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RESEARCH PAPER

Retrofit cost-effectiveness: Estonian apartment buildings

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The economic viability and investment cost of the energy retrofit of apartment buildings are analysed through different energy efficiency levels. To analyse retrofit policy cost-optimal energy efficiency levels and investment costs, a baseline of measured actual energy usage of apartment buildings was created and then individual energy-saving measures and retrofit packages were composed. The cost-optimal level over a 20-year period for apartment building retrofit was a low-energy-building energy performance level, with an investment cost of €150–170/m^2. Retrofit to low energy building level would be economically viable but the investment capability of apartment owner associations is found to be insufficient for the necessary investments to achieve low-energy-building energy performance. Therefore, it is necessary to determine what levels of financial support can encourage retrofit to occur. The analysis of the current retrofit shows that subsides will increase investment by apartment owner associations into energy efficiency improvements. The target group for energy efficiency retrofit subsidies should be apartment buildings that reach low energy building performance level or at least match the energy performance requirement for new buildings.

Keywords: apartment buildings, cost-effectiveness, cost estimates, energy consumption, energy efficiency, retrofit, Estonia

Introduction

There are approximately 25 billion m^2 of useful floor space in the EU-27, Switzerland and Norway (Economidou et al., 2011). Residential buildings account for the largest share (approximately 75%) of that building stock (Economidou et al., 2011) and therefore the residential sector also accounts for a large share of the total energy consumption. In the European Union approximately 17% of the total primary energy (PE) consumption and 25% of the final energy consumption are used in residential buildings (European Commission, 2006). Apartment buildings in Northern Europe consume energy for heating at approximately 90–170 kWh/(m^2·a) (Balaras, Droutsa, Argiriou, & Asimakopoulos 2000; Engvall, Lampa, Levin, Wickman, & Öfverholm, 2014; Paihoa, Pinto Seppä, & Jimenez, 2015). A study conducted in Latvia concluded that the average current energy need for domestic hot water (DHW) in apartment buildings is 33 kWh/(m^2·a) (Grasmanis, Talcis, & Grekis, 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), for preparing DHW is 27 kWh/(m^2·a), and for electricity is 35 kWh/(m^2·a) (Arumägi & Kalamees, 2014; Kuusk, Kalamees, & Maivel, 2014).

Large energy consumption also brings a range of possibilities for energy savings, and the residential sector has the biggest potential for cost-effective savings (European Commission, 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 & Sunikka-Blank, 2013) showed that the total saving potential of renovating residential buildings to EnEV (Eniergieeinsparverordnung, 2009) 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% by applying an ‘advanced’ renovation (Ballarini, Corgnati, & Corrado, 2014). In total, it was found (Tuominen, Klobut, Tolman, Adjei, & Best-Waldhober, 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.

The Energy Roadmap 2050 (2011) states that decarbonization is possible and can be less costly than current policies in the long run. Renovation of the existing residential building stock is a key factor for this future task as the replacement rate of the existing stock is only 1–2% per year. In addition to high energy consumption issues, the indoor climate conditions (of existing residential buildings) also have an impact an inhabitants' health. The World Health Organization (WHO) (2009) has stated that problems of indoor air quality are important risk factors for human health in both low- and high-income countries. The renovation of existing apartment buildings can negatively affect the indoor environment of apartments if the renovation does not include measures to improve indoor environmental quality (Földvary, Bekő, & Petráš, 2014). Studies have shown (Krajčík, Pustayová, & Petráš, 2011) that the improvement of the indoor climate conditions can be also a motivation for the 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 in understanding the fact that the better indoor climate will come with an additional cost for operating the ventilation system.

Despite the large energy-saving potential, earlier studies (Wesselink, Harmsen, & Eichhammer, 2010) have found that the European Union 2020 energy-saving target will not be fulfilled. The same study concluded that closing the gap between planned targets and realized energy savings requires a threefold increase in policy impact compared with 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 the reduction of CO_2 emissions, including a consideration of 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, house owners gave 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, which are in line with future environmental goals. A study conducted in Wales (Jones, Lannon, & Patterson, 2013) concluded that the cost of deep integrated renovation is a major barrier to the large-scale renovation of existing buildings. Tuominen et al. (2012) studied nine European Union countries and reported that a common renovation barrier is the low priority for energy efficiency improvements among consumers and insufficient funding. At the same time, one of the common public policy measures to overcome the renovation barrier was the partial public funding of energy efficiency retrofits. The lack of money up front and low investment capacity are particularly problematic in the owner-occupied residential sector (Meijer, Itard, & Sunikka-Blank, 2009). A study for developing the Estonian energy roadmap ENMAK 2030+ (Kurnitski et al., 2014) pointed out that in order to realize the full energy-saving potential, support schemes are necessary, especially in residential buildings, as financial support allows requirements to be set for the renovation measures and also helps to promote deep integrated renovation. The establishment of 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, Mitchell, Hallinan, & Kissock, 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 they might not even share. Weiss, Dunkelberg, and Vogelpohl (2012) concluded that different support programmes with different goals are needed. One funding programme was for building owners willing to invest in higher levels of energy efficiency, and another programme also considered a social criteria for energy-renovation measures meeting lower standards.

In Estonia there are a total of approximately 27,000 apartment buildings, with approximately 10,000 of these built during the Soviet Union era (1940–91) when energy prices and the thermal quality of the building envelope were much lower than today. A total of 82% of dwellings are privately owned in Estonia (Pittini, Ghekiere, Dijol, & Kiss, 2015), and apartment buildings are generally managed by apartment owners associations (AOAs). During 2009–10, AOAs could apply for a renovation loan, which provided a more favourable interest rate than a commercial loan. During the period 2010–14 over 600 apartment buildings have been renovated in Estonia with a support scheme (Fund KredEx, n.d.) financed by CO_2 emissions trading and a 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) $\leq$ 220 kWh/(m^2·a) (minor renovation), PE $\leq$ 180 kWh/(m^2·a) (major renovation), and PE $\leq$ 150 kWh/(m^2·a) (energy efficiency level of a new building). European Union Structural Funds for the next financing period 2014–21 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 creation of appropriate policy measures to promote energy renovation is a difficult topic. If there is too little financial support, then building owners will be unmotivated to undertake an integrated energy renovation. Conversely, a grant that is too high will encumber the governmental budget. In this study, the energy performance of existing apartment buildings, the necessary investments for renovation works and the possible need for financial support for energy renovation are evaluated in order to establish the economic viability of a deep retrofit of apartment buildings. Estonian apartment buildings are used as an example.

Methods

The general approach is based on an analysis of energy consumption and the current technical condition of 105 Estonian apartment buildings of which 70 provided full energy consumption data. For space heating consumption and DHW use, it was possible to use the data from all 105 buildings. These data were used empirically in order to detect the current state of buildings before renovation. The reference buildings chosen were based on three main prefabricated large-panel apartment building types. These reference buildings were the basis for the simulations and economic calculations of the renovation measures. More information on the methods are described below.

Studied buildings

Prefabricated concrete large-panel apartment buildings were used to calculate the energy efficiency and cost-effectiveness of renovation measures. This type of apartment building was the most dominant during the construction industrialization period in 1970–90. Over 6 million m^2 of prefabricated concrete large-panel apartment buildings were built during that period in Estonia (Figure 1). 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 a large number of apartment buildings. Therefore, 105 apartment buildings composed of concrete large-panels constructed between 1962 and 1992 were selected for the energy efficiency analysis of this study. All the buildings studied were in private ownership.

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

The building envelopes contain significant thermal bridges. Previous studies have concluded that in a 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 $\Psi = 1.30$ W/(m·K) as a maximum and $\Psi = 0.70$ W/(m·K) as the most probable value to be used in the energy audit (Ilomets, Kuusk, Paap, Arumägi, & Kalamees, 2014).

The 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 room temperature. The indoor temperature in buildings with old heating systems was regulated in heat substations, depending on outdoor temperatures. DHW was also prepared in heat substations with a heat exchanger. Distribution pipes and circulation pipes were usually uninsulated.

All the studied dwellings had natural passive stack ventilation and some apartment owners had 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 a bad indoor climate and high indoor humidity loads (Kalamees et al., 2011; Maivel, Kurnitski, & Kalamees, 2014).

Measured energy consumption

The actual energy performance was determined by energy audits of 105 large-panel apartment buildings. The measured use of delivered energy (electricity, gas, water, DHW and space heating, which includes the heating of ventilation air) on a monthly basis over a three-year period was analysed. Energy usage was determined for the whole building.

For buildings where all the delivered energy components data were available (70 buildings), PE was calculated. It takes into account the use of the PE (space heating, ventilation, DHW, all electricity loads – including lighting and appliances, *i.e.* plug loads) and environmental impact according to the energy source. The following weighting factors (Minimum requirements for energy performance of buildings, 2012) were applied:

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

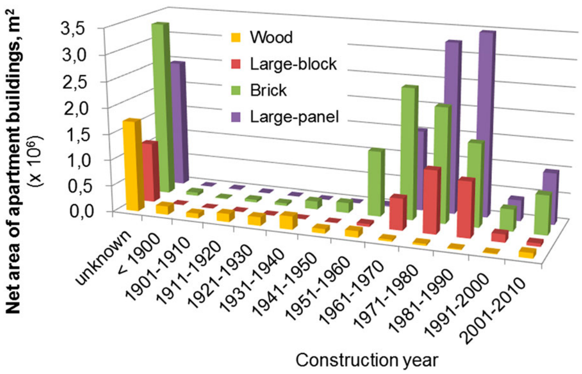

Figure 1 Distribution of apartment buildings in Estonia according to age group and construction types

Simulations of energy-saving measures

Simulations of reference buildings were used in order to analyse different energy-savings measures that could be used for improving the energy efficiency of existing apartment buildings. In this study a limited number of reference buildings were used, which was considered sufficient for the estimation of the technical energy-saving potential and investment cost need. Detailed energy and cost simulations were undertaken. Three typical types of large-panel apartment buildings were selected as reference buildings from different construction periods (Figures 2 and 3, and Table 1) for detailed energy-renovation measures simulations and economic calculations. Reference buildings were selected to represent the distribution of age and size of large-panel apartment buildings (Figure 2).

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

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 Travesi, Maxwell, Klaassen, and Holtz (2001) and Loutzenhiser, Manz, and Maxwell (2007). An Estonian test reference year (Kalamees & Kurnitski, 2006) was used for outdoor climate conditions (annual heating degree-days at t_i 17°C = 4160°C·d).

The zoning of the simulation model is shown in the example of reference building A. The model of the building was divided into different zones according to apartment layouts (Figure 4), and third-floor zones were multiplied by three also to represent the second and fourth floors. 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 standard usage (Methodology for calculating the energy performance of buildings, 2012; Minimum requirements for energy performance of buildings, 2012). This was done because the aim was to analyse the energy usage of the building type during standard usage and not the energy usage of a specific 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 and 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 the 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, 2007) and 0.42 l/(s·m^2) for renovation packages representing indoor climate category II.

Figure 2 Reference buildings used in simulations

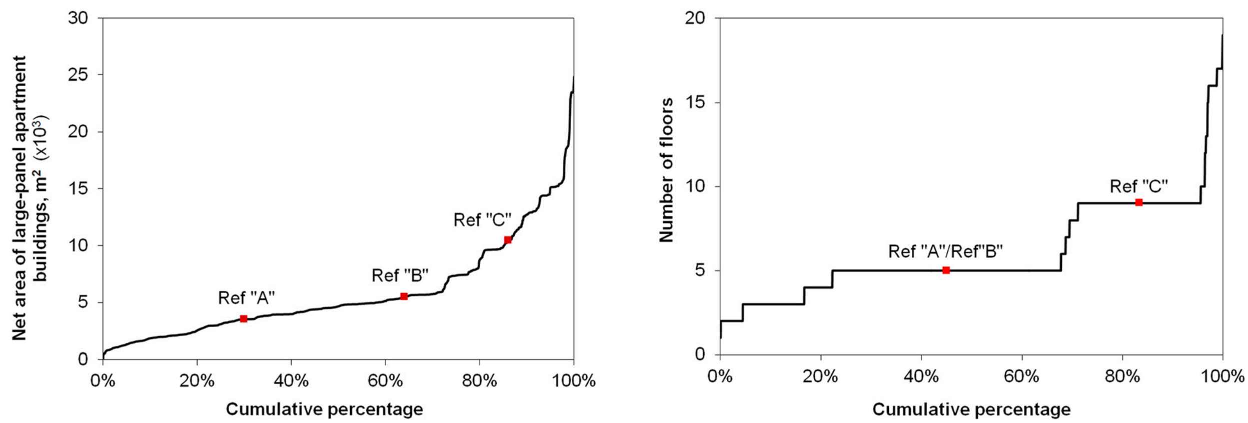

Figure 3 Net area (left) and number of floors (right) of reference buildings and the whole building stock of large-panel apartment buildings

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 DHW heating need was 520 l/(m^2·a)/30 kWh/(m^2·a).

Ventilation heat recovery was solved with two technical solutions: an apartment-based air-handling unit with heat recovery and mechanical exhaust ventilation with a heat pump for heat recovery. The principle of mechanical exhaust ventilation with a heat pump for heat recovery is that supply air enters through a fresh air intake that filters and heats 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 by a 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. A lower COP in summer results from use of the heat pump only for DHW, which has a higher temperature (55°C) (Kõiv, Mikola, & Kuusk, 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 an adequate ventilation system in order not to compromise the indoor climate. Different heat sources than district heating (gas boilers, heat pumps etc.) were not analysed in this study. Apartment buildings are mostly heated with district heating in Estonia, and when a building is in a district heating area, it is obligated by law to use district heating as the heat source. 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 (nZEB))

Simulation results of energy-renovation measures in the results section are presented as a weighted average from three reference buildings simulation results based on the proportion of the net area of the reference building type from all the net areas of large-panel apartment buildings.

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 current practice, the cost of renovation was calculated by considering an 85% loan financing and 15% self-financing. A discount period of 20 years was selected because the maximum period for renovation loans for AOAs in Estonia is 20 years:

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

where $C_g(\tau)$ is the global cost (referred to the starting year) (€/m^2); C_i is the initial investment cost (self-

Table 1 Characterization of reference buildings based on energy audits

	Reference buildings		
	A	B	C
Construction period	Pre-1970	1971–80	1981–90
Share of the building type net area from all the net area of large-panel apartment buildings (%)	50	16	34
Number of floors	5	5	9
Net area (m^2)	3519	5484	10 421
Heated area (m^2)	2968	4481	8262
Compactness: building envelope (m^2)/volume (m^3) ($= m^{-1}$)	0.35	0.35	0.29
Number of apartments	60	75	144
Thermal transmittance			
Side exterior walls U_{wall}, W/(m^2·K)	1.1	1.0	0.8
End external 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

financing of a renovation loan) (€); $C_{a,i}(j)$ is the annual cost of year i for 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 buildings reference state (current state) (€); and A_{floor} is the net floor area (m^2).

Construction costs (Table 2) were calculated on the basis of real costs and estimations were made by the construction companies. The 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. An escalation rate for energy prices of 3% and an interest rate of 4% were used as typical interest rates for a renovation loan for AOAs in Estonia. These rates were used in the Estonian energy roadmap ENMAK 2030+ (ENMAK, 2030+, 2013). All costs include value added tax (VAT) of 20%.

Results

Energy use for the current state of the buildings

The average annual use of delivered energy of 105 buildings measured is shown in Table 3. The average annual use of electricity was 32 kWh/(m^2·a). Electricity was used for lighting and for household appliances.

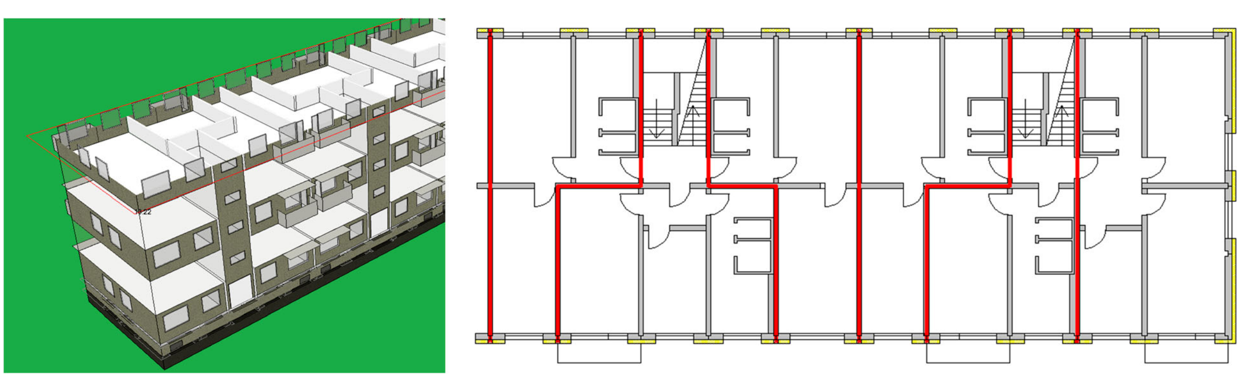

Figure 4 Simulation model (left) and floor plan (right) of the reference building

The annual average use of gas was 8 kWh/(m^2·a). Gas was used only for cooking. Energy use for heating DHW 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, through thermal bridges, due to infiltration and 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 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 two-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

The average use PE was 224 kWh/(m^2·a) (standard deviation (SD) = 25 kWh/(m^2·a)) (Figure 5). 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 DHW and 30% for electricity from the weighted delivered energy.

Buildings were divided into different groups according to the realized renovation measures. An analysis of space heating usage showed that single energy-saving measures (additional insulation on roofs, additional insulation on end walls, a new heating system) had no significant impact on building space heating energy usage (Figure 6). The statistical difference in space heating consumption compared with buildings without renovation measures was between the following building groups: buildings with additional insulated end walls (50–150 mm) and additional insulation for roofs (150–300 mm) ($p = 0.02$), buildings with additional insulation on end walls and a renovated heating system ($p = 0.01$), and buildings with additional insulation on end walls, side walls and roof ($p = 0.0001$).

Cost-effectiveness of energy retrofits

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 7.

The insulation of external wall leads to the greatest reduction in the global cost and PE. Insulation thicknesses of 200 or 300 mm are most reasonable with PE reductions of 17% and 18%. The thickness of roof insulation and insulation of the basement ceiling has a small effect on 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 decreases PE 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 coatings), which had the same range of

Table 3 Annual use of energy in 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

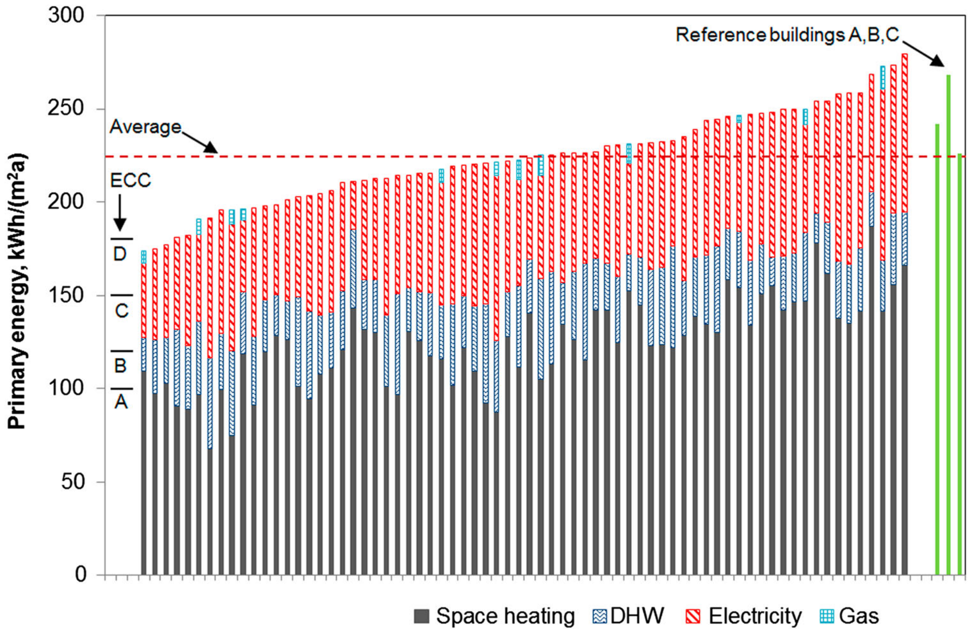

Figure 5 Use of primary energy in measured buildings

global cost reduction but a higher decrease of PE than U–1.1 W/(m^2*K). Window U–1.1 W/(m^2*K) decreased PE by 6% and window 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 global cost due to considerably higher costs at the moment. When evaluating the energy efficiency of the replacement of windows, one must recall that window replacement as a single energy efficiency measure does not eliminate the thermal bridge in the window/external wall junction. When windows are replaced together with additional insulation to the external walls, then the energy savings would be higher. If windows are installed in the additional insulation layer on the external wall, then the thermal bridge at the window/external wall junction would be eliminated.

Renovation of the ventilation system by installing an exhaust air heat pump for heat recovery increases the

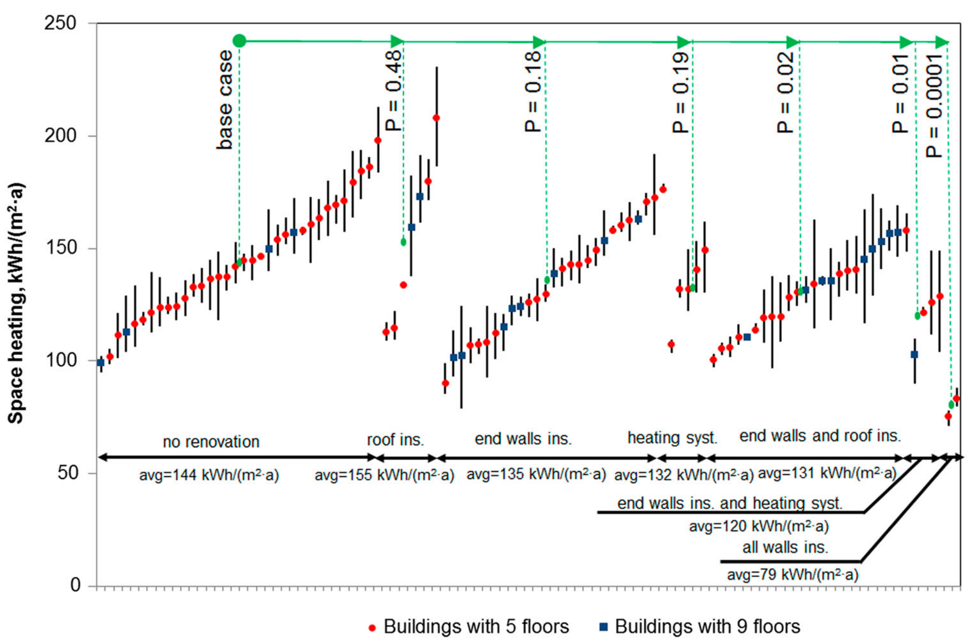

Figure 6 Energy use for space heating in the studied apartment buildings

global cost and PE consumption due to the improved ventilation airflow and electricity use. Apartment-based air-handling units with a heat exchanger efficiency of 80% will decrease PE consumption by 13%. Due to the high electricity consumption, the heat pump of the exhaust air ventilation has the highest global cost. In terms of delivered energy, the ventilation system with an exhaust air heat pump decreases delivered energy usage by 7%.

Energy-renovation packages

Analysis showed that the renovation of the ventilation system effects energy usage significantly. Therefore, renovation packages are divided by different renovation solutions of ventilation systems. The weighted average use of the PE in the current state was PE 241 kWh/(m^2·a). The economic optimum of energy-renovation measures is around the PE 120 kWh/(m^2·a) level, which corresponds to the requirements for low-energy apartment buildings (Figure 8). Therefore, it is possible to reduce PE consumption by 50% without increasing the current state of global costs. Reduction of energy usage relative to the current state of apartment buildings is shown in Table 4. Cost-optimal energy-saving opportunities are mainly in space heating energy and energy use for heating DHW. Electricity use will increase in every renovation package because of installed mechanical ventilation systems.

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 ground floor apartments. A 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 PE-level packages of new apartment buildings with the use of solar collectors for heating DHW. A PE level of a 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 onsite electricity production from renewable energy sources. This required the maximum additional insulation of the building envelope (external wall +400 mm, roof +500 mm), windows with low thermal transmittance (U–0.6 W/(m^2·K), and use of solar collectors for heating DHW.

Investments

Analysis of the necessary investment costs shows that the correlation between the energy efficiency level and the renovation cost is relatively linear. The level of energy investment costs (Figure 9) corresponds to different levels of requirements for apartment buildings:

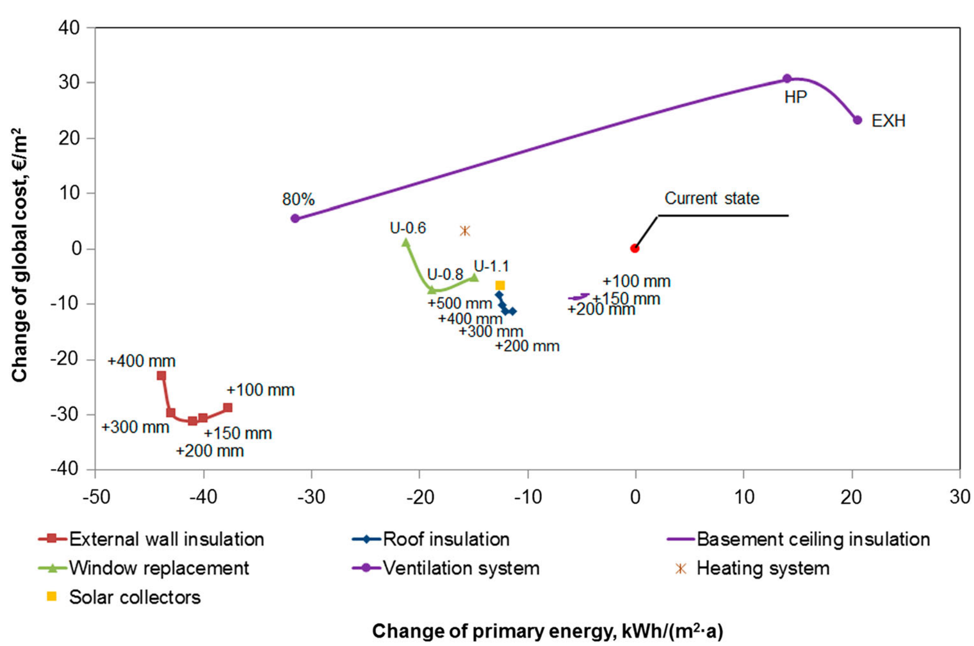

Figure 7 Change of energy performance and global cost at different individual renovation measures

- for a major renovation: €90–110/m^2
- for same energy efficiency as new buildings: €140–160/m^2
- for low energy buildings: €150–170/m^2
- for nearly zero energy building: around €200/m^2

By comparison, the construction cost for new apartment buildings to meet current energy efficiency requirements is €1000–1200/m^2.

The renovation of apartment buildings to low-energy-building energy efficiency level and nearly zero-energy-building energy efficiency level seems costly, but for comparison it can be observed that renovation costs account for only approximately 20% of the construction cost of new buildings (approximately €1000–1200/m^2, VAT included). The costs of renovation and the construction of new building are not fully comparable as renovation costs are without interior remodelling, but renovation cost analysis show that deep renovation of existing apartment buildings is significantly cheaper than the construction of new apartment buildings.

Analysis of 168 realized renovation costs made with grant support and reported by AOAs showed that total investments were often lower than our investment need calculation results. One reason is that investments needed to improve the indoor climate (a new ventilation system) were not often a priority in the renovation process. Another reason is that AOAs undertook energy-renovation works before the grant application and the cost of those energy-renovation works are not included in the grant scheme investment cost data. Our analysis of investment costs included only the replacement of windows and additional insulation of end walls as the energy-renovation measure, which has previously been made. For example, the possible scenario when the roof was previously insulated and only the external walls need to be insulated was not addressed in the current analysis.

The influence of a grant support scheme on investments is shown in Figure 10. The square represents total investment with a energy-renovation grant (that varies between 15% and 35% depending on the achieved energy certification class) and the circle represents investments made by AOA (total investment cost minus the grant support). The average total investment for apartment buildings over 3000 m^2 achieving energy certification class E (minor renovation) was €36/m^2 and AOA's share (total investment minus grant) was €31/m^2. The average total investment for achieving energy certification class D (major renovation) was €71/m^2 and AOA's share (total investment minus grant) was €53/m^2, and average total investment for achieving energy certification class C (requirement for new building) was €120/m^2 and AOA's share (total investment minus grant) was €78/m^2. Before the renovation grants, only a renovation loan was available to apartment owners. Investments made only with a loan and without grant support (marked with a triangle and a dotted line) for energy efficiency measures has been set as a baseline in order to analyse how the grant support has changed the

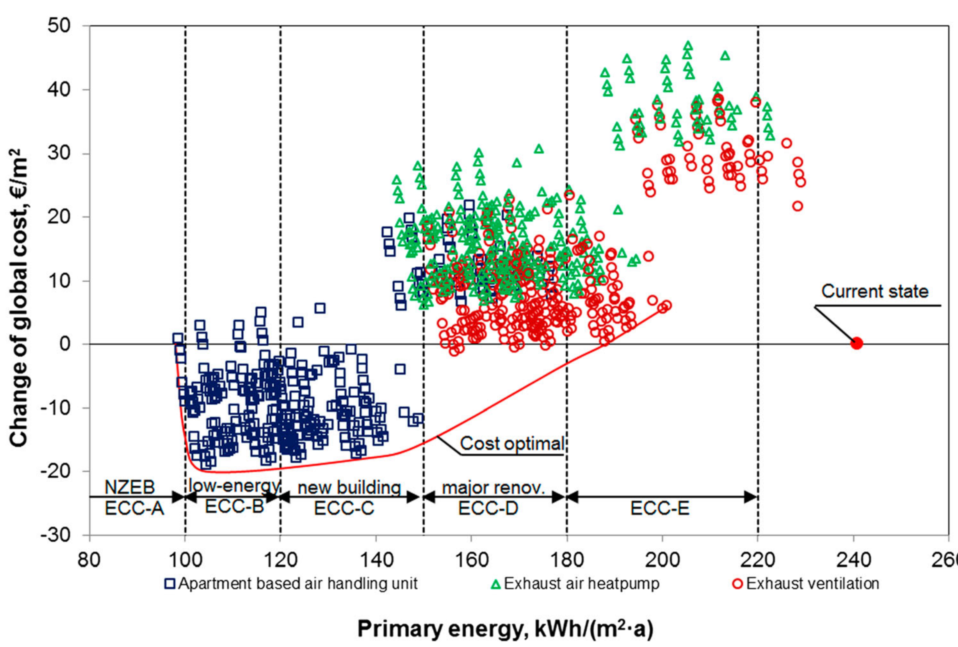

Figure 8 Change of global cost and energy performance relative to the current state of weighed average of three reference buildings

Table 4 Reduction of energy usage of reference buildings relative to current state and global cost of renovation to different energy efficiency levels

	Reduction of energy usage from the current state under standard use of the building (%)		Global cost (€/m²)
Energy certification class	**Primary energy (%)**	**Delivered energy (%)**	
Current state (ECC F)			288–317
Minor renovation (ECC E)	3–18	16–31	299–358
Major renovation (ECC D)	20–33	26–39	285–344
New building (ECC C)	34–44	43–53	273–324
Low energy building (ECC B)	47–55	58–66	271–315
nZEB (ECC A)	56–63	71–76	278–309

investments for renovation. The results show that the grant support scheme has raised apartment owners' contribution to energy renovation. In order to apply a 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 the 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 a 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 a new apartment building energy efficiency level has raised AOAs' investments to energy efficiency measures by more than twice.

A comparison of the necessary investment needs and investments made only by AOAs shows that without a grant the AOAs cannot make the necessary investments to improve the building energy efficiency significantly.

The total renovation cost (Figure 9) is more expensive than only energy renovation (Figure 7) due to inevitable side works. Even if the renovation of a ventilation system is not so cost-effective; it is unavoidably needed due to public health requirements. Investment capability is usually the limitation for renovation down to low energy of nearly a zero energy level. In order to make renovation more affordable for the AOAs, the new grant share had a proposal for a new renovation scheme in Estonia, which started in 2015. Financial support for the best energy-efficient level was raised from 35% to 40% in order to compensate for additional investment costs when installing mechanical supply–exhaust ventilation systems with heat recovery. A renovation grant of 40% lowers the renovation costs needed to achieve a new building energy efficiency level of approximately €80/m^2, which is affordable for AOAs (Figure 11). The renovation of

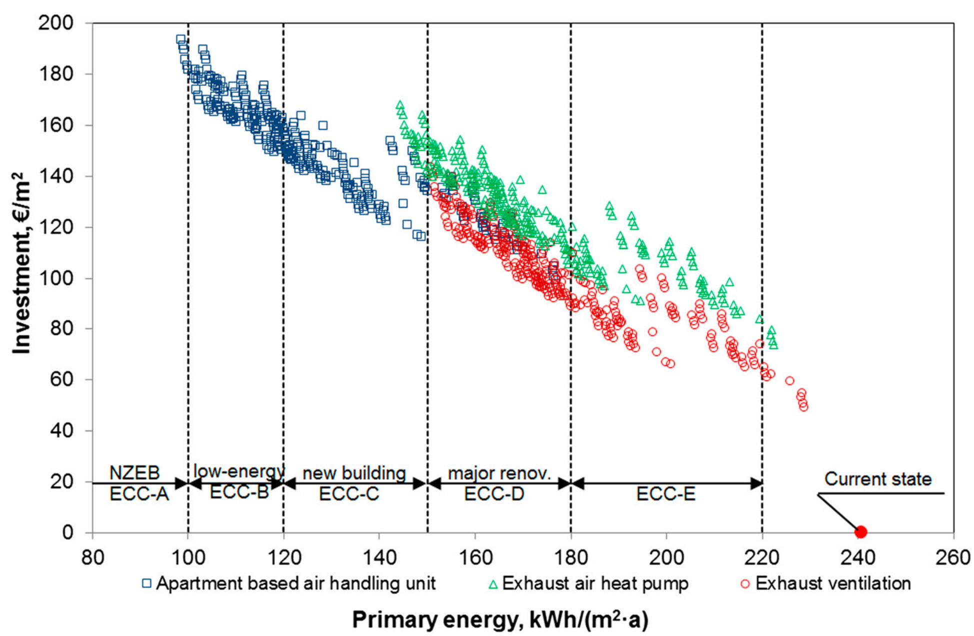

Figure 9 Change of energy performance and investment need

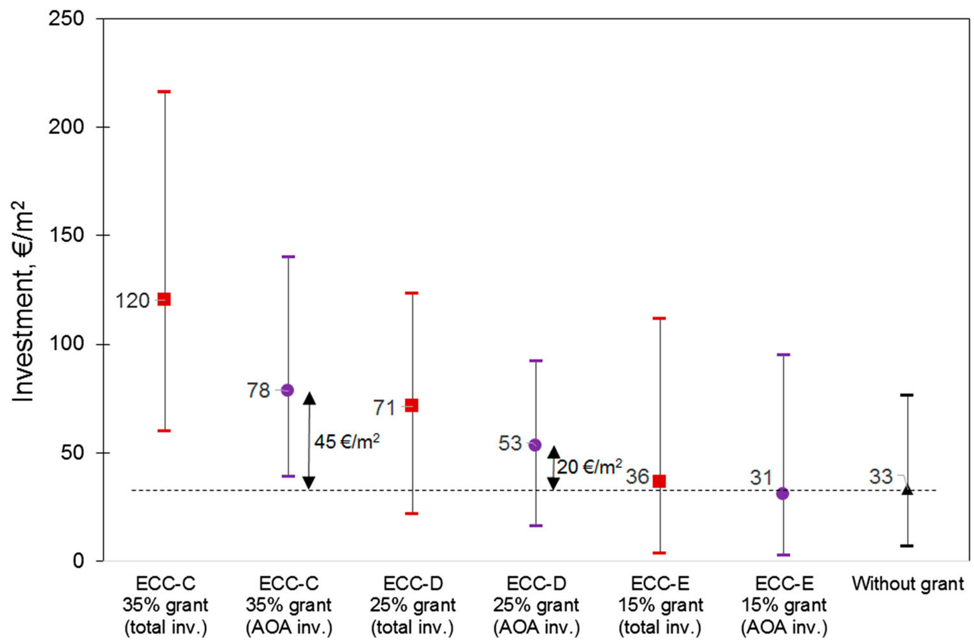

Figure 10 Investments made in apartment buildings in order to achieve different energy certificate classes. The dotted horizontal line represents renovation without grant that is selected for comparison

the building to ≤ ECC-C level is economically much more attractive and hopefully will help to decrease the overall energy use of buildings and achieve the energy-saving targets.

Discussion

Until recently, mainly minor energy retrofit works to Estonian apartment buildings were undertaken, *i.e.* the replacement of windows and replacement of old heat supply substations. The end walls of some large-panel apartment buildings have also been insulated, but the thickness of the additional insulation layer is generally low at 100–150 mm. Those minor retrofit works have not significantly reduced the apartment buildings' energy usage. The average PE 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 PE usage 120 kWh/(m^2·a), which is the energy efficiency requirement for low-energy apartment buildings. A cost-optimal PE usage level around 120 kWh/(m^2·a) that is lower than previous studies for Estonia has been indicated. Studies by Kurnitski et al. (2014) and Kuusk et al. (2014) concluded that the cost-optimal energy performance level of a deep-integrated retrofit corresponded to minimum energy performance requirements of new apartment buildings (energy certification class C). The difference in the results is caused by the difference between the reference buildings used for analysis. Previous studies also used smaller apartment buildings (net area < 1000 m^2) as their reference buildings. The current study used large-panel apartment buildings which are larger and therefore cost-optimal energy performance level is lower.

One problem that is often left unsolved in the retrofit 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 the 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 a retrofit to achieve the energy performance level of a new building and a low-energy building is economically viable, the high investment cost for renovation is a major barrier for renovation. The viability of retrofit is also affected by the energy price and cost of additional renovation works. Our study findings are based on an annual energy price increase of 3% and included only energy efficiency-related renovation works. 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 crucial for the safe use of the building. The investment capability of AOAs is insufficient to cover

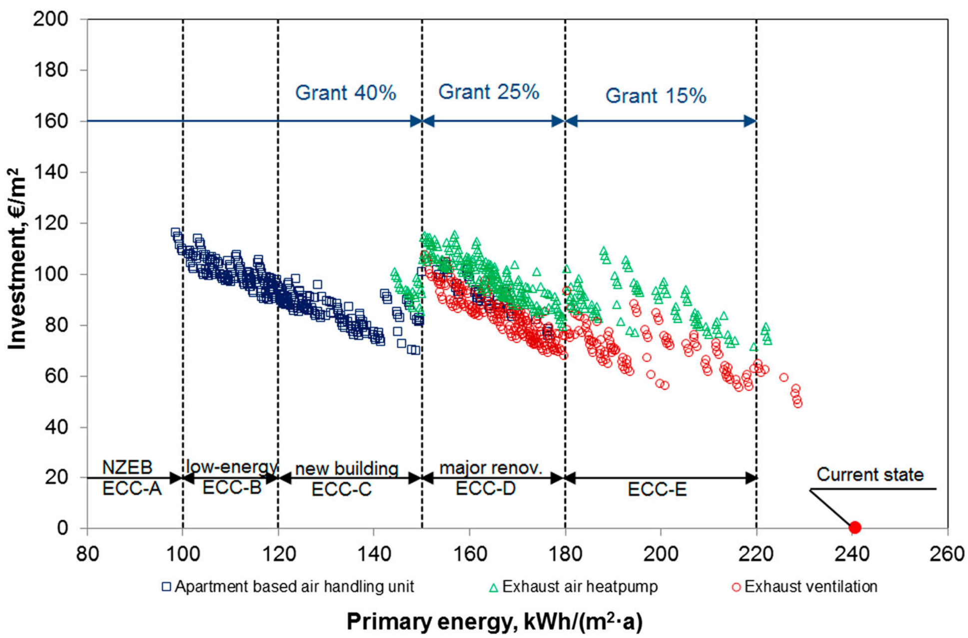

Figure 11 Investment need with renovation grants

the crucial repair works and significantly improve building energy efficiency. Analysis showed that apartment owners' capability to invest in energy efficiency is approximately four times lower than what is necessary to achieve low energy building requirements. Apartment owners' own funds often allow only single retrofit measures, which do not fulfil even the energy efficiency requirements of major retrofit (Figure 5) and often do not result with significant change in building energy usage (Figure 6). Therefore, external financial support is needed to execute retrofits in apartment buildings in order to achieve future energy efficiency targets. Without the grants, the annual cost (energy cost and renovation loan) after the retrofit would be higher for apartment owners and that would make it difficult for the apartment owners' association to make a decision for a major retrofit. Earlier studies have also shown that one of the main priorities for apartment owners in the selection of energy retrofit measures is a short payback period (Medineckiene˙ & Björk, 2011).

The availability of financial support measures will raise apartment owners' own interest to invest in energy efficiency improvement measures. Analysis of investment costs with a renovation grant showed that apartment owners' own investment with a 35% grant was roughly twice higher than investments made without the grant support. This is based on the analysis of real costs of realized retrofits of 168 apartment buildings mentioned above, which formed part of this study. 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 in addition to the building level, the national investment in buildings for energy efficiency improvement is cost-effective (Pikas, Kurnitski, Liias, & Thalfeldt, 2014). Tuominen, Forsstromb, and Honkatukia (2013) reached a similar conclusion that investing in energy-efficient buildings is an economically viable and effective way to reduce buildings' energy consumption. Based on the aforementioned studies, the investment in buildings for energy efficiency are cost optimal not only at the building level but also at the macroeconomic, national level.

The results of the current study show that in the determination of energy 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. A 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. The main purpose of the energy efficiency subsidies should be apartment buildings, which fulfil the same energy efficiency requirements for new buildings or an even lower energy level. Financial support is also necessary to execute a major retrofit 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). In order to motivate deep, integrated energy retrofits, the level of grant support should be differentiated to encourage deep, low-energy retrofits, particularly those that reach the same energy efficiency standard as for new buildings or those with an even higher level of performance. This concurs with previous studies (Uihlein & Eder, 2010) that 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. The results of the current study show that for an integrated retrofit the aim of the retrofit should be the best energy efficiency level possible.

The higher grant rates should be directed to apartment buildings that fulfil energy efficiency requirements for new buildings or a 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, but the results showed that the renovation of larger apartment buildings to a low energy efficiency level is cost optimal. Ferreira, Almeida, Rodrigues, and Monteiro Silva (2014) 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 view of the future energy efficiency goals, the current activities must be directed primarily to support the deeply integrated cost-optimal renovation of existing apartment buildings.

Conclusions

This study analysed the strategy for a supporting policy, economic viability and investment cost of energy retrofits using apartment buildings in Estonia as an example.

The results showed that single energy-efficiency measures made by AOAs' own funds have no significant impact on their buildings' energy usage. An integrated deep-energy retrofit is needed in order to achieve the future energy efficiency goals set by the European Union. The cost-optimal level for large-panel apartment building retrofit was found to be a 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 DHW. Requirements of a new support scheme for the renovation of existing apartment buildings are set to be in line with those results.

The investment capability of Estonian AOAs is not sufficient to achieve a new building or low-energy building energy efficiency level. Therefore, financial assistance is needed to promote and execute energy retrofits. Subsides can increase AOAs' investments to improve building energy efficiency. Although some financial support is necessary for smaller apartment buildings to execute a major energy retrofit, the main target group of subsidies should be those apartment buildings that undertake a retrofit to reach the same energy performance as new buildings or beyond that.

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