challenge in the built environment far into the future. The focus should be on sustainable design from the materials that contain a low amount of energy, on the use of local materials and the durability of buildings during both renovation and new construction.

Economic calculations of renovation scenarios showed that the global costs of low-energy apartment building packages are in the same range as or lower than the current global costs of reference buildings. It is possible to reduce the energy consumption of apartment buildings by up to 70% without increasing occupants' current costs. Although renovation to the energy performance level of a new building and low-energy building is in longer terms economically viable, the high investment costs for renovation are the major barrier to renovation. This study included only energy efficiency related renovation works but often there is a need to replace the existing electrical system and plumbing, fix the load-bearing structures etc. Those works increase the investment costs and are more crucial in terms of safe use of the building than energy efficiency improvements works.

Apartment owners' associations' own investment capability is not sufficient to cover the cost of crucial repair works and significantly improve the building' energy efficiency. Analysis showed that the apartment owners' capability to invest in energy efficiency is ca four times lower than it is necessary to meet low energy building requirements. Apartment owners' own funds often allow only single renovation measures, which do not fulfil even the energy efficiency requirements of major renovation and often do not result in any significant change in energy use. Therefore, financial support is needed to execute renovation in apartment buildings in order to achieve future energy efficiency targets. Without grants, the annual cost (energy cost and renovation loan) after the renovation would be higher for apartment owners and that would make it difficult for the apartment owners' association to make a decision for major renovation. Subsidies raise apartment owners' interest in investing in energy efficiency improvement. Analysis of investment costs with a renovation grant showed that apartment owners' own investment with 35% grant was ca two times higher than without the grant. This shows that apartment owners will invest more when there is a significant grant, even when the grant requires renovation to the same energy efficiency level as a new building.

Previous studies have concluded that investment in buildings for energy efficiency improvement is cost effective on a national level as well. Pikas et al. (2014) stated that a total of 17 jobs per 1 M€ of investment in renovation had been generated per year and the average total tax revenue from the deep renovation projects was 32–33%, including VAT and direct and indirect labour taxes. Tuominen et al. (2013) also reached the conclusion that the investments in energy-efficient buildings are an economically sound and effective way to save energy. The required investments carry manageable costs and a few percent rise in annual construction and renovation investments can decrease total PE consumption 3.8–5.3% by 2020 compared to the business-as-usual scenario. Based on the aforementioned studies, we can say that the investment in buildings for energy efficiency is not only cost optimal on a building level but also on a national economic level.

Achievement of energy saving targets

Analysis of an implemented renovation project showed that the PE consumption was higher than estimated. The main reason is the performance of the heat recovery system with the exhaust air heat pump. It was estimated that the heat pump would cover the total energy need for DHW. Yet measurements after renovation showed that the heat pump covered only 40% of the energy need for DHW. Identification of the exact causes requires further investigation of the system; however, it seems that the system did not start working as expected. That kind of system was a new solution for the renovation of apartment buildings in Estonia. Previous studies about retrofitting have concluded that innovative systems will probably not work exactly as predicted (Branco et al., 2004). Subsequent research in Estonia (Kõiv et al., 2012) showed that the estimation of the coefficient of the performance of an exhaust air heat pump was correct (COP = 3.0).

One of the reasons for failure to achieve the PE consumption criterion was that thermal bridges were not eliminated in the external wall/window junction. Calculations showed that in the current case the heat loss through thermal bridges around the windows and the heat loss through additionally insulated external walls are at a similar scale (Ilomets and Kalamees, 2013). In energy calculations it was estimated that the linear thermal transmittance of thermal bridges in the external wall/window junction would be diminished. The reality was that the linear thermal transmittance of thermal bridges in the external wall/window junction increased because not all the windows were replaced and therefore remained in their original position. The decision not to replace all the windows was made by the apartment owners' association, who had to approve the designed renovation solutions. The apartment owners found it too expensive to replace all windows and move them into the insulation layer. The back-up plan to place additional insulation to the window jamb was not possible in the extent that was planned. Removing part of the concrete layer surrounding the windows and replacing it with a layer of insulation was not possible. Therefore it was impossible to install a sufficient layer of insulation to the window jambs, but the thermal bridge in the external wall/window junction is very sensitive to the thickness of insulation on a window's jamb (Ilomets and Kalamees, 2013).

Another reason why meeting the PE consumption criterion failed was that the airtightness of the building envelope was not improved. In the energy calculations, it was estimated that the air leakage rate after renovation would be $q_{50} < 3$ m^3/(h·m^2). The actual air leakage rate after renovation was $q_{50} = 5$ m^3/(h·m^2). Measurements after the renovation showed that airtightness improved only in the apartments where all windows had been replaced, which was the expected result. As studies have shown, replacing old draughty windows with modern sealed windows will reduce the background infiltration rate by the order of 0.1 ach to 0.3 ach (Ridley et al., 2003). If windows were not replaced, the air leakage rate would actually increase. This is probably caused by new openings for ventilation inlets behind the fresh air radiators. A gap remains around the air inlet sleeve and the external wall that is difficult to tighten.

Measurements of the indoor temperature before and after the renovation show improvements due to a better adjustment of the new heating system. Overheating is avoided during colder periods. The problem is that considering the CO_2 concentration, the indoor climate category II criterion was not achieved. After the renovation, the bedroom indoor air CO_2 concentration met indoor climate class II requirements only for 66% of the measurement time. The main reason for this is the reduction of the airflow in the ventilation system by the inhabitants. The design airflow for the ventilation system was 2.1 m^3/s. After renovation the measured airflow was 1.43 m^3/s. Fan speeds in two air handling units were reduced by the inhabitants because of the problems with thermal comfort caused by fresh air radiators. In spring and autumn, the air that enters the radiator does not heat up sufficiently. The reason lies in the fact that an insulated building does not need substantial heating in spring and autumn, so radiators are at a low temperature and the entering cold air does not heat up, causing thermal discomfort. Another problem associated with the renovation of the ventilation system is the airtightness of the ventilation shafts. The existing ventilation shafts were not airtight and new ventilation ducts were placed in the existing air shafts to ensure the required airtightness of the ventilation ducts. Installation of new ducts was not always successful because the joints of the existing shafts were not perfectly aligned. In some shafts it was impossible to insert a new duct to the entire length of the existing shaft. So the airtightness of all the exhaust ducts was not ensured and therefore it is difficult to achieve the design exhaust airflow from all apartments.

From an economic point of view, the pilot project was successful. Apartment owners' annual costs were reduced and the cost criterion of renovation works was fulfilled. Annual cost reduction was achieved due to grants for renovation works. Without the grants, the annual cost after the major renovation would be higher for apartment owners and that would make it difficult for apartment owners' association to make a decision for major renovation as one of the main priorities for apartment owners is a short payback period (Medineckienė and Björk, 2011). Such an approach is insufficient for choosing renovation solutions. The effectiveness of retrofitting an apartment building should be evaluated from various perspectives: energy conservation, improved state of the building structures, prolonged lifetime of the building and an increase in its market value taken into account (Zavadskas et al., 2008). Some studies have shown that renovated buildings are less sensitive to fluctuations in the heat price than those where renovation is not performed. Despite constant loan payments, renovated buildings will be in a better position in the sense of the overall payment rather than non-renovated buildings (Biekša et al., 2011). This study showed that although the impact of the heat price on the overall payment is significantly diminished after the renovation, the overall payment would be higher than with non-renovated buildings if no grants are available for apartment owners' associations. The reason is that existing apartment buildings have natural ventilation systems which need replacement with mechanical ventilation systems with heat recovery to ensure a good indoor climate quality. Fans and, depending on the solution, exhaust air heat pumps or heating coils in apartment-based air handling units need electricity, therefore the overall electricity consumption of the apartment buildings will increase. Adding a loan payment and considering the fact that electricity is significantly more expensive than district heating, the reduction of the heating energy need does not cover the loan payments and increased electricity bills. Grants for renovation works are required to guide inhabitants to choose a better indoor climate and to make the decision to install a proper ventilation system which seems costly at first sight.

It was found that renovation of apartment buildings to the nZEB level is economically profitable but there are some limitations on this conclusion. The studied building is perfectly aligned towards north−south with the longer wall, which allows installing on-site renewable energy production equipment on a large area. If the building faced east–west with its longer wall, possibilities of on-site renewable energy production would be lower and energy efficiency requirements of nZEB renovation should be achieved with a thicker insulation layers on external walls or with windows with lower thermal transmittance. Those renovation measures have higher investment costs and the NPV of the renovation scenario would be higher.

The annual increase of the lease income in this study is the same for all renovation packages from the major renovation level to the nZEB level. The annual energy cost on the nZEB level is almost 60% lower than on the major renovation level. Therefore the annual increase of the lease income may be higher in a nZEB level building. A higher lease income would make renovation to the nZEB level more profitable than major renovation or new building energy efficiency level renovation.

An increased annual lease income plays the main role in the economic viability of nZEB renovation. The results show a slight reduction of the NPV of nZEB renovation without a higher lease income after renovation. When a building needs higher investments to achieve the nZEB energy efficiency level, the NPV may increase after the renovation if the annual lease income is not taken into account. For a private owner of an apartment, the nZEB renovation of the building is profitable when the apartment does not need modernization. More detailed information about the lease rate changes according to the energy efficiency level of the apartment building is needed for further analysis. If the increase in the annual lease income is the same for all renovation scenarios, we cannot make a conclusion which renovation scenario (new building, low-energy building, nZEB) has the highest profitability for the building owner but we can conclude that nZEB renovation is profitable if the increase of the annual lease income is taken into account.

Renovation strategy for cost-optimal savings

Our results show that as to energy supporting policy, there is no direct need for subsidies for minor energy efficiency improvements. Apartment owners' own funds should allow them to execute minor energy renovation works. Some grants may be needed rather as a tool for maintaining or improving the current state of the existing buildings in areas where inhabitants' incomes are low and therefore apartment buildings are not renovated at all. Energy efficiency subsidies should be targeted to apartment buildings that attempt to fulfil energy efficiency requirements for new buildings or low-energy level. Financial support is also necessary to execute major renovation of smaller buildings for which cost-optimal levels are around PE 180 kWh/($m^2 \cdot a$), which means major renovation energy efficiency requirements. Grant support for major energy renovation should be lower than grant support for renovation to the new building energy efficiency level or low-energy energy efficiency level in order to motivate building owners to execute deep integrated renovation to at least new building energy efficiency level. This result complements the conclusion of a previous study (Uihlein and Eder, 2010) that it is reasonable to ensure that at refurbishment in any case the best energy efficiency level possible is installed, not only for major renovations, but also for individual building elements. The current study analysed integrated renovation up to low-energy energy level and it was found that the aim of integrated renovation should be the best energy efficiency level possible.

Grants of higher rates should be directed to apartment buildings that aim to fulfil energy efficiency requirements for new buildings or low-energy level. Our analysis did not cover the renovation of apartment buildings to nZEB energy performance level with sufficient depth in order to draw conclusions about its economic viability. For larger apartment buildings renovation to low-energy energy efficiency level was found to be cost optimal. In view of the future energy efficiency goals, the current activities should be directed primarily to supporting the deep integrated renovation of existing apartment buildings.

6 CONCLUSIONS

This study analysed the strategy for supporting policy, economic viability and investment costs of energy renovation using apartment buildings in Estonia as an example. The measured energy use of brick apartment buildings and concrete large-panel apartment buildings was analysed to determine the current state before renovation. Individual energy saving measures and renovation packages were composed for reference buildings in order to analyse cost- optimal energy efficiency levels and investment costs. All renovation packages included the installation of a ventilation system and renovation of the heating system in order to avoid energy savings at the expense of indoor climate.

From individual measures, insulating external walls has the highest effect on the reduction of the delivered energy consumption. However, as the most comprehensive solutions for individual measures are not the most effective, energy renovation packages give the best results. Additional thermal insulation on the building envelope with the replacement of windows, installation of a new two-pipe heating system and installation of a ventilation system with heat recovery will allow the energy efficiency requirements for new apartment buildings to be achieved. Depending on the building type, installing solar collectors for producing domestic hot water are needed in addition to the previous package to reach full technical energy savings potential (up to 70%) and to fulfil the criteria of low-energy buildings.

Global cost calculations for different energy performance levels showed that the cost-optimum level for the renovation of apartment buildings, depending on the building type, was close to the energy efficiency requirements of a new apartment building or close to the energy efficiency requirements of a low-energy building. Reductions of up to 70% in the delivered energy consumption are both technically feasible and economically reasonable to apartment owners.

Single energy efficiency measures financed from apartment owners' associations' own funds were found to have no significant impact on the buildings energy consumption. Integrated deep energy renovation is needed in order to achieve the future energy efficiency goals set by the European Union. Although deep renovation would be economically viable in longer terms, the investment capability of apartment owners' associations is not sufficient to achieve new building or low-energy building energy efficiency level. Therefore financial assistance is necessary to execute deep renovation. Analysis showed that subsidies would increase apartment owners' associations' investments to improve building energy efficiency. Although some financial support is necessary for smaller apartment buildings to execute major renovation, the main target group of subsidies should be apartment buildings that perform renovation of the new buildings level or low-energy performance level.

Analysis of an executed renovation project showed that the success of the renovation project depended on the detailed design of the renovation solutions and ability to direct the apartment owners to make the right choices. Although at large the renovation was successful, as the heating costs were reduced and indoor climate and aesthetics improved, there were some key issues that led to failure to achieve some of the targets set before renovation. Thermal comfort provided by the ventilation system is a key factor. Otherwise inhabitants will block the ventilation system and the designed indoor climate is not achieved. Thorough information and explanations to apartment owners are required to encourage them to make decisions that may seem costly at first sight, but are required to achieve the full energy efficiency potential of renovation works.

Analysis of the planned nearly zero-energy building renovation project showed that nearly zero-energy building renovation is profitable when the increase in the annual lease income is taken into account. Only the energy consumption reduction is not enough to make nearly zero-energy building renovation profitable for the building owner. The payback period of nearly zero-energy building renovation without the lease income rise is at least around 30 years. With the best scenario, the nearly zero-energy building renovation payback period is around 8 years when the increase of the annual lease income is taken into account.

Calculation of future cost-optimal savings showed that cost-optimal energy performance level of deep integrated renovation corresponded in most cases to minimum energy performance requirements of new buildings (energy certification class C). The typical cost-optimal renovation cost was around 200 €/m^2, indicating that a high investment cost is one of the major barriers to deep renovation. Therefore, in order to realize the potential of cost-optimal energy saving, support schemes are needed especially in residential buildings, in order to provide financial support on condition that deep integrated renovation measures be used.

Cost-optimal energy savings were remarkable in heating energy, which was reduced by a factor 3 in residential buildings. Electricity use, on the contrary, tended to increase because of increased ventilation and use of heat pumps. This resulted in a negligible technical and cost-optimal electricity saving potential in the building stock (0.3% and 0.7%, respectively) while heating energy saving potentials were 60% and 40% of the energy use in 2010, respectively.

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Tallinn University of Technology	2009	Environmental Engineering, Master of Science
Saaremaa Co-Educational Gymnasium	2003	Secondary education
Aste School	2000	Lower secondary education

Language competence/skills

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Estonian	Native language
English	Average
Russian	Basic

Special courses

Period	Educational or other organization
11.-13.06.2011	Sustainable and energy-efficient building design and refurbishment, Tallinn University of Technology
13.-16.12.2010	Net-zero-energy-buildings and on-site renewable energy, Aalto University
17.-18.02.2010	Solar Energy Systems, Tallinn University of Technology

Professional employment

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2012 – ...	Tallinn University of Technology	Early Stage Researcher
2010 – ...	Fund KredEx	Project Manager for Energy Efficient Buildings
2007 – 2010	NCC Ehitus AS	Site Engineer

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Hariduskäik

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Tallinna Tehnikaülikool	2009	Ehitusteaduskond, Kütte- ja ventilatsiooni õppetool, magistrikraad
Saaremaa Ühisgümnaasium	2003	keskharidus
Aste Põhikool	2000	põhiharidus

Keelteoskus

Keel	Tase
eesti	emakeel
inglise	kesktase
vene	algtase

Täiendusõpe

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11.-13.06.2011	Säästlik ja energiatõhus hoonete kavandamine ja renoveerimine, Tallinna Tehnikaülikool
13.-16.12.2010	Liginullenergiahooned ja taastuvenergia kasutamine, Aalto University
17.-18.02.2010	Päikeseenergia süsteemid, Tallinna Tehnikaülikool

Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2012 - ...	Tallinna Tehnikaülikool	Nooremteadur
2010 - ...	SA KredEx	Hoonete energiatõhususe projektijuht
2007 - 2010	NCC Ehitus AS	Objektiinsener

Publications

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PAPER I

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Cost effectiveness of energy performance improvements in Estonian brick apartment buildings

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ABSTRACT

The paper discusses energy renovation measures for brick apartment buildings in Estonia (cold climate). The study analyses the energy usage of brick apartment buildings and simulations for four reference building types selected to represent the brick apartment building stock. Our results show that renovation of old apartment buildings enables the same energy performance requirements as in new apartment buildings to be achieved. Therefore, focus should be on deep renovation of apartment buildings. It is particularly relevant in the context of the EU climate and energy targets for 2020 target. Deep renovation projects will result in low level energy usage in a building but at the same time substantial financial support packages are required to motivate apartment owners to take an extra step.

1. Introduction

In terms of energy performance, the environmental impact of new residential buildings is negligible compared to the impact of the existing residential building stock in the European Union [1]. Therefore, it is important to focus on renovating the existing residential building stock, in addition to the demonstration projects of the new Nearly Zero Energy (n*ZEB*) buildings. To reduce the energy consumption of buildings, the European Commission has put forward an Energy Performance of Buildings Directive [2], which, among other items states that under major renovations the energy performance of the building or the renovated part thereof is upgraded in order to meet minimum energy performance requirements in so far as this is technically, functionally and economically feasible.

Apartment buildings in Northern Europe consume energy for heating 150 kWh/(m^2 a) and for electricity 40 kWh/(m^2 a) [3]. It is possible to reduce space heat demand up to 10 times, for example according to the Passive House standard, one of the main energy performance criteria is the maximum space heating demand of 15 kWh/(m^2 a) [4]. It is well known that current energy consumption of apartment buildings can be significantly reduced, but in terms of the apartment owners, the renovation measures must be cost effective in order to enable the implementation.

Estonia was selected as a research base because Estonian apartment building stock contains many buildings of the same type, which allows conclusions to be drawn on the basis of the results from the reference buildings in the apartment building stock. According to the National Reform Programme "Estonia 2020" of Estonia's competitiveness strategy [5], the most important measures of the energy saving strategy are to set up more stringent energy efficiency requirements, investing into apartment buildings and detached houses.

In Estonia most of the apartment buildings were built during the period 1960–1990. Preliminary studies have shown that the total heat consumption for typical apartment buildings prior to retrofit was between 170 kWh/(m^2 a) [6] and 280 kWh/(m^2 a) [7]. These values are close to the results of other Eastern European countries [8,9].

There is an urgent need for solutions to improve energy performance of dwellings because of rising energy prices and energy saving policies that focus on energy use in dwellings. Earlier studies suggest that the European Union (EU) 2020 energy savings target will be missed by a wide margin but at the same time the EU has sufficient cost-effective energy end-use savings potential to realise its overall 20% energy savings target [10]. The aims of this study are:

- to provide economically viable deep renovation measures for apartment buildings in cold climate;
- to find out the extent of renovation that makes financial support packages for apartment owners most useful.

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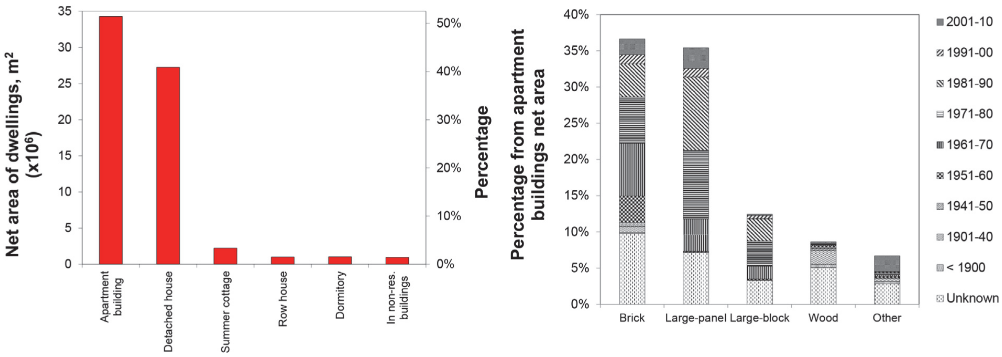

Fig. 1. The net area of dwellings (left) and distribution of construction types by the net area of apartment buildings in Estonia (right).

2. Methods

2.1. Studied buildings

This study focuses on the energy performance of apartment buildings, as they form the largest share of dwellings in Estonia. According to statistics, there are 264 000 dwellings with a total net area of 66 700 000 m^2, see Fig. 1 left. Apartment buildings account for 51% (34 300 000 m^2) of the total net area of dwellings. Another large group of dwellings is detached houses with 41% (25 100 000 m^2) of the total net area of l dwellings.

Brick apartment buildings were selected for the study because that constructional material is dominant in Estonia, and 80% of brick apartment buildings are over 30 years old, see Fig. 1 right. Only during the main industrialisation period in the 1970–1980s, prefabricated concrete large panels were the dominant type of buildings.

For further investigation of indoor climate and energy performance, 30 brick apartment buildings were randomly selected from the database of the Estonian Union of Co-operative Housing Associations, based on age, number of floors, size and structures of buildings. The buildings were constructed between 1940 and 1990. All the buildings studied were in private ownership.

Typically, the studied dwellings had natural passive stack ventilation. In some apartments, kitchens were supplied with a hood. In all of the dwellings, windows could be opened for airing purposes. Buildings were heated with district heating and mainly one-pipe radiator heating systems. Typically, radiators were not equipped with special thermostats; therefore, individual control of the room temperature was impossible. Room temperature for the whole building was regulated in heat substations depending on outdoor temperatures.

Original drawings of the buildings were analysed to determine the thermal properties of the building envelope. The thermal transmittance of the external wall was measured in six buildings. The thermal transmittances of the building envelope of the apartment buildings were:

- External walls: $U_{wall} \approx 0.8–1.2$ W/(m^2 K) (thickness was typically 43–56 cm, some cases including ~5 cm mineral wool $\lambda \approx 0.05$ W/(m K) for thermal insulation);
- Roof-ceilings: $U_{roof} \approx 0.7–1.1$ W/(m^2 K) (~20 cm mixture of sand and sawdust or ~5 cm mineral wool $\lambda \approx 0.05$ W/(m K) for thermal insulation);
- Windows: $U_{window} \approx 2.9$ W/(m^2 K) (a two-pane window tightened to the wall with a tow (not an airtight connection) and windows designed to be leaky to guarantee natural ventilation);
- The building envelope contains considerable thermal bridges [11].

In many cases buildings were insufficiently heated and ventilated. This resulted in bad indoor climate and high indoor humidity loads [12], but at the same time reduced occupants' energy bills.

Based on typology, age, size and number of floors of the building, four building types were selected as reference buildings from different construction periods (<1960, 1961–1970, 1971–1980, 1981–1990) (Fig. 2 and Table 1) for energy simulations and economic calculations. Most apartment owners' associations had already realised some minor energy saving measures; to perform energy simulations for the current state of buildings it was assumed that 2/3 of the windows had been replaced ($U_{window\ (glass/frame)}$, 1.8/2.0 W/($m^2$ K)) and the building end walls had been insulated with a 50 mm thermal insulation [13].

Building types Ref "A", Ref "B" and Ref "C" had unheated basements. Building type Ref "D" had no basement. Storage rooms and technical rooms were located in the heated area of the first floor.

Reference buildings were selected to represent the whole distribution of age, size and number of floors, see Fig. 3. By changing the net areas of the reference buildings by ±25%, we can cover 50% of the whole building stock of brick apartment buildings.

2.2. Measurements

The actual use of energy was determined for the building as a whole and differences between the apartments were not distin-

Table 1
Characterisation of reference buildings "as built" based on measurements and calculations from drawings.

	Reference buildings			
Construction period	Ref. "A" <1961	Ref. "B" 1961–1970	Ref. "C" 1971–1980	Ref. "D" 1981–1990
Number of floors	2	4	5	10
Net area, m^2	508	1383	3147	11 374
Heated area, m^2	388	1154	2623	10 781
Compactness: building envelope, m^2/volume, m^3, m^{-1}	0.60	0.44	0.47	0.32
Number of apartments	8	32	40	162
Thermal transmittance of walls U_{wall}, W/(m^2 K)	1.1	1.0	0.8	0.8
roof U_{roof}, W/(m^2 K)	1.1	1.1	0.9	0.7
windows $U_{window\ (glass/frame)}$, W/($m^2$ K)	2.9/2.0	2.9/2.0	2.9/2.0	2.9/2.0

Fig. 2. Reference buildings for the analysis of energy renovation of Estonian brick apartment buildings.

guished. Our analysis includes measurements of electricity, gas, water, domestic hot water and heating (space heating and heating of ventilation air) over a 3-year period. The data about energy use were retrieved from energy companies and apartment owners.

For buildings where all the delivered energy components data were available, the Primary Energy (PE) was calculated. PE takes into account the use of the primary energy (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:

- wood, wood-based fuels, and other bio fuels: 0.75,
- district heating: 0.9,
- fossil fuel (gas, coal. etc.): 1.0,
- electricity: 2.0.

2.3. Simulations

Simulations were done in two steps. First, the model was calibrated based on the field measurements, second, the calibrated model was simulated on the standard use of the building to evaluate energy saving measures. Energy performance of reference buildings was simulated by the energy and indoor climate simulation programme IDA Indoor Climate and Energy 4.5 (IDA-ICE) [14–16]. This software is meticulously validated [17–21] and allows the modelling of a multi-zone building, internal and solar loads, outdoor climate, HVAC systems, dynamic simulation of heat transfer, and air flows, and has been used in many energy performance and indoor climate applications [22–26].

Simulation models were calibrated based on the field measurements of indoor climate, building envelope, performance of service systems, and the energy use of buildings. Real dimensions, thermal transmittance and air leakage of the building envelope, linear thermal transmittance of thermal bridges, ventilation airflow, and occupation were used in the calibration of the model. To calibrate the building model the real use of electricity, the factor 0.7 for heat emission of appliances was used [27]. To limit solar heat gain, usage of internal blinds varied between 0.25 and 0.5. As a result of the comparison of the simulated (ideal heater) and the measured (radiators without thermostats) space heating consumption,

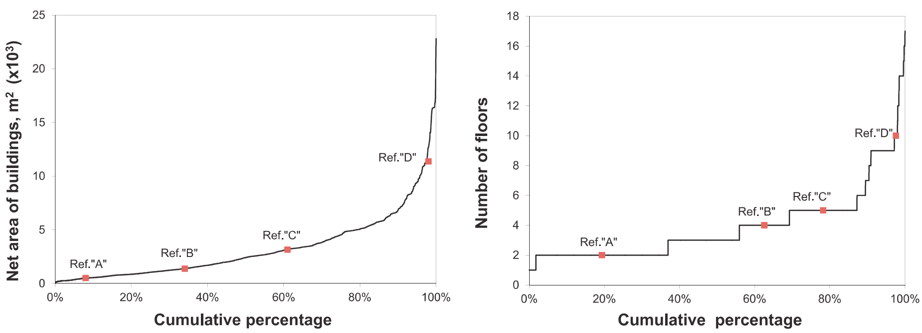

Fig. 3. Net area (left) and number of floors (right) of reference buildings and the whole building stock of brick apartment buildings.

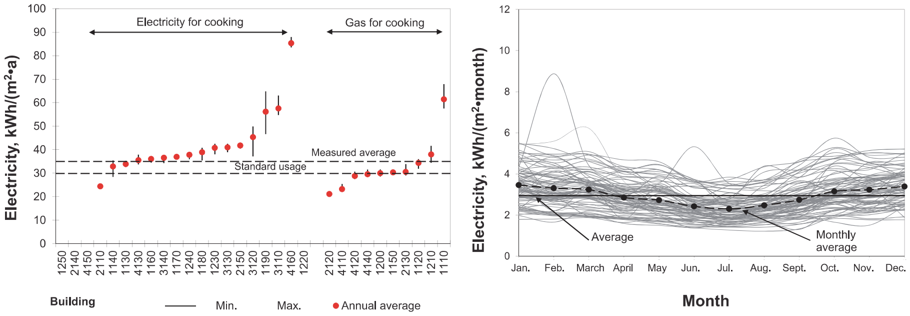

Fig. 4. The average annual (left) and monthly (right) use of electricity.

the simulated consumption was found higher due to the efficiency of using internal heat gains and control of the real heating system (0.5–0.7).

After calibration of the simulation model, the energy renovation measures were calculated according to a unified calculation methodology and with a standard usage [27–28] because of our aim to analyse the energy usage of the building type. Occupant behaviour related energy usage is variable and not related to the building type. Internal heat gains in the renovation measures were as follows:

- Occupants: 15.8 kWh/(m^2 a). Heat from occupants was counted from 3.0 W/m^2 and 80 W/person using the ISO 7730 standard (1.2 met, 0.7 clo);
- Appliances, equipment: 15.8 kWh/(m^2 a). Heat from appliances and equipment was counted using 3.0 W/m^2 and the usage rate was 0.6.
- Lighting: 7.0 kWh/(m^2 a). Heat from lighting was counted using 8 W/m^2 and the usage rate was 0.1.

Ventilation airflow was 0.35 l/(s m^2) for a non-renovated case representing indoor climate category III (an acceptable, moderate level of expectation for indoor climate) and 0.42 l/(s m^2) for renovation packages representing indoor climate category II (normal level of expectation for indoor climate) [29] counted per heated area. Infiltration airflow in a non-renovated case was calculated with the measured value for brick apartment buildings (q_{50} = 4.4 m^3/(h m^2)) and in a renovated case a slight improvement in the airtightness of the buildings (q_{50} = 4.0 m^3/(h m^2)) was assumed. The use of domestic hot water (DHW) heating need was 520 l/(m^2 a)/30 kWh/(m^2 a), which makes approximately 35–45 l/(pers. × day) depending on the density of living.

The Coefficient of Performance (COP) of exhaust air ventilation heat pump was 3.5 during the heating period and 3.0 during summer. Lower COP in summer results from the use of the heat pump only for domestic hot water (DHW), which has a higher temperature (55 °C) [30].

An Estonian Test Reference Year [31] was used for outdoor climate conditions (design outdoor temperature for heating −21 °C, annual heating degree days at t_i 17 °C: 4160 °C d). Energy simulations were made for different individual renovation measures (different thicknesses of additional external thermal insulation, improvement of windows, ventilation system) and renovation packages to correspond to different energy certification levels:

- Energy Certification Class D: PE ≤ 180 kWh/(m^2 a) (criteria for major renovation);
- Energy Certification Class C: PE ≤ 150 kWh/(m^2 a) (criteria for a new building);
- Energy Certification Class B: PE ≤ 120 kWh/(m^2 a) (criteria for a low-energy building).

2.4. Economic calculations

The global cost ([32], Eq. (1)) and payback period (Eqs. (2)–(4)) calculations were used to assess the cost effectiveness of the renovation measures and renovation packages relative to "as built" state and the current state of the reference buildings. The cost of the renovation was calculated considering 85% loan financing and 15% self-financing. A discount period of 20 years was selected because

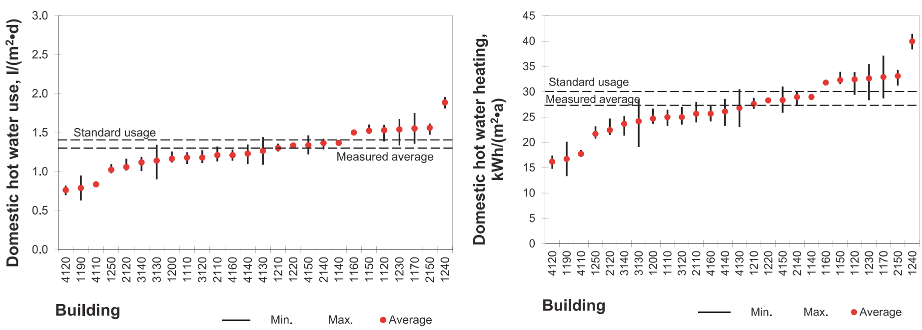

Fig. 5. The daily average hot water use (left) and energy use for heating domestic hot water (right).

the maximum period for renovation loans for apartment owners' associations in Estonia is 20 years.

$$C_g(\tau) = \frac{C_i + \sum_{i=1}^{20}(C_{ai}(j) \times R_d(i))}{A_{\text{floor}}} - \frac{C_g^{\text{ref}}}{A_{\text{floor}}} \tag{1}$$

where: $Cg(\tau)$ is the global cost (referred to the starting year), €/m^2; C_i is the initial investment cost (self-financing of a renovation loan), €; $C_{a,i}(j)$ is the annual cost of year i for the component j (energy cost and loan payback cost), €; $R_d(i)$ is the discount rate for year i; C_g^{ref} is the global cost of the reference building, €; A_{floor} is the net floor area, m^2.

The payback period (Eq. (2)) was calculated using return on investment (Eq. (3)) and total loan payment with interest (Eq. (4)):

$$T = \frac{100\%}{E} \tag{2}$$

where: T is the payback period in years; E is the return on investment, %.

Return on investment was calculated for each year of the loan considering the escalation of the energy prices:

$$E = \frac{\sum(\text{En}_i \times S_i)}{A} \times 100\% \tag{3}$$

where: En_i is the delivered energy decrease for year i, MWh/a; S_i is the delivered energy cost for year i, €/MWh. Payback period was calculated using the median return on investment.

The total loan payment with interest was calculated:

$$A = \text{MB} \times \left[\frac{i \times (1+i)^m}{((1+i)^m - 1)}\right] \times 12 \times n \tag{4}$$

where: A is the total loan payments with interest, €; MB is the initial loan, €; i is the month interest (year interest/12), %; m is the loan duration in months; n is the loan period in years.

Calculations of global cost and payback period were made with a typical interest rate 4%. To show sensitivity to the escalation rate, three escalation rate scenarios were considered: 1% escalation (minimum scenario), 3% escalation (base scenario), and 5% escalation (maximum scenario).

In Estonia reconstruction grants are offered to the energy renovation projects of apartment owners' associations [33]. Construction costs (Table 2) were calculated on the basis of reports from apartment owners' associations submitted after completion of renovation works. The energy price levels used were 0.14 €/kWh for electricity and 0.075 €/kWh for district heating.

Table 2
Construction costs of renovation measures.

Energy renovation measure	Price
Additional insulation for external walls, €/m^2	
+100 mm	65
+150 mm	68
+200 mm	70
+300 mm	80
+400 mm	100
Additional insulation for flat roof, €/m^2	
+200 mm	60
+300 mm	65
+400 mm	75
+500 mm	90
Additional insulation for attic floor, €/m^2 (includes replacement of roof construction)	
+200 mm	100
+300 mm	102
+400 mm	105
+500 mm	110
Additional insulation for basement ceiling, €/m^2	
+100 mm	25
+150 mm	27
+200 mm	30
Replacement of windows, €/m^2	
U – 1,4 W/m^2 K	110
U – 1,1 W/m^2.K	140
U – 0,6 W/m^2 K	240
Renovation of heating system, €/m^2 (net area)	
Renovation of current 1-pipe system	10
New 2-pipe system	20
Renovation of ventilation system, €/m^2 (net area)	
Exhaust ventilation without heat recovery (HR)	5
Exhaust air heat pump	25
Room based ventilation with HR	35
Apartment based ventilation with HR	45
Renewable energy systems, €/MWh	
Solar collectors	1500

3. Results

3.1. Energy use before renovation

3.1.1. Electricity

Fig. 4 shows annual (left) and monthly (right) use of electricity. The average annual use of electricity (lighting, household electricity and space heating in some cases) was 35 kWh/(m^2 a) (22–49 kWh/(m^2 a)). The percentage of electricity use in apart-

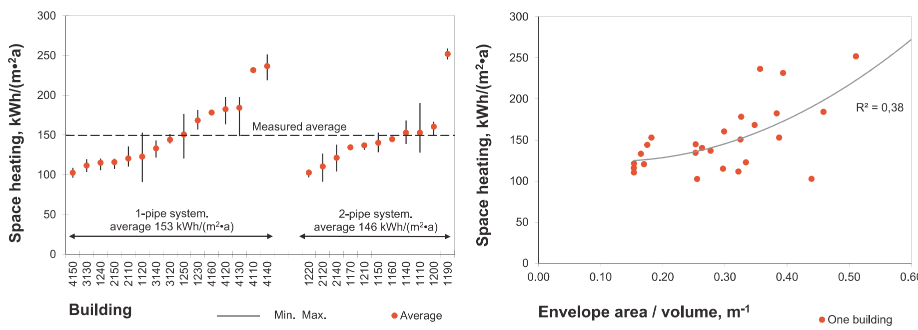

Fig. 6. Energy use for space heating in brick apartment buildings depending on the heat distribution system (left) and compactness of the building (right).

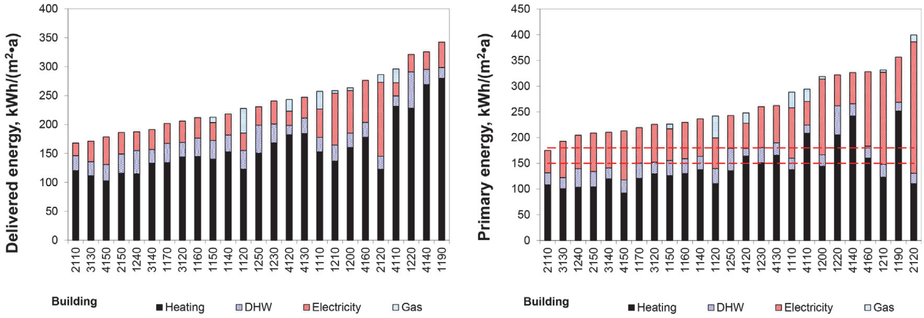

Fig. 7. Delivered energy usage (left) and Primary Energy usage (right).

ments (from the total use of electricity) was 80–98%. The use of electricity changed +15 to −28% from annual average, mainly due to lower use of lighting.

3.1.2. *Gas*

The annual average use of gas for cooking was 0.5 $m^3/(m^2\,a)$ (st. dev. 0.34 $m^3/(m^2\,a)$ and for cooking and heating of domestic hot water 3 $m^3/(m^2\,a)$ (st. dev. 1.0 $m^3/(m^2\,a)$). In buildings where gas was used for cooking, the annual average use of gas was 26 $m^3/(m^2\,a)$ for heating of domestic hot water and for space heating.

3.1.3. *Water*

The annual average daily hot water use was 1.3 $l/(m^2\,d)$ (st. dev. 0.3 $l/(m^2\,d)$) and energy use for heating domestic hot water was 27 $kWh/(m^2\,a)$ (st. dev. 6 $kWh/(m^2\,a)$), see Fig. 5. The annual average daily overall (hot and cold) water use was 3 $l/(m^2\,d)$ (st. dev. 0.6 $l/(m^2\,d)$) and 202 l/(apartm. d) (st. dev. 64 l/(apartm. d)). An average percentage of domestic hot water from overall water use was 40%. The use of domestic hot water (DHW) was 35 l/(person) (st. dev. 10 l/(person)).

3.1.4. *Space heating and ventilation*

Energy for space heating and ventilation covers:

- heat losses through the building envelope,
- heat loss through the thermal bridges,
- heat loss due to infiltration,
- heat loss due to natural ventilation.

The average energy use for space heating was 150 $kWh/(m^2\,a)$ (st. dev. 41 $kWh/(m^2\,a)$), see Fig. 6 left. The heating energy use was higher in buildings with a one-pipe heat distribution system (complicated balance and temperature regulation) and in buildings with larger compactness, see Fig. 6 right. The highest space heating energy usage per m^2 is typical of buildings with a small net area but with a relatively large building envelope area.

3.1.5. *Overall primary energy consumption*

Delivered energy usage (Fig. 7 left) was added to show the difference between the delivered energy and the PE. PE takes into account the use of the primary energy by multiplying the delivered energy usage with the weighting factors. The average use of PE was 263 $kWh/(m^2\,a)$ (st. dev. 58 $kWh/(m^2\,a)$), see Fig. 7 right. Only one measured building was found to meet the requirements for major renovation of apartment buildings. In buildings without gas: 57% was used for space heating, 12% for domestic hot water and 31% for electricity from the weighted delivered energy.

3.2. *Simulations*

3.2.1. *Energy use of the reference building*

Table 3 shows energy use in the standard use of buildings with original structures ("as built" conditions), and current state (with some minor energy saving measures).

The weighted average use of the primary energy considering the net areas of reference buildings in the current state was PE 264 $kWh/(m^2\,a)$, which matches the measured energy use, where an average PE was 263 $kWh/(m^2\,a)$. Therefore, energy simulation results can be used as a base case to compare energy renovation packages.

3.2.2. *Individual renovation measures*

The influence of individual energy renovation measures on the primary, and delivered energy is shown in Fig. 8.

Insulating the exterior of the external wall showed the highest energy saving effect. Depending on the building compactness and the window area ratio to the facade area, insulated external wall reduces the PE by 20–30%. Insulation layer thicknesses over 200 mm have smaller impact on the reduction of the PE or delivered energy. The influence of insulating the roof and floors depends strongly on the number of floors: >9 floors – the PE decreases 3%, >4 floors – 6–7%, >2 floors – 14%. As an individual measure, additional roof insulation over 300 mm showed no impact on the PE or the amount of delivered energy.

Table 3
Original and current state of reference buildings.

Reference building	Original structures, "as built" conditions				Current state with some minor energy saving measures			
	PE ($kWh/m^2\,a$)	Delivered energy ($kWh/m^2\,a$)	Space heating ($kWh/m^2\,a$)	NPV (€/m^2)	PE, ($kWh/m^2\,a$	Delivered energy ($kWh/m^2\,a$)	Space heating ($kWh/m^2\,a$)	NPV 20 years (€/m^2)
Ref. "A"	375	380	320	357	338	339	279	331
Ref. "B"	281	275	215	311	260	253	193	301
Ref. "C"	265	258	198	304	250	241	181	298
Ref. "D"	232	221	161	325	215	202	142	315

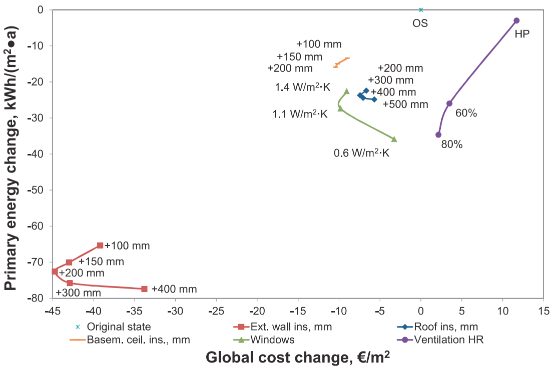

Fig. 8. The change of energy performance and global cost at different individual renovation measures.

Replacement of windows reduced the PE in all cases because of the high thermal transmittance of existing windows.

The best ventilation system from an energy efficiency point of view is an apartment based on the air handling unit with heat recovery. But as apartment based air handling units and ductworks are difficult to install into existing apartments, the ventilation systems primarily used with heat recovery are room based air handling units and exhaust air heat pumps. Delivered energy reductions are similar in both systems with ca 10–15%, but as a heat pump uses considerably more electricity, it reduces the PE to 0–2%.

3.2.3. Packages for energy renovation

Energy performance and global cost of renovation packages are shown in Table 4.

In all the packages, a 150 mm additional insulation of basement ceilings was installed to improve the thermal comfort of the first floor occupants.

The major renovation requirement was achieved by using additional thermal insulation for the whole building envelope and by replacing windows. From an energy point of view, it is not necessary to insulate the basement ceiling, but it is included to avoid cold floors in the first floor apartments. To renovate 1-pipe heating systems in case of a ventilation system without heat recovery (EXH), thermostats must be installed, but with an exhaust air heat pump (HP), new 2-pipe heating systems thermostats are required to achieve the maximum usage of lower temperatures produced by a heat pump. For smaller brick apartment buildings with a net area of ca 500 m^2 (Ref "A"), either room based air handling units (HR 60%) or apartment based air handling units (HR 80%) are needed to achieve the required PE for major renovation.

To achieve the energy performance levels typical of new buildings, it is required to insulate the building envelope under major renovation, and to install the ventilation systems with heat recovery and the new 2-pipe heating system with thermostats. As an exhaust air heat pump uses a considerable amount of electricity, room based and apartment based air handling units are used in the renovation packages. PE requirements of new apartment buildings are not feasible at the current common renovation practice (150 mm additional insulation for external walls, 300 mm additional roof insulation and replacing only original wooden windows) using a heat pump for ventilation heat recovery. Solar collectors for DHW are needed to achieve the new building PE requirement for smaller brick apartment buildings (Ref "A").

Energy renovation packages for low energy buildings differ from the PE level packages of new apartment buildings with a need for solar collectors for DHW. A low-energy level is not achievable for smaller brick apartment buildings (Ref "A"). To show a minimum PE for every reference building, one renovation package consisted of maximum insulation of the building envelope, maximum heat recovery and solar collectors for DHW. A low-energy level gave the best result. A PE level of nearly zero energy building is infeasible in brick apartment buildings without on-site electricity production from renewable energy sources.

3.3. Cost effectiveness

3.3.1. Individual renovation measures

The change of the global cost and energy performance was selected to assess the cost effectiveness of individual renovation measures. The results are shown in Fig. 8.

Insulating external wall leads to the greatest reduction in the global cost and primary energy. In terms of economy, an insulation thickness of 200 mm is most reasonable. However, insulation thicknesses of 300 and 400 mm reduce global costs more than renovation of other structures. Thicknesses of roof insulation and basement ceiling insulation have an insignificant effect regarding to the global cost because of their small area. As the global cost rate of a 400 mm insulation layer is the same as at 200 mm, it is reasonable to use a 400 mm layer since adding an extra layer of insulation afterwards to a partly insulated building is not cost effective [34].

Due to considerably higher costs (low market demand) of modern windows with the lowest thermal transmittance 0.6 W/(m^2 K) (triple glazing with two low emissivity coating layers and insulated frames), the most reasonable window in terms of economy is with the thermal transmittance 1.1 W/(m^2 K) (double glazing with a low emissivity coating).

Installing a ventilation system with heat recovery increases the global cost due to the improved ventilation airflow and electricity use. The global costs of room based and apartment based air handling units are in the same range, but higher efficiency reduces the PE at HR 80%. Due to electricity consumption, the heat pump of the exhaust air ventilation has the highest global cost.

3.3.2. Energy renovation packages

The absolute global cost of renovation packages is shown in Table 4. The global cost values of renovation packages with room based air handling units and with apartment based air handling units are in the same range. Packages with an exhaust air heat pump are not included in the calculation of the cost optimal range for brick apartment buildings, as their global cost values are noticeably higher than those of other renovation packages.

The economical optimum of energy renovation measures is close to the PE 150 kWh/(m^2 a), which corresponds to the requirements for new apartment buildings, see Fig. 9. The performance level of a low-energy building is achievable without increasing the current state of global costs.

Payback periods for cost effectiveness are similar to the global cost method, see Fig. 10. Payback periods for large building packages (Ref "D") with major renovations are significantly longer, thus energy renovations at small reductions (current state PE 215 kWh/m^2 a) in the PE are not economically viable. An economically optimum range of the payback period is at the PE 150 kWh/m^2 a, with the payback period between 19 and 21 years.

All economic calculations were made with an interest rate of 4% and an escalation rate of 3%. To show sensitivity to the changes of the escalation rate, global costs and payback periods were also calculated with the escalation rates of 1 and 5%, see Fig. 11. In addition to escalation rates, the results are sensitive to the renovation costs. The current outcomes were calculated using the cost indicated in Table 2 at the average results of reference buildings. At an escalation rate of 1%, renovation packages are not economically viable. At an escalation rate of 5%, renovation packages are all viable and

Table 4
Solutions for energy renovation packages to reach different energy performance criteria.

Criteria	Reference building	External wall ins (mm)	Roof/attic floor ins (mm)	Windows (W/(m²*K))	Ventilation system	PE (kWh/(m²*a))	Delivered energy (kWh/(m²*a))	NPV (€/m²)
Major ren.	"A"	+200	+400	1.1	HR 60–80%	151–157	124–136	316–318
	"B"	+200	+400	0.6/1.1	EXH./HP.	154–170	100–148	283–301
	"C"	+200	+300	0.6/1.1	EXH./HP.	159–175	107–153	288–307
	"D"	+200	+300	0.6/1.1	EXH./HP	153–170	99–147	313–328
New building	"A"	+200/+400	+400/+500	0.6	HR 60–80%	124–150	94–127	323–345
	"B"	+200	+400	0.6/1.1	HR 60–80%	121–134	90–151	281–290
	"C"	+200	+300	0.6/1.1	HR 60–80%	128–141	148–156	289–297
	"D"	+200	+300	0.6/1.1	HR 60–80%	124–138	90–159	306–316
Low-en.	"B"	+200/+400	+400/+500	0.6	HR 80%	103–117	71–86	292–303
	"C"	+200/+400	+300/+500	0.6	HR 80%	110–114	79–84	299–316
	"D"	+200/+400	+300/+500	0.6	HR 80%	108–111	77–80	318–319

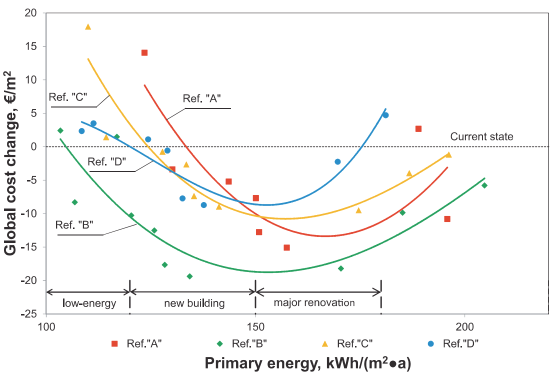

Fig. 9. The change of global cost and energy performance relative to the current state of reference buildings.

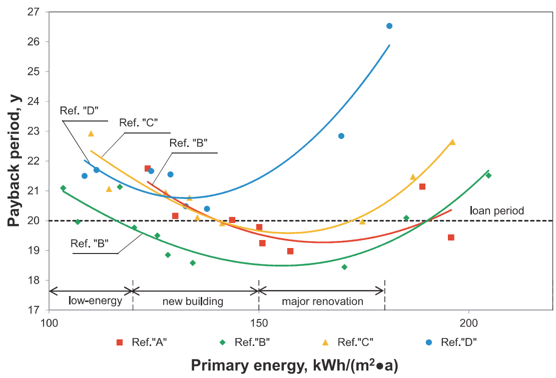

Fig. 10. Payback periods of renovation packages.

global cost reductions in all packages are relative to the current state.

4. Discussion

The average heating energy (space heating, ventilation and DHW) consumption was 175 kWh/(m^2 a) in brick apartment buildings, which is higher than the average in Northern Europe [3], but significantly lower than the results of previous studies for Estonian apartment buildings [6,7]. One of the reasons for lower heating energy consumption may be that previous studies were conducted prior to renovations and installation of apartment based water metres. DHW consumption decreased by 30% from 1999 to 2004 [35]. Possible energy savings of up to 70% from energy renovations correspond to previous studies conducted in Eastern European countries [7,9]. The economic renovation calculations of previous studies focused mainly on payback periods. This study analyses the global cost of renovations for apartment owners, as 64.5% [36] of the Estonian population lives in apartments and renovations of apartment buildings require apartment owners to act collectively.

Until recent years, under renovations primarily small scale construction works, such as replacement of windows by apartment owners, replacement of old heat supply substation, have been done. External walls of some brick apartment buildings have been insulated, but the thickness of the additional insulation layer is generally 100–150 mm. The results of this study indicate that the global cost optimum for brick apartment renovations

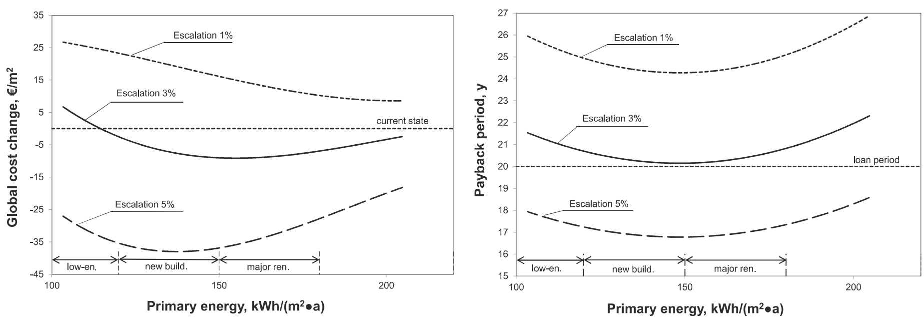

Fig. 11. Global cost (left) and payback period (right) at different escalation values.

is close to PE 150 kWh/m^2 a, which is the requirement for new apartment buildings [23]. Still, it should be noted that global cost optimum depends on the net area of the apartment building. For smaller buildings (such as Ref "A"), global cost optimum resulted at a higher PE: close to the criteria for the major renovation PE 180 kWh/(m^2 a). But it has an inconsiderable impact on the generalised results as brick apartment buildings with a net area <1000 m^2 form under 25% of the net area of all brick apartment buildings. Therefore, complete renovation that meets the PE requirements of a new apartment building is most reasonable to modernise brick apartment buildings.

One of the most difficult tasks in the renovation of apartment buildings is the ventilation system. The economic calculations of individual renovation measures showed that a ventilation system with heat recovery is the only group measured that increases global costs relative to a building's original state. This is partly due to the low air change rate in apartments, high costs of ventilation and finishing works, and also due to increased ventilation airflows and electricity use of mechanical supply-exhaust ventilation systems. Current natural ventilation systems are not regulated and apartments are mostly under-ventilated. Ensuring that ventilation airflows meet indoor climate standard requirements increases global costs, but energy savings cannot be achieved through lower indoor air quality as indoor air pollutants affect inhabitants' health [37].

Our results showed that global cost values and payback periods for renovation packages with HR are in the same range at solutions without HR, but ensure a lower PE. Therefore, ventilation systems with heat recovery are reasonable as better PE is achieved over the same payback period.

A low-energy apartment building PE level $\leq$120 kWh/(m^2 a) is achieved when solar collectors are added to the deep insulation of the building envelope and ventilation with heat recovery. Again, exceptions are smaller brick buildings where PE $\leq$ 120 kWh/(m^2 a) was not achieved. For smaller buildings, achieving a low-energy level requires on-site electricity production or using energy efficient appliances. Average reduction in the consumption of electricity from energy efficient appliances is around 22% [38]. Economic calculations showed that the global cost of low-energy apartment building packages are in the same range as the current global costs of reference buildings. It is possible to reduce the energy consumption of brick apartment buildings up to 70% without increasing occupants' current costs. As the occupants' main motivation for renovation is energy cost savings, the apartment owners' associations need some kind of a financial support mechanism for renovation packages that exceed economic optimum solutions. Maximum possible energy savings with technically reasonable solutions will not be achieved without external financial support.

5. Conclusions

Total energy consumption of 30 brick apartment buildings was measured and four reference building types were selected to represent brick apartment building stock. Economically viable deep renovation measures were presented as a simulation result of the different energy renovation scenarios.

From individual measures, insulating external walls has the highest effect on the reduction of the delivered energy consumption. But since frequently the most comprehensive solutions for individual measures are not the case, the energy renovation packages give the best results. Additional thermal insulation on the building envelope with replacement of windows and a ventilation system with heat recovery will allow the energy efficiency requirements for new apartment buildings to be achieved. Solar collectors are needed in addition to the previous package to reach full technical energy savings potential (up to 70%) and fulfil the criteria of low energy buildings.

Global cost calculations for different energy performance levels showed that the cost optimum level for the renovation of brick apartment buildings was close to the energy efficiency requirements of a new apartment building. Reductions of up to 60% in the delivered energy consumption in brick apartment buildings are both technically feasible and economically reasonable to apartment owners. To achieve a full technical potential of energy savings in the renovation of apartment buildings, external financial support for apartment owners' associations is needed to lower economic risks and encourage occupants to undertake deep renovation.

Acknowledgments

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PAPER II

Kuusk, K., Kalamees, T. The analysis of renovation cost effectiveness of apartment buildings. Building Research & Information 00 (Submitted 30.04.2015).

The analysis of renovation cost effectiveness of apartment buildings

Kalle Kuusk*, Targo Kalamees

1. Introduction

There are approximately 25 billion m^2 of useful floor space in the EU27, Switzerland and Norway (Economidou et al. 2011). Residential buildings account for largest share (approximately 75%) of that building stock (Economidou et al. 2011) and therefore residential sector also accounts for large share of the total energy consumption. In the EU, approximately 17% of the total primary energy consumption and 25% of the final energy consumption are used in residential buildings (EC, 2006). Apartment buildings in Northern Europe consume energy for heating approximately 90-170 kWh/(m^2·a) (Balaras et al., 2005; Engvall et al., 2014; Paiho et al., 2015). Those numbers correspond to the recent studies in Estonia, which have shown that average heating energy consumption for apartment buildings is 150 kWh/(m^2·a) and for electricity 35 kWh/(m^2·a) (Kuusk et al., 2014, Arumägi and Kalamees, 2014).

Large energy consumption brings also range of possibilities for energy savings and residential sector has the biggest potential for cost-effective savings (EC, 2006). At the country level, the potential for energy savings is different because of the different size and condition of the building stock. For example, study conducted in Germany (Galvin and Sunikka-Blank, 2013) showed that the total saving potential of renovating residential buildings to EnEV standard is 33% and the economically viable potential of renovation is around 25%. At the European level, over 40% of energy savings could be obtained by the residential building stock applying a “standard” renovation and in some countries up to 86% applying an “advanced” renovation (Ballarini et al., 2014). In total, is has been found (Tuominen et al. 2012) that 146 TWh of heating energy (88 TWh in detached houses and 58 TWh in apartment buildings) could be saved annually by the year 2020.

Energy Roadmap 2050 (2011) states that decarbonisation is possible and can be less costly than current policies in the long-run. Renovation the existing residential building stock is key factor on this future task as replacement rate of the existing stock is only 1–2% per year. Studies have shown (Nemry et al., 2010) that the existing residential building stock have significantly higher environmental impact than new residential buildings. In addition to high energy consumption issues, the existing residential buildings indoor climate conditions have also an impact to inhabitant´s health. WHO (2009) have stated that problems of indoor air quality are important risk factors for human health in low-income and high-income countries. Renovation of existing apartment buildings can negatively affect the indoor environment of the apartments if renovation does not include measures to improve indoor environmental quality (Földváry 2014). Studies have shown (Krajčík et al. 2011) that improvement of the indoor climate conditions can be also a motivation for renovation of existing apartment buildings. When the dwelling is originally unheated and –ventilated, the improvement of indoor climate consumes additional energy and that may be surprising for inhabitants. For example, inhabitants often have difficulties to understand the fact that the better indoor climate will come with additional cost for operating ventilation system.

Despite the large energy saving potential, earlier studies (Wesselink et al., 2010) have found that the European Union 2020 energy saving target will not be fulfilled. Same study concluded that closing the gap between planned targets and realized energy savings requires a threefold increase in policy impact compared to energy savings policies adopted since the 2006 Energy Efficiency Action Plan. Galvin and Sunikka-Blank (2013) showed that policy makers should emphasise also other reasons than only reduction of CO_2 emissions and consider a more systematic approach to inhabitants behaviour change in order to promote renovation to economically viable levels. Joelsson and Gustavsson (2008) found that when choosing an energy-renovation measure, the house owners gave higher priority to economic aspects than to environmental ones. This indicates that the use of economic instruments would be efficient way to promote energy-renovation measures, which are in line with the future environmental goals. Study conducted in Wales (Jones et al., 2013) concluded that the cost of deep integrated renovation is a major barrier to large-scale renovation of existing buildings. Tuominen et al. (2012) studied nine EU countries and reported that common renovation barrier is the low priority for energy efficiency improvements among the consumers and insufficient funding. At the same time, one of the common public policy measures to overcome renovation barrier was partial public funding of energy efficiency retrofits. The lack of money up front and the low investment capacity are particularly problematic in the owner-occupied residential sector (Meijer et al., 2009). Study for developing the Estonian energy roadmap ENMAK 2030+ (Kurnitski et al., 2014) pointed out that in order to realize the full cost optimal energy saving potential, support schemes are necessary especially in residential buildings, as financial support allows to set requirements for the renovation measures and promote deep integrated renovation. Setting up the correct requirements for the energy-renovation measures is essential and regulations must be flexible and consider local conditions as a ‘‘one size fits all’’ set of regulations would often be unjustified (Brecha et al., 2011). Galvin (2014) stated that whenever policy-makers set mandatory standards for upgrades, this often entails people paying large sums of money and therefore policy-makers need to be very sure they are doing these residents a good turn and not forcing them to pay for aims and goals these residents might not even share. Weiss et al. (2012) concluded that different support programmes whit different goals are needed. One funding programme for building owners willing to invest to a higher levels of energy efficiency and another programme, which consider also a social criteria, for energy renovation measures meeting lower standards.

There are approximately 27 thousand apartment buildings in Estonia and ≈10 thousand buildings built during Soviet Union era when energy prices and the thermal quality of building envelope were much lower than today. During 2009-2010, apartment owners associations (AOA) could apply renovation loan, which provided a more favourable interest rate than commercial loan. During 2010-2014 over 600 apartment buildings have been renovated in Estonia with support scheme of Fund KredEx financed by CO_2 emissions trading and governmental budget. The grant amount was 15%, 25% and 35% of the total project cost depending on the energy efficiency level (correspondingly Primary Energy (PE) ≤ 220 kWh/(m^2·a) (minor renovation), PE ≤ 180 kWh/(m^2·a) (major renovation), and PE ≤ 150 kWh/(m^2·a) (energy efficiency level of new building). EU Structural Funds for the next financing period 2014…2021 will be used for the new energy renovation supporting scheme which was needed to work out taking into account changed investment and energy costs and also previous experiences.

The setting up of correct policy measures to promote energy renovation is difficult topic. Without support or too low support may not motivate building owners to execute integrated energy-renovation. Too high grant encumbers governmental budget. In this study, energy performance, necessary investments, possible need for support scheme, and influence of realized support scheme are evaluated in order to show the economic viability of deep renovation of apartment buildings. Estonian apartment buildings are used as an example.

2. Methods

2.1 Studied buildings

Prefabricated concrete large-panel apartment buildings were used to calculate energy efficiency and cost effectiveness of renovation measures. This type of apartment building was the dominant during the construction industrialisation period in the 1970-1990. Approximately 2 million m^2 of prefabricated concrete large panel apartment buildings were built during that period in Estonia. In Estonia approximately 36% of the apartment building stock total net area is constructed from prefabricated large-panels. This means that the results can be generalized to large number of apartment buildings. Therefore 105 apartment buildings composed by concrete large-panels constructed between 1962 and 1992 were selected for the energy efficiency analysis of this study.

Buildings with different renovation extent were included in the study. For example, window replacement rate ranged from 15 to 90%. Average window replacement range was 65%. In 2/3 of the studied buildings there was additional insulation installed to some parts of building envelope (either on end walls or on roof or on end walls and roof). Thermal transmittance of building envelope was following:

- External walls: $U_{wall} \approx 0.8–1.1$ W/(m^2·K)
- Roof-ceilings: $U_{roof} \approx 0.9–1.1$ W/(m^2·K)
- Windows (old): $U_{window} \approx 2.9$ W/ (m^2·K)
- Windows (changed): $U_{window} \approx 1.6$ W/ (m^2·K)

Building envelope contains significant thermal bridges. Previous studies have concluded that in comparison of the construction types, the situation is the worst for large panel concrete element buildings, where the linear thermal transmittance of the thermal bridge in the external corner of external walls might be up to Ψ=1.30 W/(m·K) as maximum and Ψ=0.70 W/(m·K) as the most probable value to be used in the energy audit (Ilomets et al., 2014).

Buildings were heated with district heating and mainly by one-pipe heating systems, by hydronic radiators. Only 10% of the buildings had new or renovated heating systems with thermostats, allowing individual control of the room temperature. Indoor temperature in the buildings with old heating system was regulated in heat substations depending on outdoor temperatures.

All the studied dwellings had natural passive stack ventilation and some apartment owners have installed mechanical kitchen hoods. According to the energy audits and previous measurements, buildings were often insufficiently heated and ventilated. Insufficient heating and ventilation in existing apartment buildings causes bad indoor climate and high indoor humidity loads (Kalamees et al., 2011, Maivel et al., 2014).

2.2 Measured energy consumption

The real energy performance was determined by energy audits of 105 large-panel apartment buildings. Measured use of delivered energy (electricity, gas, water, domestic hot water and space heating (including heating of ventilation air)) on monthly basis over a 3-year period was analysed. The energy usage was determined for the whole building.

The use of primary energy (PE) was calculated based on the weighting factors: district heating 0.9, electricity 2.0. Primary energy takes into account the use of the primary energy (space heating, ventilation, domestic hot water, all electricity loads (including lighting and appliances (plug loads)) and environmental impact according to the energy source.

2.3 Simulations of energy saving measures

In this study, limited number of reference buildings was used, which was considered enough for the estimation of the technical energy saving potential and investment costs need. Effort was put to detailed energy and cost simulations. Three types of large panel apartment buildings were selected as reference buildings from different construction periods (Figure 1, Figure 2, Table 1) for detailed energy simulations and economic calculations. Reference buildings were selected to represent the distribution of age and size of large panel apartment buildings, see Figure 2.

Ref."A" Ref."B" Ref."C"

Figure 1 Reference buildings used in simulations.

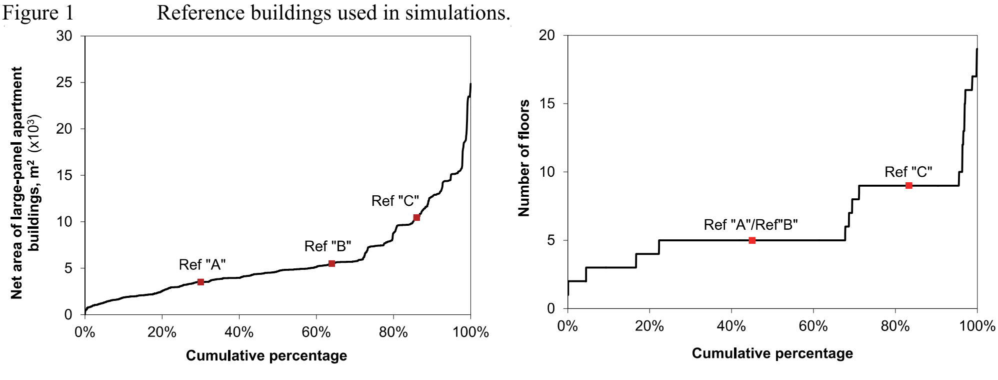

Figure 2 Net area (left) and number of floors (right) of reference buildings and the whole building stock of large panel apartment buildings.

To take into account that some minor energy saving measures are already realized for the current state of buildings, it was assumed that 65% of the windows had been replaced ($U_{\text{window (glass/ frame)}}$, 1.8/2.0 W/(m^2·K)) and end walls of the buildings had been insulated with a 50 mm thermal insulation. Insulation thickness 50 mm is chosen to represent the situation where half of the buildings have 100 mm of additional insulation on end walls.

Table 1 Characterisation of reference buildings based on energy audits

	Reference buildings Ref."A"	Ref."B"	Ref."C"
Construction period	<1970	1971-80	1981-90
Share of net area from all the net area of large panel apartment buildings	0.5	0.16	0.34
Number of floors	5	5	9
Net area, m^2	3 519	5 484	10 421
Heated area, m^2	2 968	4 481	8 262
Compactness: Building envelope, m^2 / volume, m^3, m^{-1}	0.35	0.35	0.29
Number of apartments	60	75	144
Thermal transmittance of side exterior walls U_{wall}, W/(m^2·K)	1.1	1.0	0.8
end exterior walls U_{wall}, W/(m^2·K)	0.45	0.45	0.40
roof U_{roof}, W/(m^2·K)	1.1	1.1	0.9
windows $U_{window\ (glass/\ frame)}$, W/($m^2$·K)	1.8/2.0	1.8/2.0	1.8/2.0

Energy performance of the reference buildings was simulated by the energy and indoor climate simulation program IDA Indoor Climate and Energy 4.6 (IDA-ICE). This software has been validated, for example, in Travesi et al. (2001) and Loutzenhiser et al. (2007). An Estonian Test Reference Year (Kalamees and Kurnitski, 2006) was used for outdoor climate conditions (annual heating degree days at t_i 17ºC: 4160 ºC·d).

The zoning of the simulation model is shown on the example of reference building A. The model of building was divided into different zones according to the apartment layouts (Figure 3), and third floor zones were multiplied by 3 to represent also the second and fourth floor. Simulation models were calibrated based on the measured energy use of the reference buildings. After calibration of the simulation model, the energy renovation measures were calculated according to a unified calculation methodology and with a standard usage (RT I, 18.10.2012, 1, 2012 and RT I, 05.09.2012, 4, 2012) because of our aim to analyse the energy usage of the building type during standard usage and not the energy usage of specific building.

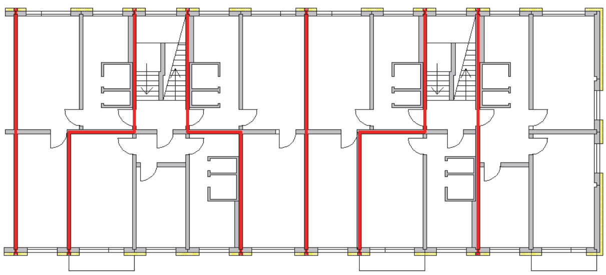

Figure 3 Simulation model (left) and floor plan (right) of reference building.

Internal heat gains in the renovation measures were as follows:

- Occupants: 15.8 kWh/(m^2·a). The usage rate was 0.6.
- Appliances, equipment: 15.8 kWh/(m^2·a). The usage rate was 0.6 and the heat gains of equipment were divided by 0.7 to calculate delivered energy.
- Lighting: 7.0 kWh/(m^2·a). The usage rate was 0.1.

Ventilation airflow was 0.35 l/(s·m^2) for a non-renovated case representing indoor climate category III (EN 15251) and 0.42 l/(s·m^2) for renovation packages representing indoor climate category II. Infiltration airflow in a non-renovated case was calculated with the average measured value for large panel apartment buildings (q_{50}=4.3 m^3/(h·m^2)) (Kalamees et al., 2011) and in a renovated case a slight improvement in the airtightness of the buildings (q_{50}=4.0 m^3/(h·m^2)) was assumed. The use of domestic hot water (DHW) heating need was 520 l/(m^2·a) / 30 kWh/(m^2·a).

Ventilation heat recovery was solved with two technical solutions: apartment based air handling units with heat recovery and mechanical exhaust ventilation with heat pump for heat recovery. The principle of mechanical exhaust ventilation with heat pump for heat recovery is that supply air enters through fresh air radiators being filtered and heated at the same time. Extract air moves through ventilation shafts to an air handling unit cooling coil where heat is transferred with a brine loop to water to a water heat pump. The heat pump provides heat to the domestic hot water and the space heating system. The Coefficient of Performance (COP) of exhaust air ventilation heat pump was 3.5 during the heating period and 3.0 during summer. Lower COP in summer results from the use of the heat pump only for domestic hot water (DHW), which has a higher temperature (55 ^{0}C) (Kõiv et al., 2012).

Energy simulations were made for different individual renovation measures (different thicknesses of additional external thermal insulation, improvement of windows, ventilation system). All renovation packages included the installation of adequate ventilation system in order not to compromise indoor climate. Results from individual measures were summarized in order to create renovation packages to correspond to different Energy Certification Classes (ECC):

- ECC F: PE ≤ 280 kWh/(m^2·a) (current state of reference buildings);
- ECC E: PE ≤ 220 kWh/(m^2·a) (minor renovation);
- ECC D: PE ≤ 180 kWh/(m^2·a) (criteria for major renovation);
- ECC C: PE ≤ 150 kWh/(m^2·a) (criteria for a new building);
- ECC B: PE ≤ 120 kWh/(m^2·a) (criteria for a low-energy building),
- ECC A: PE ≤ 100 kWh/(m^2·a) (criteria for a nearly zero energy building).

Simulation results are presented as weighted average from three reference buildings simulation results based on the proportion of net area of the reference building type from all the net area of large panel apartment buildings.

2.4 Economic calculations

The global cost (EN 15459, Equation 1) calculations were used to assess the cost effectiveness of the renovation measures and renovation packages relative to the current state of the reference buildings. Based on the current practice, the cost of the renovation was calculated considering 85% loan financing and 15% self-financing. A discount period of 20 years was selected because the maximum period for renovation loans for apartment owners associations in Estonia is 20 years.

$$C_g(\tau) = \frac{C_i + \sum_{i=1}^{20}(C_{ai}(j) \times R_d(i))}{A_{floor}} - \frac{C_g^{ref}}{A_{floor}} \quad (1)$$

where: $C_g(\tau)$ is the global cost (referred to the starting year), €/m^2;C_i is the initial investment cost (self-financing of a renovation loan), €; $C_{a,i}(j)$ is the annual cost of year i for the component j (energy cost and loan payback cost), €; $R_d(i)$ is the discount rate for year i; $C^{ref}{}_g$ is the global cost of the reference building, €; A_{floor} is the net floor area, m^2.

Construction costs (Table 2) were calculated on the basis of real costs and estimations made by the construction companies. Construction cost of renovation variants was calculated as full cost where all costs of construction works and installations were taken into account, not only energy performance related renovation works. For example, in the case of roof insulation, all construction works of roof repair were included. Renovation variants did not include interior remodelling, but internal finishing was taken into account in the case of window replacement and heating and ventilation installations.

The energy price levels used were 0.14 €/kWh for electricity and 0.075 €/kWh for district heating. Escalation rate was 3%. All costs include VAT of 20%.

Table 2 Construction costs of renovation measures

Energy renovation measure		Price
Additional insulation for external walls, €/m^2		
	+ 100 mm	65
	+ 150 mm	68
	+ 200 mm	70
	+ 300 mm	80
	+ 400 mm	100
Additional insulation for flat roof, €/m^2		
	+ 200 mm	60
	+ 300 mm	65
	+ 400 mm	75
	+ 500 mm	90
Additional insulation for basement ceiling, €/m^2		
	+ 100 mm	25
	+ 150 mm	27

+ 200 mm	30
Replacement of windows, €/m^2	
U – 1.1 W/m^2·K	140
U – 0.8 W/m^2.K	160
U – 0.6 W/m^2·K	240
Renovation of heating system, €/m^2 (net area)	
new 2-pipe system	30
Renovation of ventilation system, €/m^2 (net area)	
Exhaust ventilation without heat recovery (HR)	5
Exhaust ventilation with exhaust air heat pump	30
Apartment based ventilation units with HR	55
Renewable energy systems, €/MWh	
Solar collectors	1200

3. Results

3.1 Energy use at current state of the buildings

The average annual use of energy of 105 buildings measured is showed in Table 3. The average annual use of electricity was 32 kWh/(m^2·a). Electricity was used for lighting and for household appliances. The annual average use of gas was 8 kWh/(m^2·a). Gas was used only for cooking. Energy use for heating domestic hot water was 39 kWh/(m^2·a). The average energy use for space heating and ventilation was 136 kWh/(m^2·a). Energy for space heating and ventilation covers: heat losses through the building envelope, heat loss through the thermal bridges, heat loss due to infiltration, heat loss due to natural ventilation. Results show that energy usage for space heating of rooms and ventilation has the largest share of energy consumption in existing apartment buildings.

Table 3 Annual use of energy in 105 studied apartment buildings.

	Delivered energy, kWh/(m^2·a)	
	Average	Standard deviation
Electricity	32	6
Gas	8	2
Hot water	39	12
Space heating and ventilation	136	25

The average use of primary energy was 224 kWh/(m^2·a) (st. dev. 25 kWh/(m^2·a)), see Figure 4. Three studied buildings met the energy efficiency requirement of major renovation (ECC D). In buildings without gas: 55 % of energy was used for space heating, 15% for domestic hot water and 30% for electricity from the weighted delivered energy.

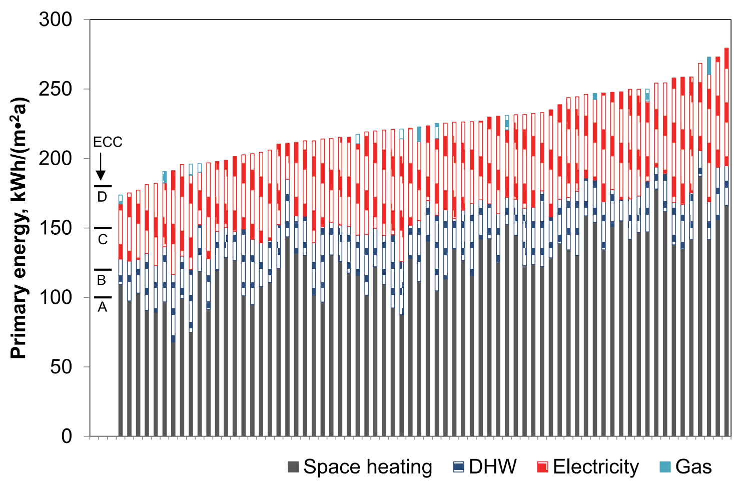

Figure 4 Use of primary energy in measured buildings

Buildings were divided into different groups according to the realised renovation measures. Analysis of space heating usage showed that single energy saving measures (additional insulation on roofs, additional insulation on end walls, new heating system) had no significant impact on building space heating energy usage, see Figure 5.

Statistical difference in space heating consumption compared to buildings without renovation measures was between the following building groups: buildings with additionally insulated end walls (50…150 mm) and additional insulation of roofs (150…300 mm) (p-value 0.02), buildings with additional insulation on end walls and renovated heating system (p-value 0.01), and buildings with additional insulation on end walls, side walls and roof (p-value 0.0001).

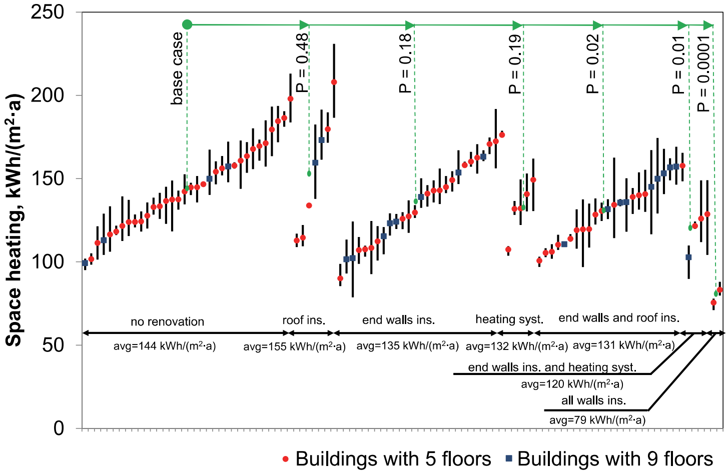

Figure 5 Energy use for space heating in studied apartment buildings.

The number of floors had also no clear effect on space heating energy consumption. Compactness of the reference buildings showed difference between the buildings with 5 floors and 9 floor. On the basis of the compactness difference, it could be assumed that buildings with 9 floors have smaller space heating consumption than buildings with 9 floors, but the results of space heating consumption analysis did not show a clear correlation between the space heating energy consumption and the number of floors.

3.2 Cost effectiveness of energy renovations

3.2.1 Individual renovation measures

The change of the global cost and energy performance was selected to assess the individual renovation measures. The results are shown in Figure 6.

Insulating of external wall leads to the greatest reduction in the global cost and primary energy. Insulation thicknesses of 200 mm or 300 mm are most reasonable with primary energy reduction of 17% and 18%. Thickness of roof insulation and insulation of basement ceiling has small effect on the global cost and primary energy consumption because of their small share of the total envelope area. Roof insulation decreases primary energy by 5% and basement ceiling insulation decreases primary energy by 2% with all modelled insulation thicknesses.

The most reasonable window is with the thermal transmittance of 0.8 W/(m^2*K) (triple glazing with two low emissivity coating), which had the same range of global cost reduction but higher decrease of primary energy than U-1.1 W/(m^2*K). Window U-1.1 W/(m^2*K) decreased primary energy by 6% and window U-0.8 W/(m^2*K) decreased primary energy by 8%. The window with lowest thermal transmittance 0.6 W/(m^2*K) increases global cost due to considerably higher costs at the moment. When evaluating the energy efficiency of the replacement of windows, we should be kept in mind that window replacement as a single energy efficiency measure do not eliminate the thermal bridge in window / external wall junction. When windows are replaced together with additionally insulating the external walls, then the energy savings would be higher. Windows could be installed into additional insulation layer on the external wall and the thermal bridge in window / external wall junction would be eliminated.

Renovation of the ventilation system by installing exhaust air heat pump for heat recovery increases the global cost and primary energy consumption due to the improved ventilation airflow and electricity use. Apartment based air handling units with heat exchanger efficiency of 80% decrease primary energy consumption by 13%. Due to the large electricity consumption, the heat pump of the exhaust air ventilation has the highest global cost. In terms of delivered energy, the ventilation system with exhaust air heat pump decreases delivered energy usage by 7%.

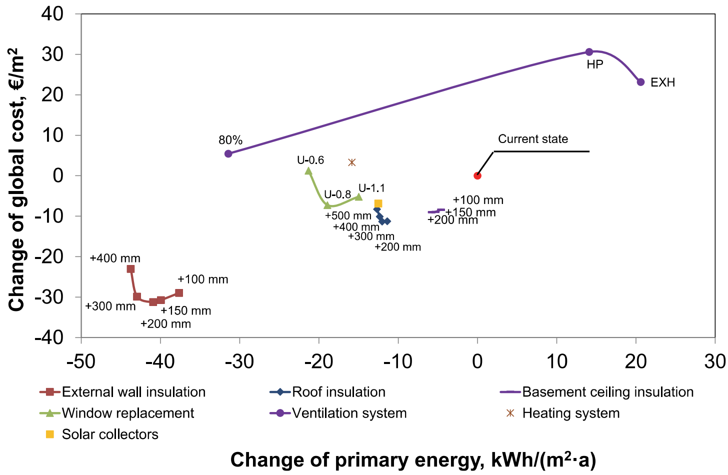

Figure 6 The change of energy performance and global cost at different individual renovation measures.

3.2.2 Energy renovation packages

Analysis showed that the renovation of ventilation system effects energy usage significantly. Therefore renovation packages are divided by different renovation solutions of ventilation systems. The weighted average use of the primary energy in the current state was PE 241 kWh/(m^2·a). The economical optimum of energy renovation measures is around the primary energy 120 kWh/(m^2·a) level, which corresponds to the requirements for low-energy apartment buildings, see Figure 7. Therefore, it is possible to reduce primary energy consumption by 50% without increasing the current state of global costs. Reduction of energy usage relative to current state of apartment buildings is shown in Table 4. Cost optimal energy saving opportunities are mainly in space heating energy and in energy use for heating domestic hot water. Electricity use will increase in every renovation package because of installed mechanical ventilation systems.

Table 4 Reduction of energy usage of reference buildings relative to current state.

Energy Certification Class	Reduction of energy usage from current state under standard use of building, %	
	Primary Energy	Delivered Energy
Minor renovation (ECC E)	3…18%	16…31%
Major renovation (ECC D)	20…33%	26…39%
New building (ECC C)	34…44%	43…53%
Low energy building (ECC B)	47…55%	58…66%
nZEB (ECC A)	56…63%	71…76%

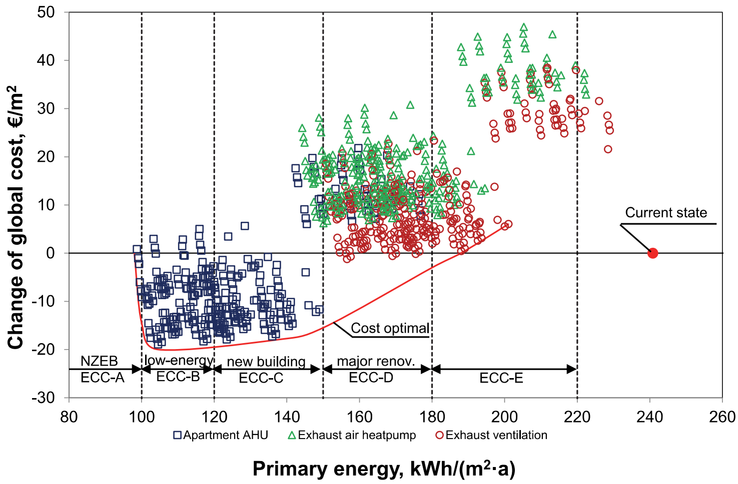

Figure 7 The change of global cost and energy performance relative to the current state of weighed average of three reference buildings.

The major renovation requirement was achieved by using additional thermal insulation for the whole building envelope and by replacing windows. From an energy point of view, it is not necessary to insulate the basement ceiling, but it is included to avoid cold floors in the first floor apartments. Ventilation system without heat recovery must also be installed, in order not to compromise indoor climate.

To achieve the energy performance level of new buildings, it is required to insulate the building envelope as under major renovation, and to install the ventilation systems with heat recovery. As an exhaust air heat pump uses a considerable amount of electricity, apartment based air handling units are mainly used in the renovation packages in order to achieve the energy performance level of new buildings. Energy renovation packages for low energy buildings differ from the primary energy level packages of new apartment buildings with a use of solar collectors for heating domestic hot water. A primary energy level of nearly zero energy building is also feasible in large panel apartment buildings. In our study, the nearly zero energy building energy efficiency level was achieved without on-site electricity production from renewable energy sources. This required maximum additional insulation on building envelope (external wall +400 mm, roof +500 mm), windows with low thermal transmittance (U-0.6 W/(m^2·K), and a use of solar collectors for heating domestic hot water.

3.2.3 Investments

Analysis of the necessary investment costs shows that the correlation between the energy efficiency level and the renovation cost is relatively linear. Energy-renovation investments costs to correspond to the requirements of major renovation are between 90…110 €/m^2, for new building between 130…150 €/m^2, for low-energy between 150…170 €/m^2, and nearly zero energy building close to 200 €/m^2 (Figure 8). Renovation costs of apartment buildings renovation to low-energy building energy efficiency level and nearly zero energy building energy efficiency level accounts for approximately 20% of construction cost of new buildings (approximately 1 000….1 200 €/m^2 VAT included). The costs of renovation and construction of new building are not fully comparable as renovation costs values are without interior remodeling, but renovation costs analysis show that deep renovation of existing apartment buildings is significantly cheaper than construction of new apartment buildings.

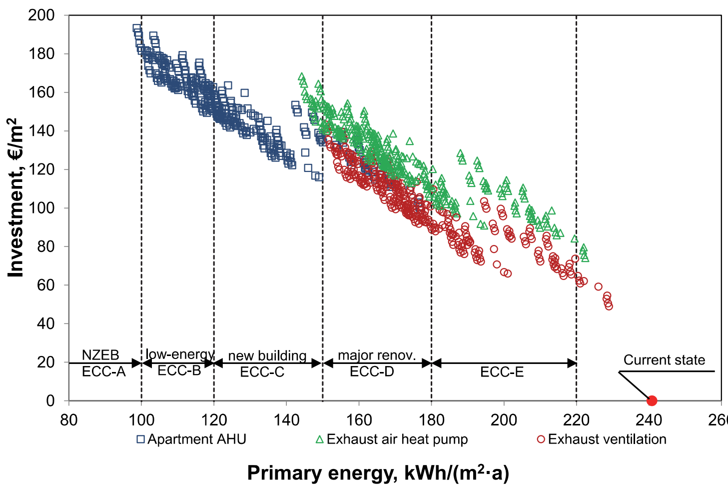

Figure 8 The change of energy performance and investment need.

Analysis of investment costs made with grant support showed that total investments were often lower than our investment need calculation results. One reason for that is that investments needed to improve indoor climate (new ventilation system) were not often priority in the renovation process. Another reason is that apartment owners associations have made energy renovation works before the grant application and cost of those energy renovation works are not included in grant scheme investment cost data. Our analysis of investment costs included only replacement of windows and additional insulation of end walls as energy renovation measure, which has previously been made. For example, possible scenario when the roof was previously additionally insulated and only external walls need to be insulated, was not addressed in our analysis.

The influence of grant support scheme to investments is show in Figure 9. Square represents total investment with energy renovation grant (that varies between 15…35% depending on achieved energy certification class) on made to improve energy efficiency and circle represents investments made by apartment owners association (total investment cost minus the grant support). Average investment for apartment buildings over 3000 m^2 achieving energy certification class E (minor renovation) was 36 €/m^2 and apartment owners association's share was 31 €/m^2. Average investment for achieving energy certification class D (major renovation) was 71 €/m^2 and apartment owners association's share was 53 €/m^2, and average investment for achieving energy certification class C (requirement for new building) was 120 €/m^2 and apartment owners association's share was 78 €/m^2. Investments made only with loan and without grant support (marked with a triangle) for energy efficiency measures has been set as a baseline. Grant support scheme has raised apartment owner's contribution to energy renovation. In order to apply grant support of 25%, apartment owners have invested on average 20 €/m^2 more to the energy efficiency measures than without any support. For example, in case of reference building "A" with a net area of 3500 m^2, this means 70 000 € more funds to improve building energy efficiency. In order to apply grant support of 35%, apartment owners have invested on average 45 €/m^2 more to the energy efficiency measures than without any support. Again, using the example of reference building "A" with a net area of 3500 m^2, this means 158 000 € more funds to improve building energy efficiency. Considering the fact that without the grant support, the average investment for improving the energy efficiency of the apartment building was approximately 30 €/m^2, the grant support for achieving new apartment building energy efficiency level has raised apartment owners associations investments to energy efficiency measures more than twice.

Comparison of the necessary investment needs and investments made only by apartment owners associations shows that without a grant, apartment owners associations are not able to make the necessary investments to significantly improve the building energy efficiency.

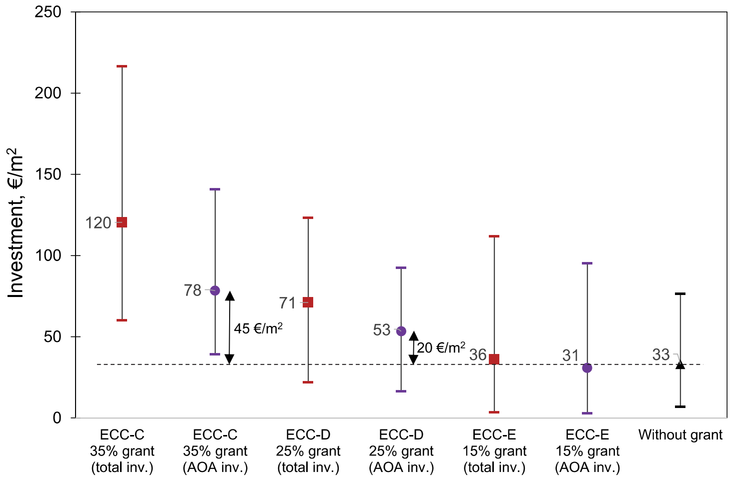

Figure 9 Investments made in apartment buildings in order to achieve different energy certificate classes. The dotted horizontal line represents renovation without grant that is selected for comparison.

The total renovation cost (Figure 9) is more expensive than only energy renovation (Figure 7) due to inevitable side works. Even the renovation of ventilation system is not so cost effective; it is unavoidably needed due to the public health requirements. Investment capability is usually the limitation for renovation down to low-energy of nearly zero energy level. In order to make renovation more affordable for the apartment owners associations in the new grant share there was a proposal for a new renovation scheme in Estonia, which starts in 2015. Financial support for the best energy efficient level was raised from 35% to 40% in order to compensate additional investment costs for installing mechanical supply-exhaust ventilation systems with heat recovery. Renovation grant of 40% lowers renovation costs needed to achieve new building energy efficiency level to approximately 80 €/m^2, which is affordable for apartment owners associations (Figure 10). Renovation of the building to ≤ ECC-C level is economically much more attractive and hopefully will help to decrease the overall energy use of buildings and help to achieve the energy saving targets.

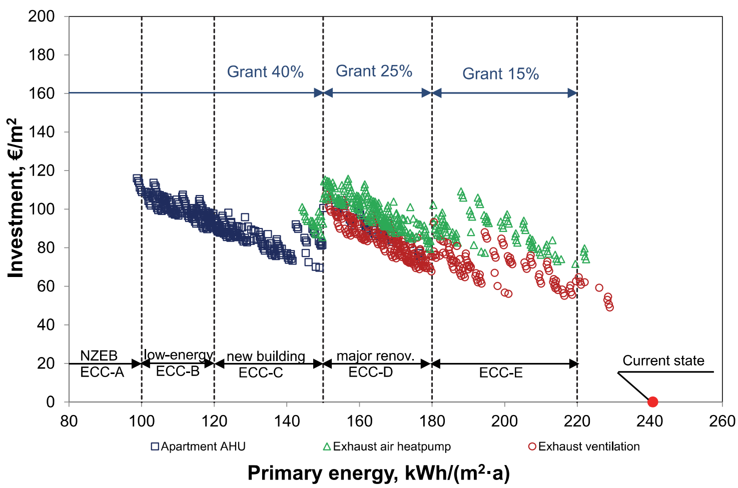

Figure 10 The investment need with renovation grants.

4. Discussion

Until recent years, mainly minor energy renovation works, such as replacement of windows and replacement of old heat supply substation, have been done. End walls of some large panel apartment buildings have also been insulated, but the thickness of the additional insulation layer is generally low, 100-150 mm. Those minor renovation works have not significantly reduced the apartment buildings energy usage. Average primary energy usage of 105 studied apartment buildings was 224 kWh/(m^2·a) which corresponds to energy certification class F. The results of this study indicate that the global cost optimum for large panel apartment renovations is close to primary energy usage 120 kWh/(m^2·a), which is the energy efficiency requirement for low-energy apartment buildings. Cost optimal primary energy usage level around 120 kWh/(m^2·a) is lower than previous studies for Estonia have indicated. Studies by Kurnitski et al. (2014) and Kuusk et al. (2014) concluded that cost optimal energy performance level of deep integrated renovation corresponded to minimum energy performance requirements of new apartment buildings (energy certification class C). The difference in the results are caused by the difference between the reference buildings used for analysis. Previous studies used also smaller apartment buildings (net area < 1000 m^2) as the reference buildings. Currents study used large panel apartment buildings which are larger and therefore cost optimal energy performance level is lower.

One of the problems which is often left unsolved in the renovation of existing apartment buildings is the ventilation system. Apartments in existing apartment buildings with natural ventilation systems are often under-ventilated. Studies (Kõiv 2008) have shown that ensuring the quality of indoor climate in apartments requires mechanical ventilation systems. As an individual measure, mechanical ventilation system may raise global cost but global cost values for renovation packages with heat recovery are in the same range or lower than solutions without heat recovery. Therefore, ventilation systems with heat recovery are economically viable as lower PE usage is achieved with the same or lower global costs as ventilation systems without heat recovery.

Although renovation to energy performance level of a new building and low-energy building is in longer terms economically viable, the high investment cost for renovation is a major barrier for renovation. Our study included only energy efficiency related renovation works but often there is a need to replace existing electrical system and plumbing, fix the load-bearing structures etc. Those works increase the investment costs and are more crucial in term of safe use of the building than energy efficiency improvements works. Apartment owners associations own investment capability is not sufficient to cover the crucial repairmen works and significantly improve building energy efficiency. Analysis showed that apartment owners' capability to invest in energy efficiency is ca four times lower than it is necessary to achieve low energy building requirements. Apartment owners' own funds often allow only single renovation measures, which do not fulfil even the energy efficiency requirements of major renovation (Figure 4) and often do not result with significant change in building energy usage (Figure 5). Therefore, financial support is needed to execute renovation in apartment buildings in order to achieve future energy efficiency targets. Without the grants, the annual cost (energy cost and renovation loan) after the renovation would be higher for apartment owners and that would make it difficult for apartment owners´ association to make a decision for major renovation. Earlier studies have also shown that one of the main priorities for apartment owners in selection of energy renovation measures is a short payback period (Medineckienė and Björk 2011).

Availability of financial support measures will raise apartment owners' own interest to invest into energy efficiency improvement measures. Analysis of investment costs with renovation grant showed that apartment owners' own investment with 35% grant was ca two times higher than investments made without the grant support. This shows that apartment owners will invest more when there is a significant grant, even when the grant requires renovation to the same energy efficiency level as new building.

Previous studies have concluded that in addition to the building level, the national investment in buildings for energy efficiency improvement is cost effective. Pikas et al. (2014) stated that in all 17 works per 1 M€ of investment in renovation had been generated and average total tax revenue from the deep renovation projects was 32-33%, including VAT and direct and indirect labour taxes. Tuominen et al. (2013) reached a similar conclusion that investing into energy efficient buildings is an economically viable and effective way to reduce buildings energy consumption. The required investments carry affordable costs and even a few percent rise in annual renovation investments can decrease total primary energy consumption up to 5.3% by 2020 compared to Business as usual scenario (Tuominen et al., 2013). Based on aforementioned studies, we can say that the investment in buildings for energy efficiency are not only cost optimal in building level but also in national economical level.

Our results show that in determination of energy supporting policy, there is no direct need for subsidies for minor energy efficiency improvements. Apartment owners' own funds should allow them to execute minor energy renovation works. Lower grant rate may be needed more as a tool for maintaining or improving existing buildings current state in areas where inhabitants' income is low and therefore apartment buildings are not renovated at all. Main purpose of the energy efficiency subsidies should be apartment buildings, which fulfil energy efficiency requirements for new buildings or low energy level. Financial support is also necessary to execute major renovation as smaller building cost optimal levels are around PE 180 kWh/(m^2·a), which means major renovation energy efficiency requirements (Kuusk et al., 2014). Grant support for major energy renovation should be lower than grant support for renovation to new building energy efficiency level or low-energy energy efficiency level in order to motivate building owners to execute deep integrated renovation which is renovation at least to new building energy efficiency level. That result complements previous studies (Uihlein and Eder 2010) which have concluded that it is reasonable to ensure that the best energy efficiency level possible is installed. This applies to any case, not only for major renovations, but also for every individual building elements. Current study analysed integrated renovation up to low-energy energy efficiency level and results show that for integrated renovation, the aim of renovation should be the best energy efficiency level possible.

The higher grant rates should be directed to apartment buildings which fulfil energy efficiency requirements for new buildings or low energy level. Our analysis did not cover the apartment buildings renovation to nearly zero energy building energy performance level with sufficient depth in order to draw conclusions about economic viability of renovation to nearly zero energy building energy efficiency level but results showed that renovation of larger apartment buildings to low-energy energy efficiency level is cost optimal. Earlier studies (Ferreira et al., 2014) have concluded that the lowest cost nearly zero-energy building can be achieved with the introduction of renewables on buildings that meet the cost-optimal levels. On-site renewable energy production can also be added later to the buildings without major construction works. Therefore in the view of the future energy efficiency goals, the current activities must be directed primarily to support the deep integrated cost-optimal renovation of existing apartment buildings.

5. Conclusions

This study analysed the strategy for supporting policy, economic viability and investment cost of energy renovation using apartment buildings in Estonia as an example. The real energy usage of 105 large-panel apartment buildings were analysed to determine the current state before renovation. Individual energy saving measures and renovation packages were composed for three reference buildings in order to analyse cost optimal energy efficiency levels and investment costs. All renovation packages included the installation of ventilation system and renovation of heating system, in order to avoid energy savings at the cost of indoor climate.

Results showed that single energy efficiency measures made by apartment owners associations' own funds, have no significant impact on buildings energy usage. Integrated deep energy renovation is needed in order to achieve the future energy efficiency goals set by the European Union. Cost optimal level for large-panel apartment building renovation was low energy level, which means additional thermal insulation for the whole building envelope, replacing all windows, installing the ventilation systems with heat recovery, and depending on the building type, installing solar collectors for heating domestic hot water. Requirements of new support scheme for renovation of existing apartment buildings are set in line with those results.

Although it would be economically viable in longer terms, apartment owners associations' investment capability is not sufficient to achieve new building or low energy building energy efficiency level. Therefore financial assist is necessary to execute renovation. Analyse showed that subsides will increase apartment owners associations' investments to improve building energy efficiency. Although the some financial support is necessary for smaller apartment buildings to execute major renovation, the main target group of subsidies should be apartment buildings, which perform renovation of new buildings level or low energy performance level.

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PAPER III

Kuusk, K., Kalamees, T., Link, S., Ilomets, S., Mikola, A. Case-study analysis of concrete large-panel apartment building at pre- and post low-budget energy renovation. Journal of Civil Engineering and Management (2014) (Accepted for publication, 08.07.2014).

CASE-STUDY ANALYSIS OF CONCRETE LARGE-PANEL APARTMENT BUILDING AT PRE- AND POST LOW-BUDGET ENERGY-RENOVATION

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Abstract. The paper presents a case study analysis of low-budget renovation of a typical concrete large-panel apartment building. Focus is on the measurements and analyses of energy consumption, indoor climate, CO_2 concentration, air leakage rate, thermal transmittance of thermal bridges, and thermal transmittance of the building envelope before and after the renovation. Results indicate that the renovation project was generally successful, with delivered energy need decreasing by 40% and heating energy need decreasing by 50%. However, some key problems need to be solved to achieve full energy efficiency potential of the renovation works. Those critical problems are the performance (thermal comfort, heat recovery) of ventilation systems, thermal bridges of external wall/window jamb and economic viability. Currently, a major renovation is not economically viable, therefore financial assistance to the apartment owners´ associations is required to encourage them to undertake major renovations.

Keywords: major renovation, case study, energy performance, economic viability, large-panel apartment buildings.

Introduction

It is estimated (Economidou et al. 2011) that there is 25 billion m^2 of useful floor space in the EU27, Switzerland and Norway. Residential buildings account for 75% of the total building stock. A substantial share of the buildings in Europe is older than 50 years. Data on typical heating consumption levels of the existing buildings by age show that the largest energy saving potential is associated with older buildings where in some cases buildings from the 1960s are worse than buildings from earlier decades. The impact of poorly insulated 1960s buildings on the building stock energy consumption was amplified by the large boom in construction in 1961-1990 when the housing stock more than doubled. A study conducted in Vilnius showed that relative heat consumption data in the prefabricated concrete large-panel apartment buildings vary more in the 1960s than in the 1970s, which indicates an increase in the quality of construction works as designing and building crews gained more experience (Juodis et al. 2009). Retrofitting of the existing housing stock is crucial as the environmental impact from new buildings is negligible compared to the impact from existing buildings (Uihlein, Eder 2010).

At the European level, it has been found that countries have very different potentials for energy savings, depending on the size and condition of the housing stock. In total, 88 TWh of heating energy could be saved annually in single family houses by the year 2020 and 58 TWh in apartment buildings, totalling 146 TWh of heating energy annually (Tuominen et al. 2012). The same study also pointed out the problem that energy efficiency improvements are a low priority for consumers. This is a major obstacle for achieving the maximum energy savings possible in retrofitting as the extent and selection of retrofitting measures depend mainly on the choices of inhabitants. Studies (Uihlein, Eder 2010) have shown that it is reasonable to ensure that at refurbishment in any case the best energy efficiency level possible is installed, not only for major renovations, but also for individual building elements. This is even more important as the residential building stock shows high inertia due to low stock turnover compared to other consumer goods such as household appliances or cars. Pilot renovation projects are helpful for inhabitants in their choices of retrofitting measures. Although the pilot projects generally involve one specific building, the general principles are transferable to other building types. This is especially true in Eastern Europe, where after the Second World War similar construction solutions were used in different countries. A survey of apartment buildings in Moscow concluded that the analysis of buildings is eased by the fact that there are only a few building types. On the other hand, in reality the used materials and their parameters can vary significantly also within the same building series. As the energy performances of the different building types do not differ significantly, an adequate analysis can be made even by using only one building type (Paiho et al. 2013).

To encourage apartment owners' associations to undertake major renovation, a pilot energy-renovation project "Healthy and Economical Home" was started in spring 2010 in cooperation with two financing institutions, the ministry, an energy company, the local municipality and a university. The global purpose was to carry out an example renovation of a typical apartment building to test renovation measures and to motivate occupants to renovate their apartment buildings. This study provides reliable data not available so far due to a small number of renovation cases where energy usage is measured before and after the renovation. The aim is to present a detailed overview of the plans and results of the apartment building energy renovation.

1. Methods

1.1 Analysed building

In the spring of 2010 an apartment building composed of prefabricated concrete large panel elements (type project I-464) (Table 1, Fig 1) was selected as the pilot object.

Fig. 1. Picture of the building before (left) and after (right)

Table 1. Characteristics of the renovated building

Construction year	1966
Number of floors	5
Net area, m^2	3519
Heated area, m^2	2968
Number of apartments	60
Compactness: Building envelope, m^2 / volume, m^3, m^{-1}	0.35

The type of construction shown in Fig. 1 was very typical in Eastern Europe during the period 1961-90. For example, 2 million m^2 of prefabricated concrete large panel apartment buildings were built during that period in Estonia (Kalamees, Õiger et al. 2009) and 4.7 million m^2 in Vilnius, Lithuania (Ignatavičius et al. 2007).

1.2 Measurements

Measurements concentrated on the indoor climate and energy performance before and after renovation:

- the use of heat and electricity was determined on a monthly basis;
- the indoor temperature and relative humidity (RH) were measured with data loggers at 1 h intervals over a two year period in four apartments;
- indoor CO_2 concentration was measured during a two week period in three bedrooms as an indicator of the indoor air quality;
- air leakages of the building envelope were measured with the standardised fan pressurisation method (EN 13829).

1.3 Criteria for renovation solutions

The main goals were set before the designing started in 2010. The aims for the renovation were:

- to select renovation solutions that offer maximum repeatability for similar apartment buildings;
- to achieve the same energy efficiency (expressed as Primary Energy, PE) as are the requirements for new apartment buildings: PE ≤ 150 kWh/(m^2·a);
- to decrease heating energy use by >50%;
- to reach the indoor climate category II (EN 15251);
- cost of renovation works ≤160 €/heated m^2;
- air leakage rate q_{50} <3 m^3/(h·m^2);
- to extend service life of the building after the renovation by 50 years;
- to receive apartment owners´ association's approval of the designed renovation solutions.

PE usage for different renovation solutions was calculated according to a unified calculation methodology and with the standard usage (Estonian Government's Ordinance No. 258). PE takes into account the use of primary energy (space heating, ventilation, domestic hot water, all electricity (including lighting and appliances (plug loads)) and environmental impact according to the energy source, with weighting factors: district heating 0.9; fossil fuel (gas, coal etc.) 1.0; electricity 1.5 (2.0 since 2013) (Estonian Government's Ordinance No. 68).

The renovation measures analysed are shown in Table 2. The potential cost of the renovation was calculated on the basis of the estimates of the construction company.

Table 2. Renovation measures and costs

Renovation measures		Thermal transmittance of building envelope U, W/(m^2·K)	Linear thermal transmittance of thermal bridges Ψ, W/(m·K)	Cost, €	Cost, €/heated m^2
Roof					
R_1:	40 cm cellulose loose-fill insulation inside the roof structure	U_{roof}=0.23	Ψ_{eave}=0.24	16 000	5
R_2:	30 cm EPS above the roof	U_{roof}=0.11	Ψ_{eave}=0.29	32 000	11
External wall					
E_1:	15 cm EPS	U_{wall}=0.21	$\Psi_{wall/wall}$=0.16 $\Psi_{wall/balcony}$=0.44	73 000	25
E_2:	15 cm GE-EPS	U_{wall}=0.17		76 000	26
E_3:	20 cm EPS	U_{wall}=0.16		78 000	26
Windows					
W_1:	replacing old windows (33 % from all windows)	$U_{old\ window}$=1.8 $U_{new\ window}$=1.1	$\Psi_{wall/window}$=0.08	21 000	7
	removing the concrete layer around the windows to add insulation to window jamb´s			7000	2
W_2:	replacing of all windows	$U_{new\ window}$=0.9	$\Psi_{wall/window}$=0.04	112 000	38
Basement wall					
	10 cm EPS	$U_{basement\ wall}$=0.36		7000	2
Balconies					
	repairing of balconies slabs and new railings			32 000	11
Heating system					
	new 2-pipe system with thermostats			96 000	32
Ventilation system					
	central exhaust system with heat recovery with exhaust air heat pump			83 000	28

Heat recovery from the ventilation system was solved with an exhaust air heat pump (Fig 2) with an estimated annual average coefficient of performance COP=3.0. Supply air enters through fresh air radiators being filtered and heated at the same time. Extract air moves through ventilation shafts to an air handling unit cooling coil where heat is transferred with a brine loop to water to a water heat pump. The heat pump provides heat to the domestic hot water and the space heating system.

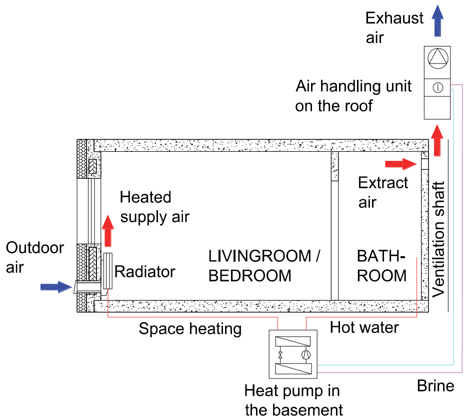

Fig. 2. The principle of heat recovery of centralised exhaust ventilation system with exhaust air heat pump

1.4 Simulations

Energy performance of potential renovation solutions was simulated using the energy and indoor climate simulation program IDA Indoor Climate and Energy 4.5 (IDA-ICE). This software is validated (Kropf, Zweifel 2001; Moinard, Guyon 2000; Travesi et al. 2001) and used for scientific modelling in research papers (Arumägi and Kalamees 2014, Kuusk et al. 2014). Software allows the modelling of a multi-zone building, internal and solar loads, outdoor climate, HVAC systems, dynamic simulation of heat transfer and air flows.

The building was simulated as a 21-zone (Fig 3) half building model because the building is symmetrical. Different zones were each apartment, staircase and a cellar. The second, third and fourth floor as identical were simulated by one floor and the results were multiplied.

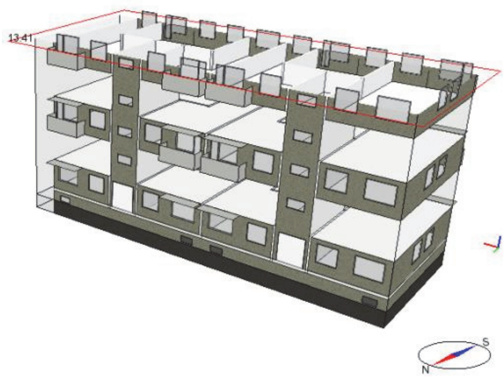

Fig. 3. Simulation model in IDA-ICE of the studied building

Internal heat gains in the renovation measures were as follows:

- inhabitants: 15.8 kWh/(m^2·a). Heat from inhabitants was counted from 3.0 W/m^2 and 80W/person using the ISO 7730 standard (1.2 met, 0.7 clo);
- appliances, equipment: 15.8 kWh/(m^2·a). Heat from appliances and equipment was counted using 3.0 W/m^2 and the usage rate was 0.6.
- lighting: 7.0 kWh/(m^2·a). Heat from lighting was counted using 8 W/m^2 and the usage rate was 0.1.

Ventilation airflow was 1.0 l/s for a bedroom and a living room m^2 for renovation packages representing indoor climate category II (EN 15251). The use of domestic hot water (DHW) is 45 l/ (pers. ×day). The number of occupants per apartment was estimated to be the number of bedrooms +1.

An Estonian Test Reference Year (Kalamees, Kurnitski 2006) was used for outdoor climate conditions (design outdoor temperature for heating -21 ºC, heating degree days at t_i 17ºC: 4160 ºC·d).

1.5 Renovation costs

The potential cost of the renovation is shown in Table 2. Project partners supported the renovation with the following grants:

- local municipality grant for renovation loan self finance (19 173 €)
- renovation grant 35% of the cost of the energy efficiency works (124 220 €)
- grant for the installation of the ventilation system with heat recovery (63 911 €)
- grant for the installation of individual space heating measuring system (12 000 €)

In addition to direct grants, the renovation loan interest rate for the pilot project was 1%. The average interest rate for renovation loans in Estonia is 4% (Fund KredEx). Global cost calculations were made for two renovation cases: with grants and without grants. In the version without grants, the renovation loan interest was taken into account with the typical interest rate of 4%. Maintenance fund payment before renovation was 0.3 € per apartment m^2 and after renovation 0.1 € per apartment's m^2.

Energy prices before the renovation were the starting point of our economic calculations. In 2010 energy prices were as follow: electricity 87 €/kWh, district heating 64 €/kWh and natural gas 38 €/kWh. Energy prices escalation for electricity and natural gas is based on Statistics Estonia database. District heating price escalation is based on the data received from district the heating company. Average escalation in 2007-2013 for electricity and natural gas was 9% and for district heating 6%.

2. Results

2.1 Selection of renovation package

The renovation packages analysed are shown in Table 3. Maximum repeatability criterion was fulfilled with the selection of the pilot object. Selected building type is widespread in Estonia, accounting for 48% of the total surface area of the prefabricated concrete large panel apartment buildings and 17% of the total surface area of all apartment buildings. All proposed renovation measures meets the renovation cost criterion (cost < 160 €/heated m^2). A decision was made considering primary energy (PE) use. Only packages containing replacement of all windows met the set criterion PE ≤ 150 kWh/(m^2·a). The selected package was $R_2E_2W_1$ (30 cm EPS above the roof, 15 cm GE-EPS on the external wall and replacing only old windows). Because before the renovation already 75% of windows had been replaced, it was decided to change only the remaining 25%. The solution was selected because it is more comfortable from the point of view of inhabitants' living conditions during the renovation (less work inside the apartment) and prevented opposition by apartment owners who were against replacing already changed windows. The PE usage criterion was planned to be achieved with the usage of a heat pump with a higher COP than 3.0, as obtained in the estimated energy performance calculations.

Table 3. Analysed renovation packages (grey shaded is the realised renovation packages)

Renovation package*	PE, kWh/(m^2·a)	Cost, €	Cost, €/heated m^2
$R_1E_1W_1$	155	334 000	113
$R_1E_2W_1$	154	338 000	114
$R_1E_3W_1$	153	340 000	115
$R_1E_1W_2$	148	437 000	147
$R_1E_2W_2$	147	441 000	149
$R_1E_3W_2$	146	443 000	149
$R_2E_1W_1$	153	350 000	118
$R_2E_2W_1$	**151**	**354 000**	**119**
$R_2E_3W_1$	151	355 000	120
$R_2E_1W_2$	145	453 000	153
$R_2E_2W_2$	144	457 000	154
$R_2E_3W_2$	144	459 000	155

* Abbreviations of renovation measures are shown in Table 2

Thermal transmittance of the building envelope and the linear thermal transmittance of thermal bridges before and after renovation are shown in Table 4.

Table 4. Thermal properties of the building envelope

Thermal transmittance of building envelope U, W/(m^2·K)	Before renovation	After renovation
walls U_{wall}	0.90	0.17
roof U_{roof}	0.70	0.11
windows U_{window}	1.85	1.40
Linear thermal transmittance of thermal bridges Ψ, W/(m·K)		
external wall/external wall	0.70	0.15
external wall/internal wall	0.30	0.01
external wall/internal floor	0.50	0.01
external wall/basement ceiling	0.50	0.06
external wall/roof	0.55	0.20
external wall/window	0.13	0.20
external wall/balcony floor	0.20	0.45
Air leakage rate q_{50}, m^3/(h·m^2)	5.1	4.9

Thermal transmittance of the external walls and of the roof was significantly reduced. Because renovation was done on a low budget, the usage of thicker layers of additional insulation on the external wall and the roof was withdrawn. The largest unused potential of the reduction of thermal transmittance of the building envelope is in the replacement of windows. The full potential was not realised because not all the windows were replaced. Stairwell doors were not replaced during renovation. Given a very small share of the total building envelope area, not changing the existing stairwell doors is not relevant in terms of overall energy usage.

Linear thermal transmittance of thermal bridges in the external wall/internal wall and the external wall/internal floor junctions was practically removed. Linear thermal transmittance of thermal bridges in the external wall/external wall and the external wall/roof junctions was significantly reduced. Problem areas are the external wall/balcony floor junctions and the external wall/window where the linear thermal transmittance of thermal bridges increased after renovation because windows stayed in their original place and were not moved into the insulation layer.

2.2 Energy performance

The usage of primary energy decreased by 20%: before the renovation it was 212 kWh/(m^2·a) and after renovation 168 kWh/(m^2·a). Figure 4 shows measured delivered energy usage before the renovation (216 kWh/(m^2·a)), calculated expected delivered energy usage (103 kWh/(m^2·a)), calculated expected heat pump (HP) heating energy production, measured delivered energy usage after renovation (132 kWh/(m^2·a)), and measured heat pump heating energy production.

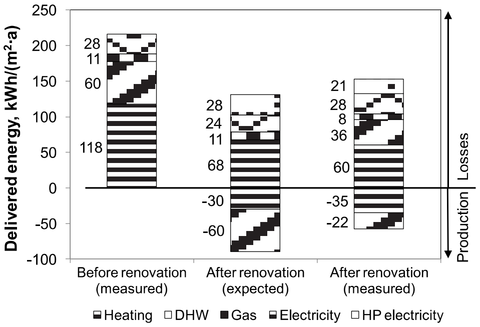

Fig. 4. Energy performance before and after renovation

Delivered space heating need decreased by 49%, delivered energy need for heating domestic hot water decreased by 40%. The main reason for failure to achieve calculated energy performance was the heat production of the exhaust air heat pump. It was estimated that the heat pump would produce 260 MWh annually and the heat pump would cover total energy need for heating domestic hot water. Actual production was 170 MWh and the heat pump covered 40% of the energy need for domestic hot water heating.

2.3 Indoor climate

There was a significant difference in the temperature measurement results before and after the renovation. Indoor temperature measurement results in accordance with indoor climate categories (EN 15251) are shown in Fig 5. Before renovation apartments were overheated, especially during cold periods. There was no significant difference in the RH or moisture excess before and after renovation. The RH was correlated with the outdoor air temperature and dropped below 20% during the coldest period.

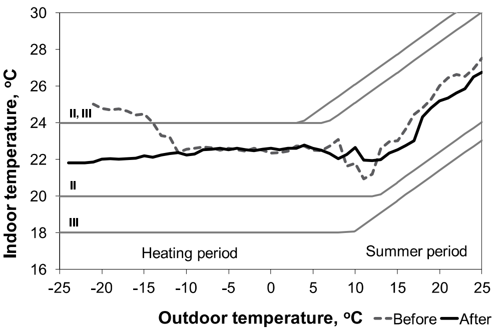

Fig. 5. Measurement results of indoor air temperature depending on the outdoor air temperature before and after the renovation

CO_2 concentration was measured in three apartments in a two-week period. Measurement results are shown for night time (23:00-07:00) before and after the renovation, see Fig 6. Results indicate that the CO_2 levels in the bedrooms decreased but the indoor climate criterion set before the renovation was not achieved.

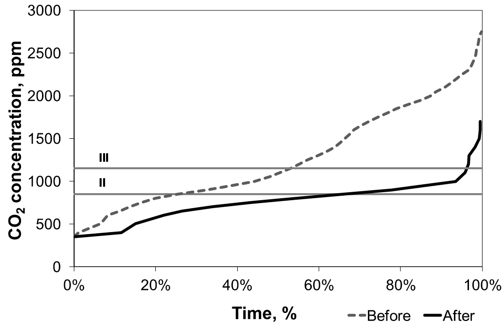

Fig. 6. Measurement results of indoor CO_2 concentration before and after the renovation

Before the renovation, the bedroom indoor air CO_2 concentration met the indoor climate class II requirements 20% of the time and the class III requirements 53% of the time. After the renovation, the CO_2 concentration met the class II requirements 66% of the time and the class III requirements 97% of the time.

Airtightness of the building envelope before and after the renovation was measured in eight apartments. Before renovation three apartments had old 2-frame wooden windows that were a part of a passive stack ventilation system. During renovation all old windows were replaced with new PVC 3-layer glass windows with one frame. The results of airtightness measurements are shown in Fig 7.

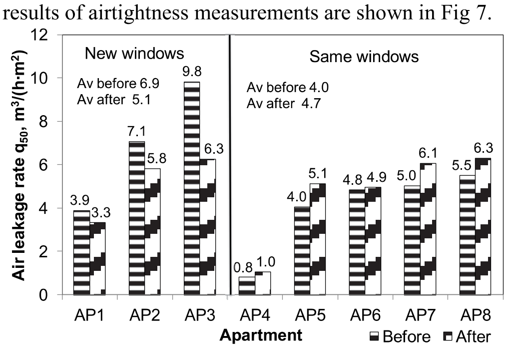

Fig. 7. Results of airtightness before and after renovation with wooden windows that were replaced (left) and existing PVC windows (right)

Airtightness of the building envelope improved only in apartments where windows were replaced during renovation, decrease of average air leakage rate was 26%. With existing PVC windows, average air leakage rate increased by 18%. Only one apartment out of the measured eight met the set post-renovation airtightness criterion of air leakage rate q_{50} <3 m^3/(h·m^2).

2.4 Renovation costs

Total cost of renovation works met the criterion set before renovation (≤160 €/heated m^2) but actual costs were 28%

higher than planned. Estimates were that renovation cost would be 119 €/heated m^2, actual costs were 152 €/heated m^2 (Table 3, Table 5).

Table 5. Expected and actual renovation measure

Renovation measure	Expected cost €	Expected cost €/heated m^2	Actual cost €	Actual cost €/heated m^2
Insulation of roof	32 000	11	40 700	14
Insulation of external walls (with foundation walls)	83 000	28	132 500	45
Replacement of old windows	21 000	7	16 500	6
removing the concrete layer around the windows	7000	2	-	-
Renovation of balconies	32 000	11	48 300	16
Renovation of heating system	96 000	32	100 000	34
Renovation of ventilation system	83 000	28	100 000	34
Installation of individual heating measuring system	-	-	12 000	4
Total	354 000	119	450 000	152

The main reason why the predictions were inaccurate was the cost of external wall additional insulation, which was 62% higher than estimated. One of the reasons is the fact that the assessments of the construction costs were made almost two years before the renovation, and the costs had risen in the meantime.

Annual costs per apartment m^2 without renovation and with renovation are shown in Fig.8. Costs are calculated as average for a loan period (20 years) and with the energy price escalation.

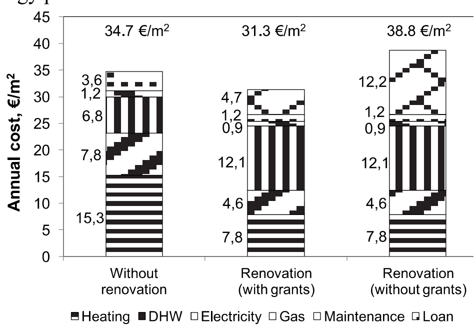

Fig. 8. Annual costs per apartment m^2 without renovation and with renovation.

Results show that the current pilot project with grants was economically reasonable for inhabitants and annual total costs per apartment m^2 were 3.4 € lower than without renovation. If the same renovation works are done without grants, then the annual costs per apartment m^2 would be 4.1 € higher than without renovation. Therefore, financial assistance to apartment owners´ associations is required to perform major renovation.

3. Discussion

PE consumption was higher than estimated. The main reason is the performance of the heat recovery system with the exhaust air heat pump. It was estimated that the heat pump would cover total energy need for heating domestic hot water. Measurements after renovation showed that the heat pump covered 40% of the energy need for domestic hot water heating. Identification of the exact causes requires further investigation of the system, however, the system did not started working as expected. That kind of system was a new solution for renovation of apartment buildings in Estonia. Previous studies about retrofitting have concluded that with the use of innovative systems, they will probably not work exactly as predicted (Branco et al. 2004). Subsequent research in Estonia (Kõiv et al.2012) has shown that the estimation of the coefficient of the performance of an exhaust air heat pump was correct (COP=3.0).

One of the reasons for failure to achieve the PE usage criterion was that thermal bridges were not eliminated in the external wall/ window junction. Calculations showed that in the current case the heat loss through thermal bridges around the windows and the heat loss through additionally insulated external walls are at a similar scale (Ilomets and Kalamees 2013). In energy calculations it was estimated that the linear thermal transmittance of thermal bridges in the external wall/window junction would be diminished. The reality was that the linear thermal transmittance of thermal bridges in the external wall/window junction increased because not all the windows were replaced and therefore not all kept their original position. That decision was made by the apartment owners´ association who had to approve designed renovation solutions. Previous studies have shown that the opinion of the decision maker has a major impact on the results and owner´s care mainly about having a short payback period (Medineckienė and Björk 2011). The apartment owners found it too expensive to replace all windows and move them into the insulation layer. The back-up plan to place additional insulation to the window jamb was not possible in the extent that was planned. Removing part of the concrete layer surrounding the windows and replacing that with a layer of insulation was not possible. Therefore it was impossible to install a sufficient layer of insulation to the window jambs, but the thermal bridge on the external wall/window junction is very sensitive to the thickness of insulation on a window's jamb (Ilomets and Kalamees 2013).

Regarding to the PE usage criterion, the problem was that airtightness of the building envelope was not improved. In the energy calculations, it was estimated that the air leakage rate after renovation would be $q_{50} < 3$ m^3/(h·m^2). The actual air leakage rate after renovation was q_{50}=5 m^3/(h·m^2). Measurements after the renovation showed that airtightness improved only in the apartments where windows were replaced, which was the expected result. As studies have shown, replacing of old draughty windows with modern sealed windows will reduce the background infiltration rate by the order of 0.1 ach to 0.3

ach (Ridley et al. 2003). If windows were not replaced, the air leakage rate would actually increase. That was probably caused by new openings for ventilation inlets behind the fresh air radiators. There was a gap around the air inlet sleeve and the external wall that is difficult to tighten.

Measurements of the indoor temperature before and after the renovation show improvements due to better adjustment of a new heating system. Overheating is avoided during colder periods. The problem is that considering the CO_2 concentration, the indoor climate category II criterion was not achieved. After the renovation, the bedroom indoor air CO_2 concentration met indoor climate class II requirements only for 66% of the measurements time. The main reason for that is the reduction of the airflow in the ventilation system by the inhabitants. The design airflow for the ventilation system was 2.1 m^3/s. After renovation the measured airflow was 1.43 m^3/s. Fan speeds in two air handling units were reduced by the inhabitants because of the problems with thermal comfort caused by fresh air radiators. In the spring and the autumn, the air that enters the radiator does not heat up sufficiently. The reason lies in the fact that an insulated building does not need substantial heating in spring and autumn and radiators are at a low temperature and the entering cold air does not heat up, causing thermal discomfort. Another problem which is associated with renovation of the ventilation system is the airtightness of the ventilation shafts. Existing ventilation shafts were not airtight and new ventilation ducts were placed in the existing air shafts to ensure the required airtightness of ventilation ducts. Installation of new ducts was not always successful since existing shafts joints were not perfectly aligned. In some shafts it was not possible to insert the new duct to the entire length of the existing shaft. So the airtightness of all the exhaust ducts was not ensured and therefore it is difficult to ensure design exhaust airflow from all apartments.

From an economic point of view, the pilot project was successful. Apartment owners' annual costs were reduced and the cost of renovation works criterion was fulfilled. Annual cost reduction was achieved due to grants for renovation works. Without the grants, the annual cost after the major renovation would be higher for apartment owners and that would make it difficult for apartment owners´ association to make a decision for major renovation as one of the main priorities for apartment owners is a short payback period (Medineckienė and Björk 2011). Such an approach is sufficient for choosing renovation solutions. The effectiveness of retrofitting an apartment building should be evaluated from various perspectives: energy conservation, improved state of the building structures, prolonged lifetime of the building, and an increase in market value taken into account (Zavadskas et al. 2007). Some studies have shown that renovated buildings are less sensitive to fluctuations in the heat price than those where renovation is not performed. Despite constant loan payments, renovated buildings will be in a better position in the sense of the overall payment rather than non-renovated buildings (Biekša et al. 2011). This study showed that although the impact of the heat price on the overall payment is significantly diminished after the renovation, the overall payment would be higher than with non-renovated buildings if no grants are available for apartment owners´ associations. The reason is that existing apartment buildings have natural ventilation systems which need replacement with mechanical ventilation system with heat recovery to ensure the indoor climate quality. Fans and, depending on the solution, exhaust air heat pumps or heating coils in apartment based air handling units need electricity, therefore overall electricity consumption of the apartment buildings increases. Adding a loan payment and considering the fact that electricity is significantly more expensive than district heating, the reduction of the heating energy need does not cover the loan payments and increased electricity bills. Grants for renovation works are required to guide inhabitants to choose a better indoor climate and make the decision to install a proper ventilation system which seems costly at first sight.

4. Conclusions

The renovation project was generally successful, but some of the goals set before the renovations were not achieved. The construction cost target was fulfilled, but the energy consumption and indoor climate goals remained unfulfilled. Success of the renovation project depends on the detailed design of the renovation solutions and ability to direct the apartment owners to make the right choices. Although at large the renovation was successful, as the heating costs were reduced, indoor climate and aesthetics improved, there were some key issues that led to failure to achieve some of the targets set before renovation:

- thermal comfort of the ventilation system needs to be improved. Otherwise inhabitants will block the ventilation system work and the designed indoor climate is not achieved;
- thorough information and explanation for apartment owners is required to encourage them to make decisions that may seem costly at first sight, but are required to achieve the full energy efficiency potential of renovation works.

Overlooking specific problems encountered in this renovation project, it can be concluded that with major renovation:

- the energy efficiency levels of new apartment buildings are achievable;
- the financial assistance to apartment owners´ associations is required to perform major renovation.

Acknowledgements

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PAPER IV

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nZEB retrofit of a concrete large panel apartment building

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Abstract

The paper discusses energy renovation scenarios from major renovation to nZEB level for apartment buildings in Estonia (cold climate). The study analyses energy usage and economic viability taking into account a possible increase in the lease income after renovation under apartment building renovation scenarios. Our results show that deep renovation of old apartment buildings enables the energy performance requirements of nearly zero energy apartment buildings to be achieved. With nZEB renovation, reductions are ca 70% in delivered energy (heating energy + electricity) need and ca 60% in primary energy need. Payback period of nZEB renovation without increased lease income is around 30 years. In the best scenario case, the payback period of nZEB renovation is around eight years when the increase of the annual lease income is taken into account.

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Keywords: nZEB retrofit; energy and cost savings; renovation of apartment buildings.

1. Introduction

In the European building energy consumption has increased at a rate of 1.5% per annum [1]. At the same time, European countries have been found to possess very different potentials for energy savings, depending on the size and condition of the housing stock. By the year 2020, a total of 88 TWh of heating energy could be saved annually in single family houses and 58 TWh in apartment buildings, totaling at 146 TWh of heating energy annually [2]. Despite the large energy savings potential, earlier studies suggest that the European Union 2020 energy savings target will be missed by a wide margin [3]. Although the monitoring results of new green residential buildings have been satisfactory [4], retrofitting of the existing housing stock is crucial as the environmental impact from new buildings is negligible compared to the impact from existing buildings [5]. The reason for low renovation volumes appears to be not in the condition of existing building structures. Results of research covering the current technical condition of Estonian old

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concrete element housing stock refer to satisfactory condition in terms of load-bearing but point out insufficient energy performance, indoor climate and hygrothermal performance of the building envelope [6]. One possible reason for low renovation volume is the relatively long payback period (around 20 years) of the energy renovation process in apartment buildings [7]. A study conducted in Portugal concluded that in the early design stage and to foster the sustainability of the entire process, it is essential to consider the cost of different options in the decision making process [8].

This case study analyses the economic viability of nZEB renovation of a large panel apartment building taking into account the effect of possible lease increase of the apartments after the renovation.

2. Methods

2.1. Case study building

The case study building (3519 m^2) shown in Figure 1 is similar to mass production apartment buildings from 1970-1990 in the former Soviet Union countries in the Eastern Europe. The five-storey building was composed from prefabricated concrete large panel elements (Series 111-121) in 1986.

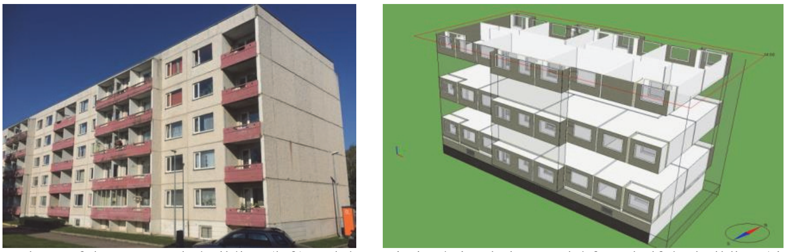

Fig. 1. Photo of the case study building (left) and the optimized simulation model from half the building (right).

The building has a natural passive stack ventilation system and one-pipe radiator heating systems. Radiators are not equipped with thermostats. Room temperature for the whole building is regulated in heat substations depending on outdoor temperatures. The thermal transmittances of the building envelope are: external walls: $U_{wall} \approx 1.1$ W/(m^2·K); roof-ceilings: $U_{roof} \approx 1.0$ W/(m^2·K); windows: $U_{window} \approx 1.6$ W/ (m^2·K).

2.2. Calculations

Energy performance of the reference buildings was simulated using the energy and indoor climate simulation program IDA Indoor Climate and Energy 4.6 (IDA-ICE) [9] with Estonian Test Reference Year for outdoor climate (annual heating degree days at t_i 17ºC: 4160 ºC·d) [10].

Primary energy use for different renovation scenarios was calculated according to an Estonian unified calculation methodology and with a standard usage [11][12] (factor for district heating is 0.9 and for electricity 2.0).

Ventilation airflow for renovation packages representing indoor climate category II is 0.42 l/(s·m^2) [13] (normal level of expectation for indoor climate). The use of domestic hot water (DHW) heating need is 30 kWh/(m^2·a).

Net present value (NPV) calculations were used to evaluate financial feasibility of different cases. The following parameters were used based on the current retrofit practice in Estonia: NPV calculation period - 20 years; real interest rate - 4%; heating energy price - 0.075 €/kWh; price of electricity - 0.14 €/kWh; escalation of energy prices - 3%; the present value factor - $f_{pv}(n)$ = 18.05.

The following formula was used to calculate the NPV [14]:

$$C_g = \frac{C_1 + C_a \cdot f_{pv}(n) - l_a \cdot f_{pv}(n)}{A_{floor}} \qquad (1)$$

where: C_g is global incremental energy performance related costs, €/m^2; C_i is initial investment costs, €; C_a is annual energy costs during the starting year, €; $f_{pv}(n)$ is the present value factor for a calculation period; l_a is an annual increase in the lease income, €; A_{floor} is the net heated floor area, m^2.

The present value factor $f_{pv}(n)$ was calculated as follows:

$$f_{pv}(n) = \frac{1-(1+(R_R-e)/100)^{-n}}{(P_R-e)/100} \tag{2}$$

where: R_R is the real interest rate, %; e is the escalation of energy prices, %; n is the length of the calculation period.

The payback period was calculated using the return on investment (Eq. 4):

$$T = \frac{100\%}{E} \tag{3}$$

where: T is the payback period in years; E is the return on investment, %.

Return on investment was calculated for each year of the loan considering the escalation of the energy prices:

$$E = \frac{\Sigma(En_i \cdot S_i + l_a)}{C_i} \cdot 100\% \tag{4}$$

where: En_i is the delivered energy decrease for year i , MWh/a; S_i is the delivered energy cost for year i , €/MWh; l_a is an annual increase in the lease income, €. Payback period was calculated using the median return on investment.

Construction costs (Table 2) were taken from the estimations of the construction companies. Increase of the lease income was estimated to be 45 € per apartment m^2 per year. No incentives are included in the economic calculations.

Table 1. Construction costs of renovation measures

Building envelope	Cost, €	Service systems	Cost, €
Additional insulation for external walls +200 mm	119 000	Renovation of 1-pipe system	40 000
Additional insulation for roof +400 mm	40 000	New 2-pipe system	112 000
Additional insulation for basement ceiling +100 mm	18 000	Exhaust ventilation without heat recovery	40 000
Replacement of windows U-0.8 W/(m^2·K)	107 000	Apartment based ventilation units with heat recovery	240 000
		Solar collectors	89 000
Modernization of apartments	800 000	PV-panels	52 000

2.3. Energy efficiency measures

The procedure of selecting energy efficiency measures and renovation scenarios was as follows. First, the current state of the building (insufficiently ventilated and without room based temperature control) was aligned with the indoor climate requirements. For that, the heating system was balanced and equipped with thermostatic valves and a mechanical exhaust ventilation system without heat recovery was installed. This state was a base case for comparing energy efficiency measures. Energy efficiency measures were combined to establish different energy efficiency levels. For energy certification class D (energy efficiency requirement for major renovation), the building envelope was insulated, windows were replaced and a new 2-pipe heating system was installed. For energy certification class C (energy efficiency requirement for a new building), apartment based ventilation units (heat recovery efficiency of 70 %, specific fan power of 1.5) were installed in addition to the previous renovation package. For energy certification class B (energy efficiency requirement for a low-energy building), solar collectors were installed in addition to the previous renovation package. For energy certification class A (energy efficiency requirement for nZEB), PV-panels were installed in addition to the previous renovation package.

The area of solar collectors was calculated by a simplified method described in [15]. The calculated solar collector area was 180 m^2. In order to achieve nZEB energy efficiency requirements, the remaining roof area was used to install PV-panels. The maximum PV-panel installation area was estimated at 150 m^2.

The building studied is used as a dormitory. I In addition to the energy renovation, its apartments need modernization. In order to analyze the economic viability from an apartment owner´s perspective when no apartment modernization is needed, correspondingly, the calculations excluded the investment need of apartment modernization.

3. Results

Energy usage and investment costs of different renovation scenarios are shown in Table 2. Delivered energy need is reduced by 70% and primary energy need by 60% at nZEB renovation. Therefore, annual reduction of energy costs is also 70%, which enables an increase in the annual income from the lease.

Table 2. Energy usage and investment costs of renovation scenarios

	nZEB	Low energy building	New building	Major renovation	Current state with indoor climate	Current state
Thermal transmittance, W/(m^2·K)						
Exterior wall	0.15	0.15	0.15	0.15	1.1	1.1
Roof	0.08	0.08	0.08	0.08	1.0	1.0
Window	0.8	0.8	0.8	0.8	1.6	1.6
Air leakage rate, q_{50}	4.0	4.0	4.0	4.0	4.4	4.4
Delivered energy (energy use of technical systems with systems losses), kWh/(m^2·a)						
Space heating	15	15	15	82	149	131
Ventilation	7.6	7.6	7.6	in space heating	in space heating	in space heating
Domestic hot water	30	30	30	30	30	30
Appliances, lighting	29.5	29.5	29.5	29.5	29.5	29.5
Fans, pumps	6.2	6.2	6.2	5.4	5.4	0.5
Total	62	67	88	147	214	191
Produced energy on site, kWh/(m^2·a)						
Solar collectors (heat)	21	21	-	-	-	-
PV panels (electricity)	5.5	-	-	-	-	-
Primary energy use, kWh/(m^2·a)						
Energy performance value	97	108	127	170	230	205
Investment costs of renovation works, €/m^2						
With modernization of apartments	413	400	376	324	-	-
Without modernization of apartments	203	190	166	114	21	-

NPV calculation results of renovation packages are shown in Fig. 2. The first renovation package that fulfills the indoor climate requirements was set as a base case for renovation packages, as an investment required to ensure a healthy living environment. Increase in the ventilation airflows raises the primary energy usage. Therefore, the NPV of the base case is higher than that of the current state. All the other renovation scenarios decreased the NPV due to lower energy consumption and increased the annual lease income. Results on the graph show a relatively straight line from the major renovation level to the nZEB level. Renovation to the nZEB level has the same global incremental cost as renovation to a new building or a low-energy building level although investment costs for the nZEB renovation have 25 % higher construction cost than the investment cost of major renovation. Higher energy efficiency compensates the higher initial investment costs. Without higher income from the lease, all renovation scenarios increased the NPV. Therefore, increased income from the lease is the main factor that makes the nZEB renovation profitable.

Excluding the investment costs for apartment modernization reduces the NPV even with no changes in the annual lease income. NPV calculation results are relatively close to zero, which means that at higher renovation costs, the nZEB renovation may increase the NPV when the annual lease income is excluded. Because increase of lease without the modernization of apartments may not be possible, this scenario has not been taken into account in the final conclusions.

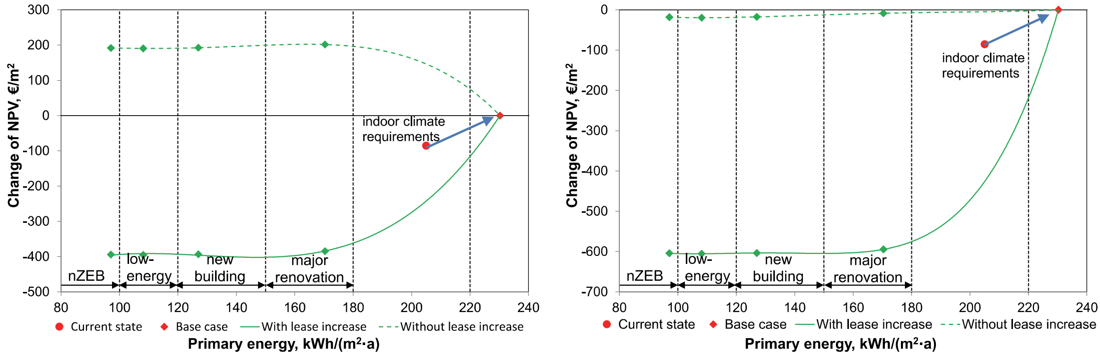

Fig. 2. Change of the NPV for renovation with investment costs of apartment modernization (left) and without investment costs of apartment modernization (right).

Calculation results for the payback period show (Fig. 3) the same principle. When the indoor climate requirements are fulfilled, the annual energy consumption is increased. It is shown on the graph as an increase of the primary energy usage. All the other renovation packages have similar payback periods of around 8 years with the investment costs for apartment modernization taken into account and payback periods of around 4 years without the investment costs for apartment modernization. Payback periods of different renovation scenarios show larger differences when an annual lease income is not considered. This means that changes in the annual lease income have higher impact on the NPV calculation than an annual reduction of energy costs.

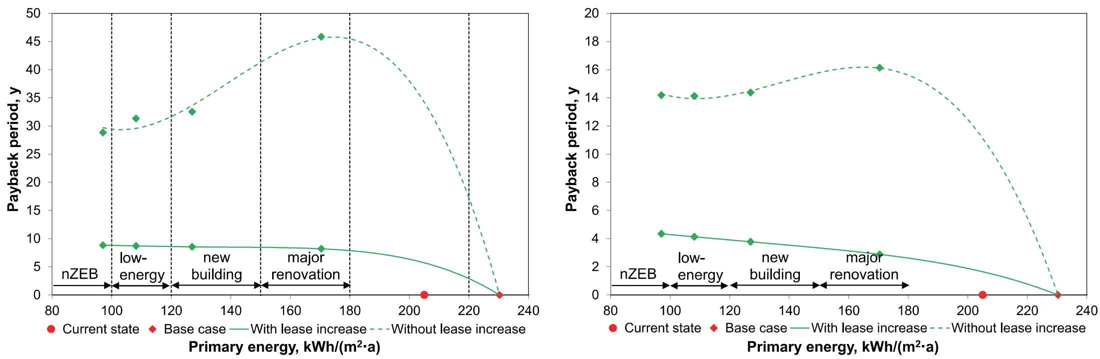

Fig. 3. Payback period of renovation with the investment costs of apartment modernization (left) and without investment costs of apartment modernization (right).

4. Discussion

This study shows that renovation of apartment buildings to the nZEB level is economically profitable but some limitations still exist. The building studied is perfectly aligned towards north-south with a longer façade, which allows installing a large area of on-site renewable energy production equipment. If the building were facing east-west with a longer façade, then the on-site renewable energy production possibilities would be lower and energy efficiency requirements of nZEB renovation would be achieved with a thicker insulation level of the external wall or with windows with lower thermal transmittance. Those renovation measures have higher investment costs and the NPV of the renovation scenario would be higher.

In this study, an annual increase of the lease income was found the same for all renovation packages from the major renovation l to the nZEB level. Annual energy costs in the nZEB level are almost 60 % lower than those in the major renovation level. Therefore, an annual increase of the lease income can be higher in the nZEB level building. Higher lease income would make the nZEB renovation more profitable than the major renovation or renovation in the new building in terms of the energy efficiency level.

Increased annual lease income is the major factor in the economic viability of nZEB renovation. Results show a slight reduction of the NPV of nZEB renovation without higher lease income after the renovation. When the building needs higher investment costs to achieve the nZEB energy efficiency level, the NPV may increase after the renovation when the annual lease income is excluded. For a private owner of the apartment, the nZEB renovation of the building is profitable without apartment modernization need, which increases the annual lease. More detailed information about the lease rate changes according to the energy efficiency level of the apartment building is needed for further analysis. When the increase in the annual lease income is the same for all renovation scenarios, it is impossible to distinguish which renovation scenario is most profitable for the building owner; however, we can conclude that nZEB renovation is profitable with the increase of the annual lease income considered.

5. Conclusions

Main findings of this study show that nZEB renovation is profitable when the increase of the annual lease income is taken into account. The annual delivered energy need as well as the annual energy costs can be reduced by 70% compared to the base case. Energy cost reduction alone is not enough to make nZEB renovation profitable for a building owner. Payback period of nZEB renovation without the lease income is around 30 years. With the best scenario case, the nZEB renovation payback period is around 8 years with the increase of the annual lease income taken into account.

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Energy and investment intensity of integrated renovation and 2030 cost optimal savings

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ABSTRACT

Energy and investment intensity of integrated renovation variants were studied to determine cost optimal energy savings by 2030 as a part of new Estonian energy roadmap preparation. For major residential and non-residential building types, 3–4 renovation variants with different ambition were defined, all including the installation of adequate ventilation system in order not to compromise indoor climate. Cost optimal energy performance level of renovation corresponded in most cases to minimum energy performance requirements of new buildings. In most of building types cost optimal renovation cost was slightly below or higher of 200 €/m^2 which could be seen as major barrier in residential buildings needing support schemes in order to realize the potential. Cost optimal energy savings were remarkable in heating energy, which was reduced by factor of 3 to 4, but electricity use tended to increase in most of building types while retail and industrial buildings showed strong electricity reduction potential. The reduction in electricity use by 2030 was without and with new construction 7 and −8%, respectively. By 2030 cost optimal renovation saved 16% of final energy, but with the inclusion of new construction the reductions in final energy and non-renewable primary energy were 8% and 0% respectively.

1. Introduction

National energy roadmaps and action plans need solid evidence based technical input about energy savings, indoor climate improvements and cost effectiveness of energy performance improvement measures. Such technical and economic data can then be used in scenarios with different ambition to predict energy use development trends in the building stock, required investments, direct and indirect economic effects in order to find most suitable measures for the implementation. This study contributes to the preparation of new Estonian energy roadmap ENMAK 2030+[1], which uses the reference level of 2010 and constructs three building stock improvement scenarios by 2030.

ENAMK 2030+ is an actual example of a national roadmap; it is partly implementing EU 2020 targets and goes up to 2030, which is the time frame for next detailed EU targets currently under discussion as described in Green Paper [2]. Green Paper reflects a need on a new 2030 framework for climate and energy policies and refers to roadmaps for 2050. Energy Roadmap 2050 [3] states that the prime focus should remain on energy efficiency, where buildings play a major role. It is stated that an analysis of more ambitious energy efficiency measures and cost-optimal policy is required which is one core activity in ENMAK 2030+. The roadmap concludes that electricity will have to play a much greater role than now (almost doubling its share in final energy demand to 36–39% in 2050), that shows an importance of electricity use also in buildings. Therefore, energy saving potential assessment in buildings cannot be limited on heating energy, as often done [4], but electricity use should be a consistent part of analyses as affecting both energy use and cost effectiveness. Roadmap 2050 [5] sets out a cost-efficient pathway to reach the target of reducing domestic emissions by 80% by 2050. To get there, Europe's emissions should be 40% below 1990 levels by 2030, and the sector specific target for residential and service sectors CO_2 reduction is 37 to 53%, which include efficiency improvements together with increase of the share of low carbon technologies in electricity mix up to 75–80% in 2030 [5].

In energy efficiency targets, the building stock and its energy performance improvements play a major role, because energy use in buildings has steadily increased and has exceeded the other major sectors: industrial and transportation [6] while the replacement rate of the existing stock is only 1–2% per year. Compared to 1994, energy use in buildings increased in 2004 by factor of 1.17, but stayed in about of 37% of total EU final energy consumption during this period [6]. In the last years, energy use in buildings has shown some decrease, but grew again substantially reaching the highest level of the last 20 years with the share of 39.9% in 2010 [7].

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Nomenclature

Final energy is the energy finally consumed in the transport, industrial, commercial, agricultural, public and household sectors. It excludes deliveries to the energy transformation sector and to the energy industries themselves.
Primary energy is the extraction of energy from a natural source.
Renewable energy includes hydroelectricity, biomass, wind, solar, tidal and geothermal energies.

Acronyms
NPV Net present value
EP Energy performance value
EPC Energy performance certificate
nZEB Nearly zero energy building
HRV Heat recovery ventilation
AHU Air handling unit

Symbols
f_{tot} Total primary energy factor
f_{nren} Non-renewable primary energy factor

Energy use in buildings varies in members states while European average annual heating energy use has been estimated 173 kWh/m^2 in apartment buildings [8] and in residential buildings between 150 and 230 kWh/m^2 [9]. Estonian data is in the range and is discussed in the results. Cost effective energy saving potential in 10 countries was calculated in [4] concluding that cost-effective saving of 10% of heating energy can be achieved by 2020 and 20% by 2030. Reported minimum and maximum costs of renovations show remarkable variation between countries, min values ranging from 3 to 70 €/m^2 and max values from 5 to 200 €/m^2 allowing to conclude that cost optimal renovation variants depend much on local conditions.

Regarding cost effective renovation measures, Nemry et al. [10] modeled building stock for the EU-25 and reported that additional roof and façade insulation as well as sealing of leakages were cost effective in houses while sealing of leakages appeared to be the only cost effective measure in multi-family and high-rise buildings. Verbeeck and Hens [11] reported economically feasible hierarchy of energy-saving measures, based on five reference building describing Belgian residential buildings, as follows: insulation of the roof; insulation of the floor, if easily accessible; new windows; more energy efficient heating system and renewable energy systems. These measures are generally in line with ones used in this study with the exception of heat recovery ventilation that is indispensable in a colder climate.

EPBD directive, launched 2007 and 2010 [12] has generated in Estonia a deep renovation of 520 apartment buildings with KredEx support scheme [13], which experience and technical solutions are utilized in this study. This study focuses on energy performance measures intended for integrated (deep) renovation of residential and non-residential buildings. By integrated renovation it is meant that both adequate indoor climate (especially improved ventilation) and improved energy performance are to be achieved.

The aim of this study was to develop a useful minimum number of alternative integrated renovation variants for minimum number of reference buildings representing building types in order to be able to predict energy use in Estonian building stock as well as required investment needs for integrated renovation. Energy use and renovation of Estonian apartment buildings has been previously comprehensively studied in [14] allowing to use representative reference buildings and renovation package variants from these studies. For other building types, reference buildings and alternative integrated renovation variants were defined in this study. For each renovation variant studied, investment cost and net present value of 20 years with corresponding energy and cost data was calculated. As an application of defined renovation variants and reference buildings, technical and cost optimal energy saving potentials of Estonian building stock were determined. Achievable energy savings by 2030 were calculated in final and primary energy with assumptions of three scenarios which included incentives and cost optimal renovation variants. The study was limited to energy and investment intensity analyses of building type specific integrated renovation variants and building stock energy analyses. These results will be used as input to national economy analyses which will be conducted in ENAMK 2030+for buildings and other sectors to show direct and indirect effects, benefits and public finance effects allowing one to identify most suitable measures for the implementation.

2. Methods

The methodology used in this study was oriented on detailed description of renovation alternatives which will most probably used in majority of renovated buildings in future. This was somehow different approach compared to building stock energy modeling, where enough detailed distributions of age and building types play an important role and for example 300 categories have been used in the modeling of Swedish building stock [15]. In this study, the accuracy of the energy modeling in the building stock was intentionally compromised, so that very limited number of reference buildings was used, to be able to cover about 80% of the building stock, which was considered enough for the estimation of the technical energy saving potential. Major effort was put to detailed energy and cost simulations of such integrated renovation variants which would be directly applicable in practice. For every reference building, 3–4 renovation variants with different ambition were studied so that even the variant with the lowest cost included the installation of adequate ventilation system, in order to strictly avoid energy savings at the cost of indoor climate that was a specific target of ENMAK 2030+and is also stated in EPBD recast [12]. The renovation variants with higher ambition were intended to be used together with relevant incentives.

The building types used, to describe the building stock with given limitations, were selected according to floor area distribution of the building stock as shown in Table 1. Major categories of residential and non-residential buildings were described with reference buildings for which detailed energy and cost simulations were conducted. For industrial buildings (without process) and retail an available sample of buildings with implemented energy performance improvement measures was used.

Table 1
The size of Estonian conditioned (heated and ventilated) building stock and the number of reference building used in the study.

Building type	Floor area (m^2)	Floor area (%)	No of ref. buildings
Multifamily	34,281,629	31	4
Single family	26,447,774	24	2
Other residential	5,962,745	5	-
Industrial (w/o process)	16,658,128	15	1
Office buildings	8,269,072	8	2
Retail	6,487,440	6	1
Educational	4,133,084	4	2
Hotels	1,741,856	2	–
Hospitals, clinics	1,840,182	2	–
Other	4,419,816	4	–
Total	**110,241,726**	**100**	

Table 2
Residential reference buildings used in the study. The compactness is defined as the ratio of building envelope surface area to volume. Old houses have a mix of stove, wood and electric heating, new houses gas or electric heating and majority of apartment buildings district heating.

	DH-New	DH-Old	AP2	AP4	AP5	AP10
						
No of stories, –	2	1.5	2	4	5	10
Net floor area, m^2	218	165	508	1383	3147	11,374
Heated floor area, m^2	182	165	388	1154	2623	10,781
No of apartments, –	1	1	8	32	40	162
Wall U-value, W/(m^2 K)	0.25	0.54	1.1	1.0	0.8	0.8
Roof U, W/(m^2 K)	0.16	0.48	1.1	1.1	0.9	0.7
Window U, W/(m^2 K)	1.8	2.8	2.8	2.8	2.8	2.8
Leakage q_{50}, m^3/(h m^2)	6	15	4	4	4	4
Compactness A/V, m^{-1}	0.98	0.8	0.60	0.44	0.47	0.32

Table 3
Description of renovation variants, classified according to Estonian energy performance certificate scale [18] which primary energy limit values in kWh/m^2 (detached houses/apartment buildings) are shown in parentheses. Thermal bridges are accounted and maximum leakage rate reduction is 50% applying for wall and roof insulation together with windows replacement.

EP-class	DH-New	DH-Old	Apartment buildings
E (260/280)	HRV 80%	HRV 80%, pellet boiler, roof insulation 250 mm	Wall insulation 200 mm, windows U = 1.1, mechanical exhaust ventilation
D (210/180)	E + pellet boiler	E + wall insulation 200 mm, windows U = 0.7	E + roof insulation 300 mm, basement ceiling 150 mm, two pipe heating system, exhaust air heat pump
C (160/150)	E + GSHP, roof insulation 250 mm, windows U = 0.7	HRV 80%, GSHP, roof insulation 250 mm, wall 300 mm, windows U = 0.7	D + HRV 60% (apartment AHU or central AHU)
B (120/120)	C + solar collectors, wall insulation 250 mm, floor insulation 300 mm	C + solar collectors, floor insulation 300 mm (B class not achieved EP = 136)	C + windows U = 0.6, solar collectors, HRV 80% (apartment AHU)

In the selection of reference buildings, previous studies were utilized. Kalamees et al. [14] has analyzed the distribution and energy use of Estonian multifamily building stock, which was described with four representative reference buildings and most cost effective integrated renovation variants with different ambition according to this study. The data of Hani [16] was utilized to select reference buildings and renovation variants of office buildings. For single family buildings, the only available data was published in [17] from which one reference building representing relatively new detached houses (DH-New) and another representing an old houses (DH-Old) with major renovation needs were used. For school buildings, two typical school buildings representing larger schools were modeled in this study. Main parameters of the residential reference buildings used are shown in Table 2 and description of renovation variants in Table 3.

For the office and school reference buildings U values of 1.1, 1.0 and 1.8 W/(m^2 K) for external walls, roofs and windows, respectively, and the ventilation rate of 30% of minimum requirements (without heat recovery) were used. Renovation variants are described in Table 4.

For retail and industrial buildings (without process) a samples of 8 and 5 buildings with measured energy data were used. For representative buildings from these samples, renovation variants shown in Table 5 were used.

The results of renovation alternatives were calculated with selected reference buildings as follows:

Old and new detached house were calculated separately and they represented 78% and 22% of detached houses according to the age distribution of detached houses;

Results of apartment buildings were calculated for all four reference buildings and then averaged with weighting according to the size of apartment building stock each reference building represented;

For office and school buildings the results were calculated for both reference buildings and then averaged with weighting according to the floor area of reference buildings.

Table 4
Renovation variants in office and school buildings classified according to EPC scale (EP values).

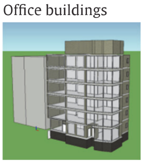
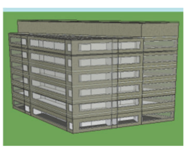
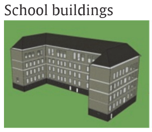
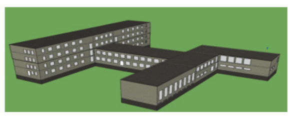
EP-class, primary energy kWh/m^2 (offices/schools)	Office buildings	School buildings
	 	 
D (210/200)	HRV 70%, wall insulation 200 mm, roof insulation 250 mm, window U = 1.2	–
C (160/160)	HRV 70%, wall insulation 150 mm, roof insulation 200 mm, window U = 0.9, demand controlled lighting	HRV 70%, wall insulation 200 mm, roof insulation 250 mm, window U = 1.2
C (160/160)	HRV 70%, wall insulation 250 mm, roof insulation 300 mm, window U = 0.9	HRV 70%, wall insulation 250 mm, roof insulation 300 mm, window U = 0.9, demand controlled lighting
B (130/120)	C + demand controlled lighting (B class not achieved, EP = 142)	C + demand controlled ventilation

Table 5
Renovation variants in retail and industrial buildings classified according to EPC scale (EP values).

EP-class, primary energy	Retail	Industrial buildings without process
E (330/–)	Renovation of lighting system	Renovation of lighting system
D (280/–)	E + renovation of heating and ventilation system, BMS	E + renovation of heating and ventilation system,
C (230/–)	D + new display cabinets	D + insulation of walls and roof
B (160/–)	C + insulation of walls and roof	

Cost effectiveness of renovation variants was assessed with financial calculation of net present value according to principles set in the Commission's cost optimality methodology [19] developed for the assessment of cost optimal energy performance levels. The net present value was calculated as global cost consisting of construction cost and discounted energy costs according to [20]:

$$C_g = \frac{C_I + C_a \cdot f_{pv}(n)}{A_{floor}} \tag{1}$$

where:
C_g global cost, NPV, €/m^2
C_I construction cost of the renovation variant, €
C_a annual energy cost during starting year, €
$f_{pv}(n)$ present value factor for the calculation period of n years, -
A_{floor} heated net floor area, m^2

Construction cost of renovation variants was calculated as full cost (i.e. not only energy performance related) where all costs of construction works and installations were taken into account. For example, in the case of roof insulation, all construction works of roof repair were included. Renovation variants did not include interior remodeling, but internal finishing was taken into account in the case of window replacement and heating and ventilation installations. To calculate the present value factor $f_{pv}(n)$, real interest rate R_R depending on the market interest rate R and on the inflation rate R_i (all in per cents) was calculated [20]:

$$R_R = \frac{R - R_i}{1 + R_i/100} \tag{2}$$

The present value factor $f_{pv}(n)$ for the calculation period of n years was calculated [20]:

$$f_{pv}(n) = \frac{1 - \left(1 + (R_R - e)/100\right)^{-n}}{(R_R - e)/100} \tag{3}$$

where:
R_R the real interest rate, %
e escalation of the energy prices, % (inflation reduced from actual price increase)
n the number of years considered, i.e. the length of the calculation period, -

3. Results

3.1. Final and primary energy use

Final energy use of Estonian building stock was determined from national statistics according to principles of Eurostat to be comparable with EU data. Energy use of buildings covers all building related energy uses in residential and service sectors (electricity, fuels and district heating), but energy use in industrial buildings were accounted in industry sector. Final energy balance in Fig. 1 is shown for 2010, which is a baseline of ENMAK 2030+. The share of buildings of 50.2% was significantly higher than EU average of 39.9% [7] and in 2011 and 2012 it was slightly lower, about 48%.

Final energy use in 2010 in Estonia and in EU-27. Estonian final energy use was 33.0 TWh/a, total primary energy use 45.5 TWh/a (the share of buildings 55%) and non-renewable primary energy use 35.3 TWh/a (the share of buildings 47%). Buildings include residential and service sectors and energy use in industrial buildings is accounted in industry sector.

In order to be able to assess building energy use impacts on total and non-renewable primary energy, primary energy factors of national energy system were estimated. These factors were calculated from fuel inputs to electricity, district heat production and direct use in buildings. Primary energy factor of electricity was calculated with Eurostat η (eta) calculation tool [21], which calculates total efficiency η as the ratio of total gross production of electricity to the primary energy consumption for electricity production. The total primary factor is an inverse value of the efficiency, $f_{tot} = 1/\eta$, which was for Estonia in 2010 $f_{tot} = 1/0.394 = 2.54$. As electricity generated from renewable sources was 10.8% of gross electricity consumption in 2010, the non-renewable primary energy factor of electricity was estimated as $f_{nren} = (1-0.108)/0.394 = 2.26$. This factor is slightly higher compared to factor of electricity of 2.0 used in Estonian regulation for minimum energy performance requirements in buildings [22].

Fuel distribution used for heating or district heating production showed that 54.7% of total fuel energy was from renewable fuels in 2010, including the district heating production where renewable fuel energy was 33%. Therefore, the average non-renewable primary energy factor for heating of buildings was calculated as the ratio of nonrenewable fuel energy to the total fuel energy resulting

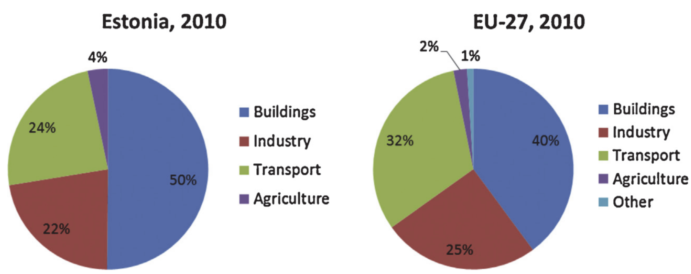


Fig. 1. Final energy use in 2010 in Estonia and in EU-27. Estonian final energy use was 33.0 TWh/a, total primary energy use 45.5 TWh/a (the share of buildings 55%) and non-renewable primary energy use 35.3 TWh/a (the share of buildings 47%). Buildings include residential and service sectors and energy use in industrial buildings is accounted in industry sector.

in f_{nren} = 0.453. These primary energy factors are used in Section 3.4 in the assessment of renovation and new construction effects on energy use.

3.2. Energy and investment intensity of integrated renovation variants

For most of reference buildings defined in Section 2, a ventilation rate problem was faced, before it was possible to start simulation of renovation alternatives. If the energy use of existing situation was simulated with minimum outdoor airflow rate requirements of [22] following category II of EN 15251 [23], the simulated energy use was much higher than statistical average in the considered segment of studied building type, because of lower ventilation rates and sometimes also lower occupancy in existing buildings. This applied for all reference buildings except the retail and industrial building, which had balanced ventilation with heat recovery and where ventilation was considered adequate. For all other reference buildings energy use with two ventilation rates was calculated:

Ventilation rate of 20–40% of minimum requirements resulting in statistical average energy use;

Standard ventilation rate equal to minimum requirements resulting in higher energy use.

The energy use calculated with lower ventilation rates describes the situation in existing building stock with poor indoor climate. This value is relevant for the assessment of average energy use in the building stock, which is needed for scenario calculations, because any scenario should be compared with existing situation. For the integrated renovation variants assessment the higher energy use value with ventilation rate equal to minimum requirements was used. The higher value corresponds to situation, where ventilation will be improved with available means (including window opening) in order to fulfill the requirements and to continue the operation of building, which could be a typical situation especially in school and office buildings. In residential buildings this option was considered also as relevant baseline, because otherwise deteriorated indoor climate could cause major public health expenses, which are to be quantified as one cost component of energy savings.

In the following figures, delivered heating energy and electricity of simulated variants are plotted as a function of investment cost of renovation. Simulated energy uses are shown with both ventilation rates and occupancy considerations for existing situation. The difference was highest in old detached houses, Fig. 2, where in the case of DH-Old, delivered heating increased from average of existing stock 201 kWh/m^2 (low ventilation rate, not all rooms occupied/heated) to 398 kWh/m^2 with standard ventilation rate and full occupancy. Correspondingly, delivered electricity increased from 30 to 142 kWh/m^2 with full occupancy, because of the mix of electric and stove heating in existing situation. Next points of the curves correspond to renovation variants, from which two last ones are with ground source heat pump (delivered heat 0 kWh/m^2 and electricity use increased). In the case of DH-New, the differences between average and standard energy use of existing situation are smaller. The difference of first renovation variants (E and D) were caused by replacement of gas boiler to pellet boiler which increased delivered heat from 150 to 159 kWh/m^2, but resulted in better EPC category, because of lower primary energy factor (1.0 vs. 0.75). Three last variants are with ground source heat pump (delivered heat 0 kWh/m^2).

In apartment buildings the difference between the average existing and standard energy use was caused by ventilation and partly by some electrical heating in existing stock. Delivered electricity of existing stock was reduced from 35 to 24 kWh/m^2 in the reference buildings with standard use and district heating, Fig. 3. Therefore this difference of electrical heating of 9 kWh/m^2

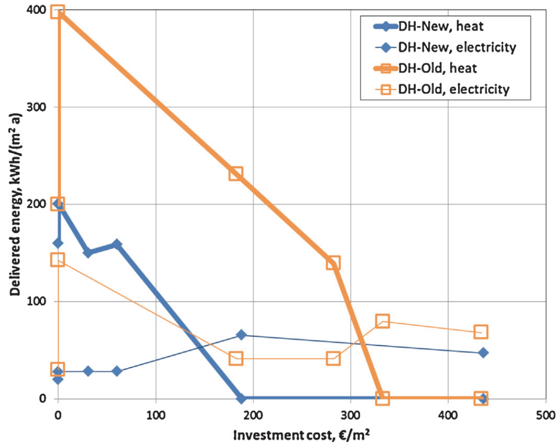


Fig. 2. Integrated renovation variants in reference detached houses. Reference houses and variants are described in Tables 2 and 3. First points from the left (investment cost 0 €/m^2) correspond to average statistical energy use (lower delivered energy value) and to existing situation with full occupancy and standard ventilation (higher delivered energy value). Next points correspond to renovation variants E, D, C and B respectively.

decreases actual difference of delivered heat, 140 vs. 178 kWh/m^2. All renovation variants were with district heating, but the results apply reasonable well for gas boiler for the cases where district heating is not available. Results show solid heating energy saving, but electricity use was slightly increased because of mechanical ventilation and exhaust air pump in the second renovation variant (D). Similar behavior applies for office buildings, where the difference between the average existing and standard energy use is purely caused by ventilation, as ventilation rate of 30% of minimum requirements provided energy use equal to average use of existing stock. Renovation variants have provided quite similar savings because energy use is dominated by ventilation, lighting and appliances in office buildings.

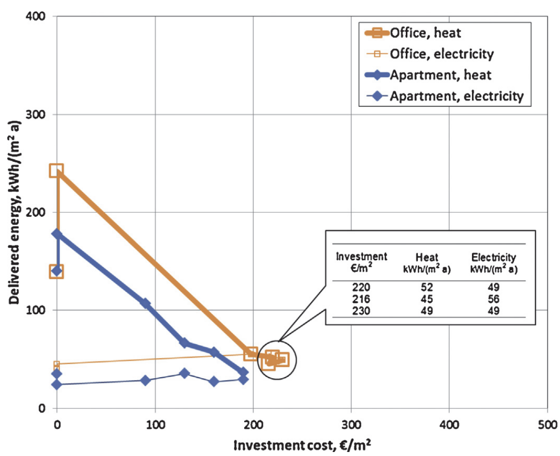


Fig. 3. Integrated renovation variants in reference apartment and office buildings. First points from the left (investment cost 0 €/m^2) correspond to average statistical energy use and to existing situation with standard ventilation. Next points correspond to renovation variants described in Tables 3 and 4.

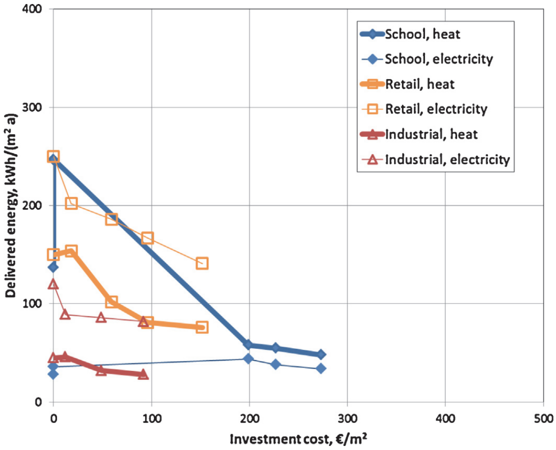


Fig. 4. Integrated renovation variants in reference school, retail and industrial buildings. First points from the left (investment cost 0 €/m^2) correspond to average statistical energy use and in the case of school building to existing situation with standard ventilation. Next points correspond to renovation variants described in Tables 4 and 5.

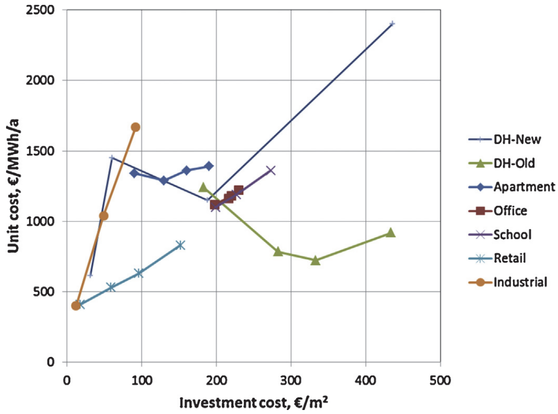


Fig. 5. Unit costs of energy savings. The points from left to right correspond to renovation variants of each building type, for example to E, D, C and B for residential buildings as described in Table 3.

School buildings, Fig. 4, show similar existing situation difference as was in office buildings, also caused purely by ventilation so that the ventilation rate of 30% of minimum requirements provided energy use equal to average use of existing stock. Renovation variants show somewhat wider range especially due to the demand controlled ventilation in the last variant which is effective in case of high ventilation rates in classrooms. This has resulted in somewhat higher electricity reduction compared to offices, however in both building types renovation variants use more electricity compared to average statistical use of existing stock. Retail and industrial buildings, shown also in Fig. 4, were the only building types with strong electricity reduction potential. In these buildings electricity use of lighting and appliances as well as energy use of HVAC dominated and heating energy was significantly smaller than electricity.

3.3. *Cost optimal integrated renovation variants*

To assess the cost effectiveness of integrated renovation variants studied, two methods were used. The first one was simple unit cost approach (invested € per MW capacity) often used for comparison of energy production plants. To be suitable for energy savings assessment, unit cost in euros per annual energy saving of one MWh was calculated. This approach has evident limitations, but the use was motivated by easy inter comparison of any energy saving measures in different sectors (transport, industry, energy production etc.). Another method used was an investment calculation with net present value method with Eqs. (1)–(3). The following input data was used:

Calculation period 20 years;

Real interest rate 4%;

Escalation of the energy prices 3% (inflation reduced from actual price increase);

Heating energy (district heat) price 0.075 €/kWh (VAT included);

Pellets 0.054, gas 0.055 and wood chips 0.031 €/kWh for heating of detached houses (VAT included);

Electricity price in residential buildings 0.14 €/kWh (VAT included);

Electricity price in non-residential buildings 0.132 €/kWh (VAT included);

The present value factor (Eq. (3)) $f_{pv}(n) = 18.05$;

All costs include VAT of 20%.

The results of unit costs shown in Fig. 5 were between 400 and 1500 €/MWh/a for majority of cases. According to these results, cost effectiveness of renovation variants was not possible to assess with this indicator, because of summing heat and electricity, not taking into account the calculation period and not providing comparison with existing situation.

Net present value results, shown in Fig. 6, are free of limitations of the unit cost approach, and show cost optimal variants with lowest NPV value. The variants studied were sound, as for all building types integrated renovation variants existed having lower NPV relative to existing situation. The number of variants was also sufficient, because the last ones with deeper and more expensive renovation measures showed the increase in NPV. Only exception were retail buildings, where the global cost curve was descending, indicating that the cost optimal can possibly occur at higher investment

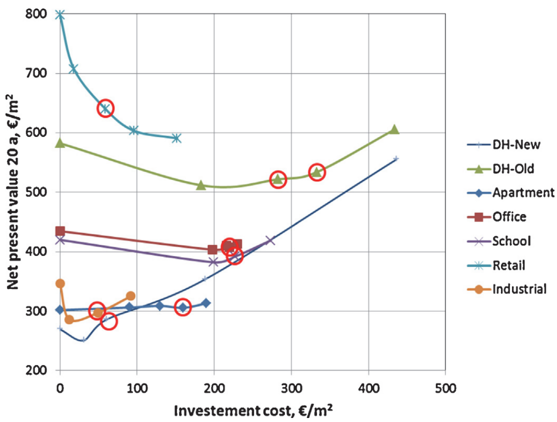


Fig. 6. Net present value of integrated renovation variants. The first points (0 €/m^2) correspond to existing situation with standard ventilation and occupancy. Other points from left to right correspond to renovation variants of each building type, for example to E, D, C and B for residential buildings as described in Table 3. The points marked with red circles show one possible selection of renovation variants for scenario analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

cost/deeper renovation than that represented by calculated renovation variants. In some cases, the last variants were still cost effective (NPV lower than in existing situation) and in some cases not (NPV higher than in existing situation). The results allow one to classify renovation variants according to investment intensity as follows:

In retail and industrial buildings very low investments (20–100 €/m^2) were highly profitable

In DH-New only small investments were cost effective indicating that these buildings are in too good shape for major renovation

In all other building types, investments slightly below or higher of 200 €/m^2 were cost optimal and in older houses deeper renovation (about 300 €/m^2) was very close to cost optimal.

Marked variants in Fig. 6, which are cost optimal or cost effective, were selected as realistically achievable in practice with proper regulation and incentives as follows:

For retail buildings, second variant with reasonable low investment cost was selected, because this one together with the first variant is most probable in free market without regulation for such buildings;

For residential buildings, direct renovation funding grants and loans were considered, which allow one to require deep renovation measures and renovation variants being cost optimal or just next to cost optimal were selected. For old houses, two selected points represent the situation of two alternative heat source so that the variant with pellet boiler was considered for 50% of cases and with ground source heat pump for 50% of cases;

For office, school and industrial buildings also the variants just next to cost optimal were selected, because of minor investment cost difference and larger energy savings;

New houses, DH-New, were the only exception where cost effective variant was not selected, because if such relatively new houses in good condition are to be renovated, slight overinvestment was needed to achieve the requirement of EPC category D which applies for major renovation.

Selection of cost effective variants with slightly higher cost than that of cost optimal ones is justified because of used renovation full cost calculation method (building quality and real estate value are increased but not valuated), relatively low escalation values of energy prices and calculation period of 20 years which is in residential buildings shorter than 30 years given in cost optimal regulation [19]. Such selection does not change the nature of comprehensive renovation, but instead of cost optimal technical solutions, slightly more effective and expensive ones are used in order to maximize cost effective energy savings.

3.4. Applications: energy saving technical potential and scenarios

Renovation variants shown in Fig. 6 allow one to calculate minimum, maximum and cost effective energy saving potential of the building stock. Because of limited number of non-residential reference buildings modeled, the floor area represented by reference buildings was needed to increase so that the full building stock would be represented. If the area of building types not modeled, reported in Table 1, was covered by proportional increase of the floor area of modeled reference buildings, an estimate of energy saving potential of the building stock shown in Figs. 7 and 8 was obtained.

Fig. 7 reports the delivered energy savings calculated as the sum of heating energy and electricity. Min values are calculated with first renovation variants, i.e. corresponding to second point from left of each building type in Fig. 6. Max values are correspondingly with the deepest renovation variants, i.e. the last points in the right, and cost optimal values correspond to marked variants in Fig. 6. Max values calculated with deepest renovation variants represent renovation rates of about 20–40% compared to construction cost of new buildings (1 200 €/m^2 VAT included). As these values are without interior remodeling, they could be considered enough deep to represent the technical potential of energy saving of the building stock. Measured as final (delivered) energy, the technical potential was as high as 9.90 TWh/a (equals to 59.7% of the 2010 final energy use of buildings), consisting of 9.85 TWh/a of heating energy and 0.05 TWh/a of electricity. Electricity saving potential was also very low in the cost optimal potential (6.62 TWh/a heating energy and 0.12 TWh/a electricity), but was higher in the minimum potential where heat pumps were applied (1.28 TWh/a heating energy and 0.31 TWh/a electricity).

Negative saving of detached houses in the case of minimum potential in Fig. 7 means that first integrated renovation variants with standard ventilation and occupancy do not save energy compared to statistical average energy use in existing buildings. Fig. 8 reports the same energy saving potential results as Fig. 7, but calculated with non-renewable primary energy factors estimated in Section 3.1. Non-renewable primary energy savings are significantly lower in building types where renovation variants increased electricity use because of high non-renewable primary energy factor for electricity. This applies for offices, schools and is remarkable in detached houses. In the case of detached houses, it has to be taken into account that energy use of renovation variants with standard ventilation and occupancy are compared to the average of the building stock, which includes many buildings not fully occupied, ventilated and heated. Therefore the result applies for energy savings in the building stock level and is not meaningful in the case of a specific building.

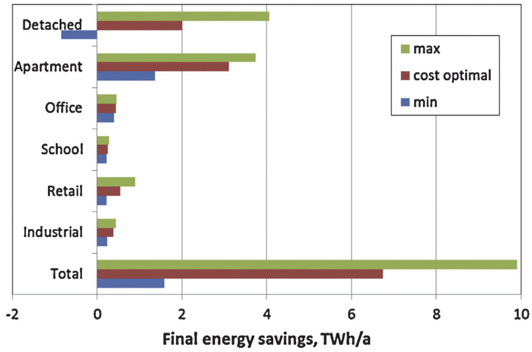


Fig. 7. Energy saving potential of the building stock calculated as the sum of heating energy and electricity.

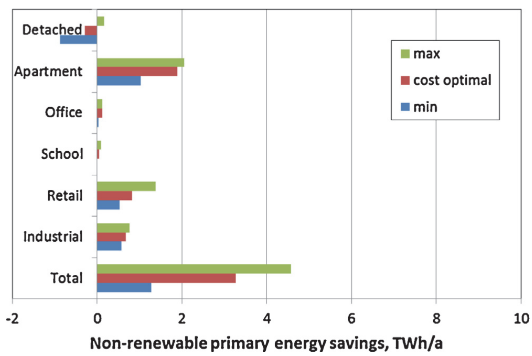


Fig. 8. Energy saving potential of the building stock calculated as non-renewable primary energy.

Table 6
Assumptions for the building stock energy use scenarios 2011–2030.

	Scenario 1	Scenario 2	Scenario 3
Integrated renovation variants	Min	Cost optimal	Cost optimal
Renovation rate of apartment buildings, %/a	0.75	1.5	2.5
Renovation rate of detached houses, %/a	0.5	1.0	2.0
Renovation rate of non-residential buildings, %/a	0.5	0.75	1.0
Building stock loss (demolition), %/a	0.3	0.3	0.3
New construction rate in residential buildings, %/a	1.0	1.0	1.0
New construction rate in non-residential buildings, %/a	1.5	1.5	1.5
Application of nZEB requirements in new buildings, a	2026	2021	2016

To assess achievable energy savings within 20 years, three scenarios were calculated with varied renovation rates for the period of 2011 to 2030. Building stock size and new construction volumes of 2010 were used as reference level. The assumptions used in scenarios are shown in Table 6. Scenario 1 operates with first integrated renovation variants described in Tables 3–5 (second points from the left in Fig. 6) and two other scenarios with cost effective renovation variants (marked in Fig. 6). Renovation rates are selected so that Scenario 1 refers to situation where renovation is not supported by incentives. In two other scenarios, direct renovation funding grants of 25% and 35% of renovation cost, corresponding to Estonian KredEx support scheme, are available for residential buildings. Selected renovation rates are justified by experience from 520 apartment buildings, where integrated renovation has been completed with KredEx grants and similar renovation variants. Because of the budgeting of grants, the renovation rates were fixed, i.e. calculated from the size of 2010 building stock and the same values were used for all years. For demolition, also 0.3% of 2010 stock was used for all years.

New construction rates are the same in all scenarios and they are calculated from construction volume of 2010 (in total 661,900 m^2). The new volume of each year was calculated from previous year with given rates, which leads to slightly increasing new volumes. Only difference between scenarios is the year when energy performance minimum requirements are replaced with nearly zero energy building requirements which are set in Estonian regulation [22]. Technical solutions of nZEB buildings, energy and cost data is reported in Kurnitski et al. [24,25]. In Scenario 2, new buildings are built according to minimum energy performance requirements due 2020 and nZEB enters into force 2021. In Scenario 1 there is 5 years delay in applying nZEB requirements and in Scenario 3 nZEB is applied 5 years in advance.

Final (delivered) energy development is shown in Fig. 9. Heating energy and electricity curves are shown with and without new construction. Because of new construction, heating energy decrease was slower (upper vs. lower curves) and electricity use increased in all scenarios. Electricity increased by 9.8, 8.5 and 6.7% in scenarios 1, 2 and 3 while without new construction these values would show reductions of 6.9, 6.6 and 6.7%, respectively. In total (with new construction) final energy decreased in 2030 relative to 2010 by −0.9, 8.4 and 17.6%, respectively in scenarios 1, 2 and 3. Without new construction, these values would be much higher, 7.4, 15.5 and 23.8%, respectively.

Primary energy development calculated with primary energy factors estimated in Section 3.1 is shown in Fig. 10. Application years of nZEB can be seen from the curves as inflection points. Primary energy savings in 2030 relative to 2012 were smaller than final energy savings and Scenario 2 provided slightly negative result in non-renewable primary energy.

When total primary energy may be attributed to energy bills to be paid for, non-renewable primary energy causes green-house gas emissions. To achieve the target of Roadmap 2050 [5] for residential and service sectors CO_2 reduction of 37 to 53% (in average 45%) in 2030, renewables or other low carbon technologies are needed in

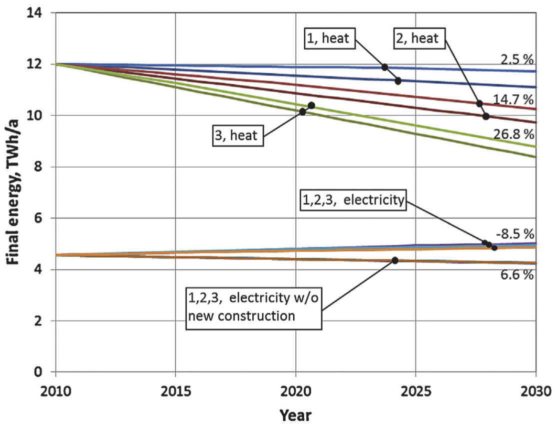


Fig. 9. Final energy development in three scenarios. Heating energy and electricity are shown in each scenario with and without new construction. The upper curves include new construction, for which reductions in % by 2030 are shown. In the case of electricity use without new construction the differences between scenarios were too small to be visible with the scale used. For electricity, % values are shown for Scenario 2.

energy production. In the case of Scenario 2, where non-renewable energy use remained almost constant, the CO_2 reduction of 45% can be achieved if renewable energy share in heating energy would be increased from current 55% to 80% and in electricity production from current 11% to 45%, which is lower than the estimate of the share of low carbon technologies in electricity mix of 75–80% in [5].

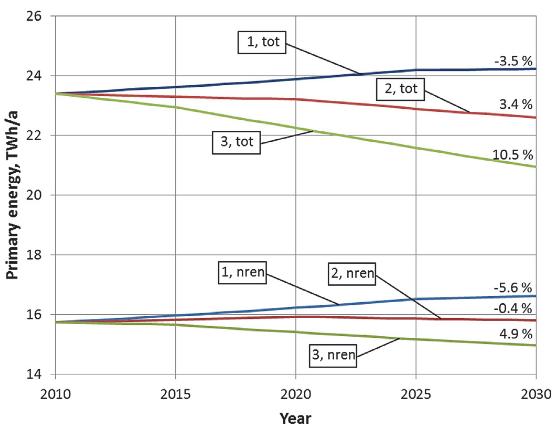


Fig. 10. Primary energy development in three scenarios. "tot" refers to total primary energy and "nren" to non-renewable primary energy.

4. Conclusions

Energy and investment intensity of integrated building type specific renovation variants were studied to determine cost optimal energy savings by 2030 as a part of new Estonian energy roadmap ENMAK 2030+preparation. For major residential and non-residential building types 3–4 renovation variants with different ambition were defined so that even the variant with the lowest cost included the installation of adequate ventilation system, in order to strictly avoid energy savings at the cost of indoor climate.

Cost optimal energy performance level of deep integrated renovation corresponded in most cases to minimum energy performance requirements of new buildings (EPC category C) both in residential and non-residential buildings. Depending on the building type, the renovation variants were possible to classify according to investment intensity as follows:

In retail and industrial buildings very low investments (20–100 €/m^2) were highly profitable;

In relatively new detached houses only small investments were cost effective indicating that these buildings are in too good shape for major renovation;

In all other residential and non-residential building types, investments slightly below or higher of 200 €/m^2 were cost optimal and in older houses even deeper renovation (about 300 €/m^2) was very close to cost optimal.

Typical cost optimal renovation cost of about 200 €/m^2 was at least by factor 2 higher than that reported in [4], indicating that high investment cost is one major barriers for deep renovation. Therefore, in order to realize cost optimal energy saving potential, support schemes are needed especially in residential buildings, in order to provide financial support which allows also to require the use of deep integrated renovation measures. This is supported by previous experience from Estonian KredEx support scheme operating with grants of 25 and 35% of renovation cost.

Cost optimal energy savings were remarkable in heating energy, which was reduced by factor 3 in residential buildings and even by factor 4 in office and school buildings. In contrary, electricity use tended to increase in all of these building types because of increased ventilation and heat pumps in residential buildings. Retail and industrial buildings were the only building types with strong electricity reduction potential. This resulted in negligible technical and cost optimal electricity saving potential in the building stock (0.3 and 0.7% respectively) while heating energy saving potentials were 60 and 40% of the energy use in 2010, respectively.

Calculated scenarios showed the significant effect of new construction which made heating energy decrease slower and led to increased electricity use in all scenarios. Without new construction the reduction in electricity use by 2030 relative to 2010 was in the middle cost optimal scenario 6.6% but with new construction it increased by 8.5%. In the middle cost optimal scenario, final energy reduction by 2030 was 8.4%. This is less than previously estimated 20% [4], however the difference would be smaller if new construction is not taken into account, in such a case the reduction was 16%.

Middle cost optimal scenario led to total primary energy reduction of 3.4% and non-renewable primary energy reduction of about 0% by 2030 which are significantly less than reductions in final energy because energy savings were mostly attributed to heating energy including a large portion of renewable biomass. While total primary energy may be attributed to energy bills to be paid for, non-renewable primary energy causes emissions. To achieve the target of Roadmap 2050 for residential and service sectors CO_2 reduction in average of 45% by 2030, in the case of middle cost optimal scenario, renewable energy share in heating energy needs to be increased from current 55% to 80% and in electricity production from current 11% to 45%.

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PAPER VI

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Renovation vs. demolition of an old apartment building: energy use, economic and environmental analysis

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KEYWORDS: *renovation scenarios; energy performance; cost effectiveness; embodied energy; apartment buildings.*

SUMMARY:
The paper analyses four renovation scenarios for one concrete element building type. These scenarios were: major renovation, low-energy renovation, low-energy renovation with extensions, demolition of the original building and construction of a new building. Results reveal that in the current case an existing building can be renovated to meet the same energy-efficiency levels as a new building. Demolition of an existing building and construction of a new one raises the global cost at least four-fold. Analyses of embodied energy via CO_2 emissions from the materials and energy production for a building during 20 years show that a new building has higher environmental impact than low-energy renovation. Therefore, the condition and low energy efficiency of an old concrete element apartment building are not the reasons to consider its demolition.

1. Introduction

Increasing energy prices and energy saving policies have shifted attention to the energy performance of dwellings. EU has made a commitment to reduce the emission of greenhouse gases by 20% by the year 2020 compared to the level of 1990. Estonia has set the goal of maintaining the final energy consumption at the same level as in 2010. However, this will require a decrease in energy use and an increase in energy efficiency. Energy economy and heat retention were included as basic requirements for construction works (Construction Production Regulation 2011) earlier but sustainable use of natural resources is a recent addition. This means that focus should also be on the durability and low long-term environmental impact of the construction process and exploitation (often expressed via carbon dioxide CO_2 emission).

The design of renovation raises the question of the extent and economic viability of renovation. Frequent discussions also address the demolition of an existing building and the construction of a new building. The agenda of Tallinn Vision Council contains a target to demolish 103 of the oldest prefabricated concrete large panel element apartment buildings (hereinafter: concrete element buildings) in Tallinn (Sarv 2013). The concept targeted to demolishing existing buildings introduces new economic and environmental challenges. Previous studies have pointed out that such areas as exact embodied energy values, the costs and applicability of refurbishment, direct energy impact of demolition and its wider environmental impact still remain unclear. However, both broad arguments and concrete evidence support maintaining a focus on renovation rather than on large-scale demolition (Power 2008).

Results of research covering the current technical condition of Estonian old concrete element housing stock refer to satisfactory condition in terms of load-bearing but to insufficient energy performance, indoor climate and hygrothermal performance of the building envelope (Kalamees 2011). Also, durability of concrete façades has been found to be problematic regarding to corrosion and frost damage (Ilomets 2011).

This study analyses different renovation scenarios for one concrete element building type. The aim was to find out how renovation, renovation with extensions, and construction of a new building affect the energy efficiency, economic viability, and embodied energy.

2. Methods

2.1 Studied building

The study object was a five-storey apartment building with prefabricated concrete large panel elements (TABLE 1, FIG 1) constructed in 1966. That type of construction was typical in Estonia and in other countries in Eastern Europe during the period 1961-90. In total, there are almost 3500 old concrete element buildings in Estonia (National Register of Construction Works).

During renovation works in 2011, additional insulation was placed to the building envelope, old windows were replaced, a new two-pipe heating system and a ventilation system with heat recovery were installed.

TABLE 1. Characterisation of the studied building

Net area, m^2	3519
Heated area, m^2	2968
Number of apartments	60
Compactness: Building envelope, m^2 / volume, m^3	0.35

FIG 1. Picture of the studied building before (left) and after major renovation (right).

2.2 Simulations and calculations

Indoor climate and energy simulations were made for different stages of the building:

- original building without any renovation measures
- major renovation
- renovation on a low-energy building level
- renovation on a low-energy building with extensions of the building
- demolition of the original building and construction of a new building

As occupant behaviour related to energy usage is variable and unrelated to the building type, the energy calculations were made at standard indoor climate and by a unified calculation methodology. The methodology is specified in local regulations (Estonian Government's Ordinance No. 68 and Ministry of Economic Affairs and Communications' Ordinance No. 63. 2012). Energy performance of buildings was calculated with dynamic simulations using the IDA Indoor Climate and Energy 4.5 simulation program.

During the first phase of our calculations, simulation models for the pre- and the post-renovation stage were validated using the measured indoor climate and energy consumption data from the building. In the second step, validated models were calculated at standard usage and energy efficiency packages for a low-energy building, for a low-energy building with extensions, and for a new building were composed (TABLE 2).

TABLE 2. Variables of the simulation model

Variables	Without renovation	Major renovation	Low-energy	Low-energy (extensions)	New building
Thermal transmittance, $W/(m^2 \cdot K)$:					
walls $U_{wall,}$	0.90	0.17	0.14	0.14	0.12
roof U_{roof}	0.80	0.11	0.11	0.11	0.08
basement ceiling $U_{basement}$	0.60	0.60	0.23	0.23	0.23
windows U_{window}	1.90	1.40	0.80	0.80	0.80
doors U_{door}	1.10	1.10	1.10	1.10	1.10
Additional insulation, mm:					
external wall	-	+150	+200	+200	+250
roof	-	+300	+300	+300	+400
basement ceiling	-	-	+100	+100	+100
Air leakage rate q_{50}, $m^3/(h \cdot m^2)$	5.0	5.0	3.0	3.0	1.0
HVAC systems:					
heating	1-pipe	2-pipe, thermostats	2-pipe, thermostats	2-pipe, thermostats	2-pipe, thermostats
ventilation	natural ventilation	exhaust air heat pump	apartment based AHU	apartment based AHU	apartment based AHU
renewable energy				solar collectors	

Extensions were attached to kitchens and staircases in the simulations of low-energy buildings with extensions. Additional space was used to accommodate the ventilation air handling units and increase the small floor area of the existing kitchen. Solar collectors were installed for heating domestic hot water (DHW) to compensate the increased heat loss caused by the additional constructions.

The construction of the new building scenario followed the principle that its energy efficiency would be higher than minimum requirements and would comply with the low-energy requirements for energy efficiency.

Estonian Test Reference Year (Kalamees and Kurnitski 2006) was used to simulate outdoor climate conditions.

Primary energy (PE) was used as the indicator for the energy efficiency. The requirements for the apartment buildings were as follows:

- major renovation: PE ≤ 180 kWh/(m^2·a)
- new buildings: PE ≤ 150 kWh/(m^2·a)
- low-energy buildings: PE≤ 120 kWh/(m^2·a)

According to the energy source, the use of the primary energy and the environmental impact were taken into account with the weighting factors:

- district heating 0.9
- electricity 2.0

2.3 Economic analysis

The global cost (EN 15459, Eq. (1)) calculation was used to assess the cost effectiveness of different renovation strategies.

$$C_g(\tau) = \frac{C_i + \sum_{i=1}^{20}(C_{ai}(j) \times R_d(i))}{A_{floor}} \qquad (1)$$

where:

$C_g(\tau)$ global incremental cost (€/m^2)
C_i initial investment cost (€)
$C_{a,i}(j)$ annual cost year *i* for component *j* (energy cost) (€)
$R_d(i)$ discount factor for year *i*
A_{floor} net floor area (m^2)

A period of 20 years was selected because the maximum period for renovation loans for apartment owners' associations in Estonia is 20 years. Global cost was calculated at the interest rate 4%. To show sensitivity to the escalation rate, five escalation rate scenarios were considered: 1% escalation, 3% escalation, 5% escalation, 7% escalation, and 9% escalation. Construction costs (TABLE 3) were taken from a database of apartment owners' associations containing reports of their real renovation costs and from the estimations of construction companies. The energy price levels used were 0.14 €/kWh for electricity and 0.075 €/kWh for district heating (mainly based on gas).

TABLE 3. Construction costs

Scenario	Cost, €	Cost, €/net m^2
Major renovation	450 000	128
Low-energy	773 000	220
Low-energy + extensions	1 051 000	278
New building	4 742 000	1348

2.4 Environmental analysis

Environmental impact of the five scenarios was analysed via the emission of CO_2 during the renovation/construction and 20 years of exploitation. An existing building before the renovation was chosen as the reference point, which means that CO_2 emissions of the construction materials used in 1966 and CO_2 emissions of energy carriers until the major renovation in 2011 were excluded from the analysis. Embodied energy of the renovation scenario was calculated for the quantity of each material from CO_2 emissions of the construction materials based on the literature. Also, thermal energy and electricity consumption were calculated and multiplied with CO_2 emissions to produce that energy.

To simplify the analysis, the following aspects were not taken into account:

- transportation
- energy and water demand at the building site
- workmanship
- HVAC systems installed into the building and the solar collector at low-energy with an extensions scenario
- small details and fixing (glue mortar, fastening, sealing foam and tapes etc.)
- thin layers (floor covering, rendering, filler, colour)
- transmission loss of district heating and electricity from the plant to the building site

It was also assumed that the impact of recycling the materials from a demolished building is negligible when replacing the existing building with a new one. The reason was that no dangerous waste (asbestos etc.) originates from the existing building and the majority of the remaining materials can be reused to a landfill construction site nearby. A minority of materials unsuitable for reuse can be sorted and handed over to the licenced company of construction waste management.

CO_2 emissions of the construction materials and the energy carriers used in the analysis are presented in TABLE 4.

TABLE 4. CO_2 emissions of the construction materials and the energy carriers (Kurnitski 2011 and Hegger 2008)

Material	CO_2 emission, kg/CO_2 eq/kg	Energy carrier	CO_2 emission, t/MWh
Expanded polystyrene	3.4	District heating	0.278
Stone wool	0.99	(mainly based on gas)	
Bitumen polymer sheeting	1.21	Electricity	1.01
Glass	0.66	(mainly based on oil shale)	
Precast concrete element	0.182		
Steel	0.73		
PVC	2.28		
Gypsum board	0.39		

3. Results

3.1 Energy usage

Delivered energy calculation results showed that the use of the delivered space heating energy can be decreased from 153 kWh/(m^2·a) to 15 kWh/(m^2·a) (FIG 2 left). The low-energy renovation scenario with extensions has a higher space heating energy need (32 kWh/(m^2·a)) than the low-energy scenario with the current building body shape (19 kWh/(m^2·a)) due to decreased compactness and additional linear thermal bridges. Solar collectors are used for heating DHW to compensate the increased heat loss through the building envelope. Use of the primary energy in the standard usage is shown in FIG 2 right. Electricity accounts for the largest share of the primary energy consumption in different renovation scenarios. For further reduction of the primary energy, it is necessary to reduce the electricity demand. Comparison of the energy use for low-energy renovation and for a new building shows no substantial differences. Thus, existing buildings can be renovated to meet the same energy-efficiency levels as new buildings.

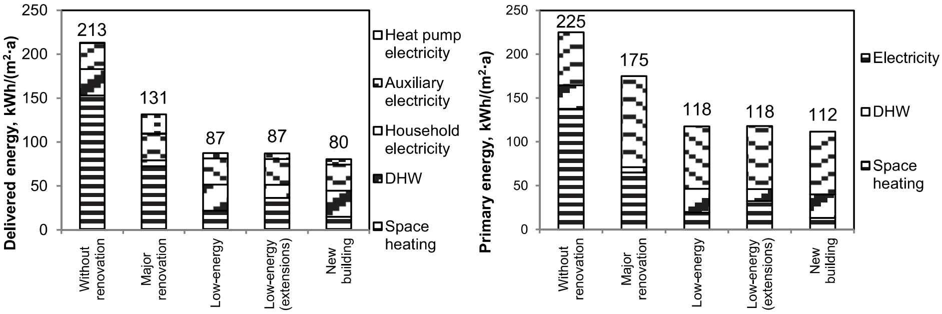

FIG 2. Delivered energy usage (left) and primary energy usage (right) of different renovation strategies.

3.2 Economic analysis

The global cost was selected to assess the cost effectiveness of renovation strategies (TABLE 5). Before the renovation stage, the global cost is lower than in other scenarios because the calculations do not take into account the maintenance costs. If the pre-renovation stage is taken as the reference point, the escalation should be 9% for the global cost to decrease in the renovation scenarios. The implemented low-budget major renovation has the lowest global cost values in the renovation strategies. Low-energy renovation with extensions has ca 15% higher global cost than the low-energy renovation without additional extensions. Demolishing of an existing building and building a new one has ca four times higher global cost than the low-energy renovation and the low-energy renovation with extensions.

TABLE 5. Global incremental cost values

Renovation	Global cost, €/net m^2				
Scenario	Escalation 1%	Escalation 3%	Escalation 5%	Escalation 7%	Escalation 9%
Without renovation	218	264	326	410	524
Major renovation	290	325	370	432	517
Low-energy	330	353	383	425	481
Low-energy (extensions)	388	412	443	485	543
New building	1463	1484	1513	1552	1605

3.3 Environmental analysis

Embodied energy of a renovation scenario can be expressed as a sum of CO_2 emitted from the production of the construction materials and CO_2 emitted from the energy production that a building consumes during the period of 20 years. Results presented in TABLE 6 indicate that the smallest embodied energy (2924 tons) is achieved by renovating an existing building to the low-energy level, being also lower than the reference case before renovation. In that case only 51 tons of embodied energy originate from the materials (1,8% of total); that is close to major renovation but the impact from energy consumption has decreased notably, especially from electricity. Extensions in the case of low-energy lead to higher need for materials and energy that ends up with a higher total value because of deteriorated compactness. Construction of a new building with the same volume has about nine times higher need of resources for materials; that leads to higher total embodied energy compared to low-energy renovation, despite of a small energy consumption during exploitation.

TABLE 6. Emission of CO_2 from the production of construction materials and from energy production

Scenario	CO_2 emissions, t			
	Materials	District heating	Electricity	Total
Without renovation	0	2891	1717	4608
Major renovation	39	1251	2990	4279
Low-energy	51	812	2060	2924
Low-energy (extensions)	104	895	2283	3282
New building	479	701	2060	3240

Subdivision of material emissions in case of a new building shows that most of the emissions originates from load-bearing walls, slabs and roofs (all together ca 89% of total). Percentage of insulation materials constitutes about 8% and windows approximately 3% of total material emissions.

4. Discussion

Our results showed that in terms of energy efficiency, economic viability, and embodied energy, no direct reasons exist to demolish old concrete element buildings and build new apartment buildings.

Energy performance of existing low-energy and low-energy buildings with extensions is close to that of a new building; however, the construction cost of a new building is about four times higher. Also, the environmental impact of a new building as a renovation scenario is the highest (15% of embodied energy comes from the materials) and the improvement of energy performance during the exploitation will have no further impact. Our result that demolition and constructing a new building has higher environmental impact refers in principle to similar conclusions found in previous studies (Ireland 2008 and Yates 2006). They report that equivalent refurbishment can be as “green” as new buildings but difference is rather small and depends on a case and chosen time period. Since all renovation scenarios have lower total environmental impact compared by status quo (without renovation), we have proven the need for renovation of older housing stock from environmental aspect. It should be noticed that some of the additional factors related to a new building (transportation, HVAC systems, construction waste management) were excluded in our analysis, in the opposite case, the difference between renovation vs new building would even have been larger.

Load bearing structures are not a critical issue as the condition of the main load bearing structures was found to be sufficient (Kalamees 2011). Therefore, the condition and low energy efficiency of old concrete element buildings are not the reasons to consider their demolition. Tallinn Vision Council has pointed out that floor planning of these old dwellings is unsuitable for families (Sarv 2013) because of small-sized bathrooms and kitchens. In addition, in the five-storey buildings, narrow staircases and absence of elevators restrict movement of families with small children and older people. Demolition is a plausible solution when some region is intended to be thoroughly renewed. At higher volumes, the construction costs would be lower and a larger macro-economic impact would be also an important factor, but here further detailed analysis is required. On a single building level, renovation is substantially cheaper than building a new dwelling. The number of old concrete element buildings reveals a potential solution in favor of renovation due to enormous construction capacity. Power (2008) has stated that even with the highest feasible level of demolition, the existing stock would remain the dominant energy challenge in the built environment far into the future. Focus should be on sustainable design from the materials that contain a low amount of energy, on the use of local materials and the durability of buildings during both renovation and new construction.

5. Conclusions

Main findings of this study reveal that in the current case an existing building can be renovated to meet the same energy-efficiency levels as a new building and demolition of an existing building and construction of a new one raises the global cost at least four-fold as compared to renovation. Analyses of embodied energy via CO_2 emissions from the materials and the energy production used in a building during 20 years demonstrate that a new building has higher environmental impact than low-energy renovation. Therefore, energy efficiency, economic and environmental issues show no support to the idea of demolition instead of renovation.

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