Niemelä, Tuomo; Kosonen, Risto; Jokisalo, Juha

Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings

Published in:
Energy and Buildings

DOI:
10.1016/j.enbuild.2016.12.031

Published: 15/02/2017

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Niemelä, T., Kosonen, R., & Jokisalo, J. (2017). Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings. *Energy and Buildings*, *137*, 60-75.
https://doi.org/10.1016/j.enbuild.2016.12.031

Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings

Tuomo Niemelä[#1,¤1], Risto Kosonen[¤2], Juha Jokisalo[¤3]

[#] *Granlund Consulting Oy*
Malminkaari 21, FI-00701 Helsinki Finland

[1] *tuomo.niemela@granlund.fi*

[2] *risto.kosonen@aalto.fi*

[3] *juha.jokisalo@aalto.fi*

[¤] *Aalto University*
School of Engineering
Department of Mechanical Engineering
FI-00076 Aalto Finland

Abstract

The paper presents cost-optimal energy performance improving measures conducted in deep renovations of typical Finnish (cold climate) brick apartment buildings, built in the 1960's. The study discusses the effects of different renovation measures on the energy performance and economic viability in a selected building. Energy performance is studied from the primary energy consumption's perspective and cost-effective renovation measures to meet higher energy performance criteria are also studied. The cost-optimal renovation concepts to meet different energy performance criteria were determined from over 2 billion potential renovation measure combinations by using sophisticated simulation-based multi-objective optimisation (SBMOO) analysis, utilising the advanced Pareto-Archive NSGA-II genetic algorithm, as the main research method. The SBMOO analysis was used to minimise the primary energy consumption and the net present value of life-cycle cost over a 25-year discount period simultaneously. The results indicate that the cost optimum renovation solutions of the brick apartment building stock provide the same energy performance criteria as the current national minimum energy performance requirements of new apartment buildings. According to the study, the investments should be focused on high performance renewable energy production systems, which deliver the best return on investment. External financial support mechanisms are also required to encourage apartment building owners to conduct deep renovations towards nearly zero-energy apartment buildings.

Keywords – cost-optimal renovation; cost-effectiveness; optimisation; energy efficiency; heat pump system; energy simulation

1. Introduction

Several studies regarding the energy performance renovations and energy saving potential of cold climate brick apartment buildings have been carried out during the last decade [1-6]. The results of these studies indicate that there are many measures that can be applied to brick apartment buildings in deep renovations, depending on the type and the energy performance target level of the renovation [1,4,6]. Typically, individual measures are applied at the moment, but recent studies indicate that larger renovation packages, including a few measures, are also economically feasible, when they are correctly selected and dimensioned and when they are combined with the mandatory large-scale maintenance renovations [1,7,8]. However, the main problem of these studies is that they mainly focus on individual and more conventional energy efficiency improving measures. In addition, the previous studies have been carried out by using a more conventional research method, where different measures and their effect on the overall energy performance of the studied buildings have been studied by means of a limited number of predefined cases. This creates a problem in larger and more detailed studies, because the conventional research method limits both the total number of studied measures that can be selected and also the accuracy and reliability of the results, when several measures and their economic feasibilities are studied simultaneously. The conventional research method cannot guarantee the global cost-optimal solution of several simultaneous measures, because there can easily be thousands or even millions of different solution combinations, depending on the case.

Earlier studies have indicated that the heat pump systems are a cost-effective measure to improve the energy performance of a building and also to utilise renewable energy production [9,10]. According to previous studies, modern heat pump technologies provide considerable improvements in energy performance cost-effectively, they utilise renewable energy, and they are reasonable heating system alternatives, especially in both new and existing residential buildings [10]. However, the cost-effectiveness and energy performance of modern heat pump systems and solar-based thermal and PV-production systems, combined with the typical and more conventional renovation measures, have not been extensively studied in previous apartment building renovation studies. Furthermore, previously carried out studies have not come up with solid solutions, and they have been limited to study only a few more popular renovation measures.

Cost-effectiveness, energy efficiency and environmental impact of residential buildings located in warmer climate conditions have also been studied by Atmaca (2015-2016) [11-14]. The results of these studies indicate that the operation phase of buildings is dominant in both urban and rural residential buildings located in warmer climate, when primary energy, CO_2-emissions and environmental impact over the life-cycle of a residential building are discussed, contributing up to 75…85 % of the total PE consumption and up to 60…85 % of the overall CO_2-emissions over a 50-year life-cycle period [11-14]. However, the cost-optimum solutions to minimise the environmental impact and to maximise the energy performance of residential buildings are different in buildings located in different climates, as the climate conditions have a significant impact on the overall optimum energy efficiency measures, such as optimum thermal insulation thickness of the building envelope or technical performance features of the building services systems. Several recent studies have been conducted to determine the energy saving and environmental impact reduction potential of existing apartment buildings located in cold climate conditions [15-20]. The studies have concluded that an essential aspect of economically viable renovation solutions is to combine the energy performance improving measures with the mandatory maintenance repairs. In addition, the studies have also concluded that innovative motivation mechanisms are needed to encourage the apartment building owners to conduct deep renovations, where the energy performance of apartment buildings is improved further than the cost-optimum level, possibly towards nearly zero-energy apartment buildings [15-20]. The conclusions of the studies indicate that the energy production systems of residential buildings located in cold climate have a significant impact on the environmental impact reduction potential and also on the overall energy efficiency of the existing residential building stock [15-20]. However, the literature review indicates that various cost-effective main heating system alternatives, such as applicable modern heat pump systems, have not been extensively studied previously and further research is needed to determine and compare the economic viability of different main heating system concepts to the more conventional individual renovation measures regarding the energy performance of the building envelope, which have been studied in detail in several recent studies [15-20].

The essential conclusions and key findings of the aforementioned recent studies regarding the significance of energy improvement of the existing building stock highlight the importance of the topic of this study. To determine economically viable renovation measures and packages for apartment building owners to be carried out in deep renovations is essential to meet the EU 2020 energy saving targets, to support sustainable development and to deliver financial savings for building owners. Due to the fact that the energy, cost and environmental saving potential of the existing residential building stock is significant and modern technologies, e.g. different heat pump systems and solar-based renewable energy production systems, are applied at an increasing pace, cost-optimal analyses of different renovation alternatives are needed to deliver optimum overall solutions and to avoid unnecessary over-investments in extensive and less cost-effective measures that are not necessary mandatory to be conducted.

This study takes all of the essential renovation measures into account that can be carried out in a brick apartment building located in cold climate conditions, including different heat pump systems and solar-based thermal and PV-production systems, for the first time. The study also utilises the simulation-based, multi-objective optimisation method to determine the global optimum solution of renovation measures using the new software MOBO as the optimisation method [21,22]. The utilisation of the simulation-based optimisation (SBO) method doesn’t limit the total number of different measures that can be studied, making it possible to study the effect and economic feasibility of all the realisable renovation measures simultaneously.

The main target of this study is to provide cost-optimum energy performance improving renovation solutions, including common renewable energy production systems and their economic and technical feasibility, for typical brick apartment buildings located in cold climate conditions. An essential objective is also to provide cost-effective energy performance improving solutions to meet higher energy performance target levels than the cost-optimum level. In addition, one key aspect of the research is to study the energy performance improving potential and economic feasibility of modern heat pump systems and solar-based thermal and PV-production systems. An essential part of the study is to determine economically feasible solutions to renovate the brick apartment building stock, to reduce the delivered and primary energy consumption of this building stock and to decrease the environmental impact of the buildings. The results and conclusions of this study can be generalised to similar climates and techno-economic environments, when deep renovations of brick apartment buildings are planned to be carried out.

2. Methods

2.1. Studied building

2.1.1 Selection of the building

This study focuses on the energy performance and cost effectiveness of the typical brick apartment buildings built in cold climate areas, such as Scandinavia. A brick apartment building located in Finland was selected as a case study building of the research, because it represents a major share of the Finnish residential building stock and also possesses a considerable energy performance improvement potential. In addition, it represents a typical cold-climate apartment building type located in the Scandinavian countries, Estonia and in Russian districts [1-6]. In addition, Finnish brick apartment building stock requires major renovation measures in the near future, which is the case in many other countries as well. Fig. 1 presents the total number and floor area of Finnish apartment buildings built in different decades (left) and the specific heat energy consumptions of residential buildings (right) in the Helsinki area, which are connected to the district heating network [23,24]. According to Helsingin Energia [24], the Finnish brick apartment buildings built in the 1960’s have the largest energy-saving potential among the Finnish apartment building stock, and they also represent the second largest share of the Finnish apartment building stock (see Fig. 1), when the total floor area of the apartment building stock is discussed. This is the main reason why the brick apartment buildings were selected for the study.

The chosen case study building represents the major share of the Finnish brick apartment buildings built in the first half of the 1960's with tile external structures and bookshelf-type frame constructed on-site [25,26]. This is the main apartment building type before the prefabricated concrete large panel construction began at the end of the decade. The studied apartment building, its exterior structures and its technical systems are in the original condition, where no major renovation measures have been carried out. This is the case in many Finnish brick apartment buildings built during the 1960's.

2.1.2 Geometry and structures

Fig. 2 presents the main geometry and the main dimensions of the studied building. The main external structures and the thermal bridges of the studied building are presented in Table 1. All of the features shown in Table 1 represent the initial situation of the building, where no energy performance improving measures have been carried out. They also represent typical Finnish brick apartment building features of the building stock built during the first half of the 1960's [25,26]. The studied building has a total of 7 floors with 6 apartment floors and a basement floor. The total heated net floor area of the building is 3 697 m^2 and the total heated volume is 10 497 m^3. The building is located in the urban environment of Vantaa, Finland.

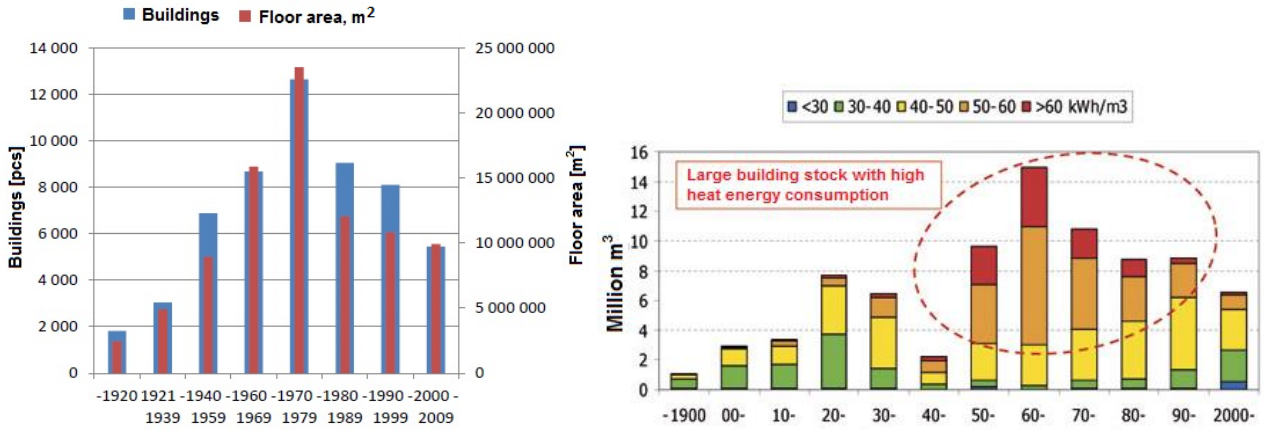

Fig. 1. The number and net area of apartment buildings (left) and the specific heat energy consumption of residential buildings (right) connected to the district heating network in the Helsinki area [23,24].

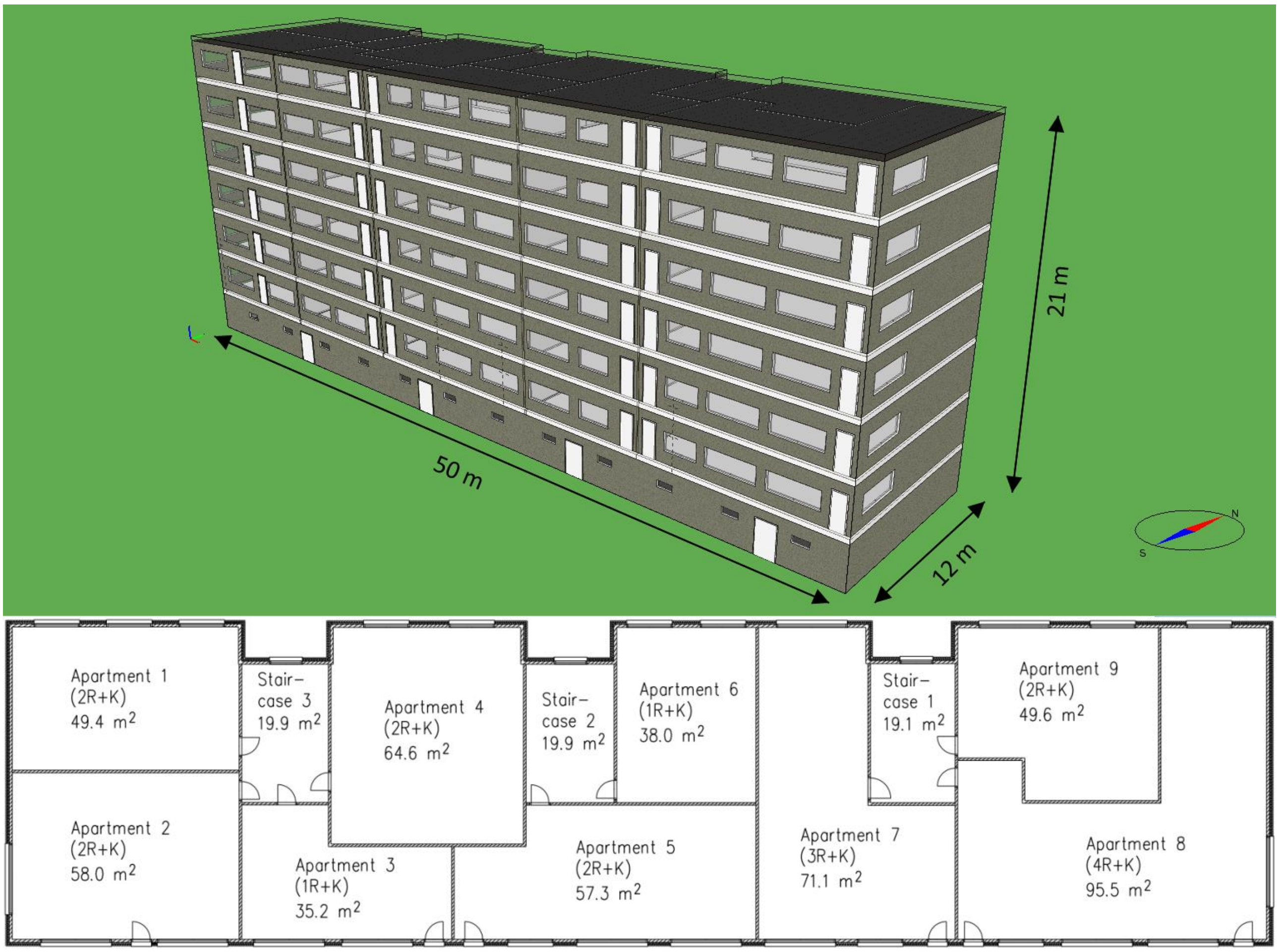

Fig. 2. The main geometry of the studied brick apartment building (above) and the floor layout of the apartment floors (below), r = room, k = kitchen.

Table 1. The main characteristics of the studied brick apartment building.

External structures and air tightness		
External walls, U-value [W/m^{2}K]	0.60	
Roof, U-value [W/m^{2}K]	0.34	
Base floor (connected to the ground), U-value [W/m^{2}K]	0.40	
Windows (2-pane structure), U-value [W/m^{2}K]	2.50	g-value: 0.76 ST-value 0.69 Frame depth: 170 mm
Integrated window shading		Blinds between panes
External doors, U-value [W/m^{2}K]	1.41	
Air-tightness of the building, the q$_{50}$-value	6.00 m^3/(m^2 h)	
Thermal bridges of the structures		
External wall/external wall	0.06 W/mK	
External window/external wall	0.04 W/mK	
External door/external wall	0.04 W/mK	
Roof/external wall	0.08 W/mK	
Base floor/external wall	0.24 W/mK	

2.1.3 HVAC systems

The HVAC systems of the studied building and their main features are presented in Table 2. All of the data presented in Table 2 represent the initial situation of the building, where no energy performance improving measures have been carried out.

Table 2. The HVAC systems of the studied brick apartment building and their main features.

HVAC systems	
Ventilation system	Mechanical exhaust ventilation system, no heat recovery system
Operation schedule of the ventilation system	Monday-Sunday, 24h/day, ventilation system is always on
Exhaust air flow rate	0.4 $dm^3/(s, m^2)$, constant air volume system
The specific fan power of the ventilation system	1.50 $kW/(m^3/s)$
Heat distribution system	Water-based radiator heating system
Dimensioning temperatures of the heat distribution system	80/50 °C
Room temperature set point for heating	21.0 °C (apartments), 17.0 °C (basement floor and stair cases)
Space heating control system	Supply water temperature control according to the outdoor temperature
Domestic hot water consumption	0.5 $m^3/(m^2,a)$
Domestic hot water circulation system	60/55 °C (designing temperatures) 0.23 dm^3/s (designing water flow)

2.1.4 Internal heat gains

The internal heat gains of the studied building and their average usage profiles are presented in Table 3. The presented internal heat gains represent the reference heat gains of the NBCF, and they must be used in the energy performance calculations of the EPC to make the energy performance of different buildings comparable [27]. The NBCF includes different internal heat gains and their usage profiles for different building types (office buildings, commercial buildings, detached houses, apartment buildings etc.) [27].

Table 3. The internal heat gains of the studied building from occupants, household appliances and lighting.

Internal heat gains	
Occupants	Average sensible gain 3.0 W/m^2, which equals to 1 occupant per 28 m^2 with activity level of 1.2 met, heat gain from occupants equals to 15.8 $kWh/(m^2,a)$ with an average usage rate of 0.6
Household appliances	Average gain 4.0 W/m^2, heat gain from household appliances equals to 21.0 $kWh/(m^2,a)$ with an average usage rate of 0.6
Lighting	Average gain 11.0 W/m^2, heat gain from lighting equals to 9.6 $kWh/(m^2,a)$ with an average usage rate of 0.1

2.1.5 Weather data

Köpper-Geiger climate classification classifies Finland to the cold climate zone (D) [28]. In addition, Finland is divided into four separate climate zones (I-IV) according to the National Building Code of Finland (NBCF) for energy performance and heating power demand calculations of buildings [27,29]. In this country-specific classification, Vantaa is located in zone I, which is the southern-most climate zone in Finland. The NBCF also requires that the primary energy consumption of the EPC must be calculated by using the updated climate zone I (Helsinki-Vantaa test reference year, TRY2012) weather data [27]. The TRY2012 weather data includes all the essential energy calculation parameters, such as hourly ambient temperature, relative humidity, wind direction and velocity and solar radiation. The annual average temperature of the Helsinki-Vantaa area is +5.4 °C, and the average degree day number (at indoor temperature of 17.0 °C, S17) is 3952 Kd [27,30]. This updated test reference year weather data used in the energy simulations has been defined in detail in a previous study carried out by Kalamees et al. (2012) [30].

2.1.6 Optimised decision variables and their cost data

The studied energy performance improving measures are the optimised decision variables in the SBO analysis. The optimised renovation concepts are presented in Table 4. The analysis includes a combination of typical renovation measures, which have been studied before as individual renovation measures and heat pump systems and solar-based thermal and PV-production systems, which have also proved to be cost-effective energy performance improving measures in recent studies [10,31-33]. The studied concepts are categorised into four separate basic concepts based on the main heating system of the building. The studied main heating systems are air-to-water heat pump (A2WHP), ground source heat pump (GSHP), exhaust air heat pump (EAHP) and district heating (DH). By categorising the renovation measures, cost-effective and recommendable renovation measures can be obtained for different energy performance criteria for all studied main heating systems. A total of four concepts are optimised using the SBO analysis and all four concepts include six decision variables. The cost data of the studied measures is presented in Table 5 [34-36]. The cost data used in the optimisation analysis is presented in more detail in references [34-36]. All prices presented in Table 5 also include the Finnish V.A.T., which is 24 % in 2015.

Table 4. Decision variables of the SBO analysis according to the optimised main heating system concept.

District heating system concept, DH concept	**Minimum value**	**Maximum value**	**Type of the variable**
- Area of solar collectors, m^2	0	90	Continuous
- Area of PV-panels, m^2	0	170	Continuous
- Renovation of the ventilation system, current mechanical exhaust air ventilation system is replaced with a mechanical supply and exhaust air ventilation system with a heat recovery unit of 72 % temperature efficiency	No	Yes	Discrete
- Additional thermal insulation thickness of external walls or just the basic refurbishment, mm	0, basic refur.	200	Discrete
- Additional thermal insulation thickness of roof, mm	0	500	Discrete
- Replacement of windows, original windows are repaired, painted and re-sealed, or new windows are installed with the U-value of 1.0 W/(m^2 K) or 0.8 W/(m^2 K)	Repair, original	New, 0.8 W/(m^2 K)	Discrete
Ground source heat pump system concept, GSHP concept	**Minimum value**	**Maximum value**	**Type of the variable**
- Dimensioning power output of the heat pump system, kW	39	156	Continuous
- Area of PV-panels, m^2	0	170	Continuous
- Renovation of the ventilation system (see DH concept)	No	Yes	Discrete
- Additional thermal insulation thickness of external walls or just the basic refurbishment, mm	0, basic refur.	200	Discrete
- Additional thermal insulation thickness of roof, mm	0	500	Discrete
- Replacement of windows, original windows are repaired, painted and re-sealed, or new windows are installed with the U-value of 1.0 W/(m^2 K) or 0.8 W/(m^2 K)	Repair, original	New, 0.8 W/(m^2 K)	Discrete
Air-to-water heat pump system concept, A2WHP concept	**Minimum value**	**Maximum value**	**Type of the variable**
- Dimensioning power output of the heat pump system, kW	14	128	Continuous
- Area of PV-panels, m^2	0	170	Continuous
- Renovation of the ventilation system (see DH concept)	No	Yes	Discrete
- Additional thermal insulation thickness of external walls or just the basic refurbishment, mm	0, basic refur.	200	Discrete
- Additional thermal insulation thickness of roof, mm	0	500	Discrete
- Replacement of windows, original windows are repaired, painted and re-sealed, or new windows are installed with the U-value of 1.0 W/(m^2 K) or 0.8 W/(m^2 K)	Repair, original	New, 0.8 W/(m^2 K)	Discrete
Exhaust air heat pump system concept, EAHP concept	**Minimum value**	**Maximum value**	**Type of the variable**
- Dimensioning power output of the heat pump system, kW	30	39	Continuous
- Area of PV-panels, m^2	0	170	Continuous
- Exhaust air restriction temperature of the ventilation system, after the evaporator, °C	-5.0	+7.0	Continuous
- Additional thermal insulation thickness of external walls or just the basic refurbishment, mm	0, basic refur.	200	Discrete
- Additional thermal insulation thickness of roof, mm	0	500	Discrete
- Replacement of windows, original windows are repaired, painted and re-sealed, or new windows are installed with the U-value of 1.0 W/(m^2 K) or 0.8 W/(m^2 K)	Repair, original	New, 0.8 W/(m^2 K)	Discrete

Table 5. Cost data of different renovation measures in the studied brick apartment building (all prices include a 24 % V.A.T.).

Energy performance improving measure	**Investment cost**	**Residual value after 25 years**
Additional thermal insulation of external walls, €/m^2		37.5 % from the original investment price
Basic refurbishment, 3-layer plastering (no insulation)	84	
+50 mm	224	
+100 mm	255	
+150 mm	286	
+200 mm	318	

Additional thermal insulation of roof, €/m^2		37.5 % from the original investment price
+50 mm	4	
+100 mm	8	
+200 mm	14	
+300 mm	20	
+400 mm	26	
+500 mm	32	
Windows, €/m^2		37.5 % from the original investment price
Basic refurbishment of the original windows	213	
Replacement of new windows, U-value 1.0 W/m^2 K	488	
Replacement of new windows, U-value 0.8 W/m^2 K	565	
Heat pump systems, €/kW		50 % from the original investment price
GSHP system	1 060	
A2WHP system	890	
EAHP system	90 00 € (initial investment) + 2 310	
District heating system (new substation and new heating control automation, renewal of the original), €/floor-m^2	15	60 % from the original investment price
Solar-based renewable energy production systems, €/m^2		
Solar electricity system (PV-panels)	263 (1.46 €/W$_p$)	0 %
Solar thermal system (solar thermal collectors)	675	75 % from the original investment price
HVAC systems, €/floor-m^2		
- New low-temperature radiators and balancing of the new radiator system (with the heat pump systems), radiators are renovated to low-temperature radiators, when a heat pump system is installed (45/35 °C)	37	
- Balancing of the original 80/50 °C radiator system (with the district heating system)	7	
- Renovation of ventilation system (centralised)	110	32.5 % from the original investment price
Installation of new main electricity connection cable and substation (GSHP system), €		
GSHP dimensioning power output 39-133 kW	15 700	
GSHP dimensioning power output 134-156 kW	11 000	

Construction costs (Table 5) for different measures were calculated on the basis of recent studies regarding energy performance renovations of apartment buildings [34-36] and also on the basis of cost estimates of system manufacturers. In addition, cost estimates and reports from various consultancy companies and research institutes were also used to obtain as detailed and accurate cost data for the analysis as possible [34-36].

The original radiator heating system is renovated to a low-temperature system with the heat pump systems to maximise the energy performance of the heat pump systems, and this has also been taken into account in the economic calculations [39]. The compressors, circulation pumps, control valves and a few temperature sensors of the heat pump systems are also assumed to be renewed after 15 years in the life-cycle cost calculations. The assumed annual maintenance costs of the following systems are [34-36]:

- 1.0 % from the initial investment cost of the system for the heat pump systems
- 0.5 % from the initial investment cost of the system for the district heating system
- 3.0 % from the initial investment cost of the system for the solar thermal system
- 2.0 % from the initial investment cost of the system for the solar electricity (PV) system
- 200 €/a for the renovated ventilation system, when the air filters of the air handling unit are replaced twice a year. The renovated ventilation system is a centralised system with a single air handling unit.

The assumed renewal costs in the life-cycle cost calculations for different systems are [10,34-36]:

- 224 €/kW for the ground source heat pump system
- 157 €/kW for the air to water heat pump system
- 256 €/kW for the exhaust air heat pump system
- 675 €/m^2 for the solar thermal system (the system is completely renewed after 20 years)
- it is assumed that other systems can be used for the discount period of 25 years without major renewal costs.

The residual values of different measures are determined according to the common technical service life-cycles of the measures and systems. The technical service life-cycles of different measures and their definitions have been discussed in more detail in several previous studies [10,34-36].

2.1.7 Calculation of primary energy consumption and the definition of nZEB and the energy classes of the EPC

To calculate the total primary energy consumption, weighing factors of different energy sources are needed [27]. The total primary energy consumption takes into account the use of heating energy for space, ventilation and domestic hot water heating, electricity used by lighting, household appliances and technical systems, including all auxiliary equipment, such as pumps and fans, and also the energy, cooling and/or electricity, used by the cooling systems of the building. In addition, the efficiencies of the energy production systems are taken into account when the total primary energy consumption is calculated. The total primary energy consumption of a building according to the NBCF D3 (2012) can be calculated by Eq. (1)

$$E_{primary,D3(2012)} = \frac{\sum_i (E_i \cdot f_i)}{A_{net}} \tag{1}$$

where: E_i is the annual delivered energy i (district heating, electricity, fuels used for energy production of the building and district cooling), kWh/a; f_i is the primary energy weighing factor of energy source i, -; A_{net} is the heated net floor area of the building, m^2 [27]. The primary energy weighing factors for different energy carrier are in Finland:

- electricity 1.7
- district heating 0.7
- district cooling 0.4
- fossil fuels 1.0
- renewable fuels 0.5 [27].

In Finland, improving energy performance in deep renovations is mandatory, and it is also regulated by the authorities [37]. The decree on improving energy performance in renovations (2013/4) presents three alternative methods to improve energy efficiency in renovations, which are [37]:

1. improving the energy efficiency of the envelope of the building by installing additional thermal insulation to external walls and roof and by replacing the original windows with new windows,
2. decreasing the calculated delivered energy consumption of the building in standard use without energy carrier specific primary energy factors below a required reference level,
3. and decreasing the total primary energy consumption of the building below a required, building type-specific level.

The third method is selected as the minimum energy performance requirement level of the renovation measures. According to the Decree [37], the minimum requirement level for existing apartment buildings is 0.85 x the initial total primary energy consumption of the building, when no energy performance improving measures have been carried out. For the studied brick apartment building, the minimum requirement level of the Decree is 0.85 x 165 kWh/(m^2,a) = 140 kWh/(m^2,a).

The buildings are categorised to different energy performance classes according to their primary energy consumption. Table 6 presents the different energy performance classes of different building types used in Finland [38].

Table 6. The energy performance classes of different building types according to the total primary energy consumption.

Building type	**Energy efficiency rating and primary energy consumption [$\text{kWh}_E/\text{m}^2,\text{a}$]**						
	A	**B**	**C**	**D**	**E**	**F**	**G**
Detached houses	**Energy efficiency ratings are based on the heated net area of the house.**						
Row and linked houses	≤ 80	81-110	111-150	151-210	211-340	341-410	411 ≤
Apartment buildings	≤ 75	76-100	101-130	131-160	161-190	191-240	241 ≤
Office buildings	≤ 80	81-120	121-170	171-200	201-240	241-300	301 ≤
Commercial buildings	≤ 90	91-170	171-240	241-280	281-340	341-390	391 ≤
Boarding houses	≤ 90	91-170	171-240	241-280	281-340	341-450	451 ≤
Educational buildings and kindergartens	≤ 90	91-130	131-170	171-230	231-300	301-360	361 ≤
Sport facilities (1	≤ 90	91-130	131-170	171-190	191-240	241-280	281 ≤
Hospitals	≤ 150	151-350	351-450	451-550	551-650	651-800	801 ≤

(1 swimming and ice hockey arenas not included)

The Finnish nearly zero-energy building requirements for new buildings have been defined by the FInZEB project, which was completed in February 2015 [39]. As a result of the FInZEB project, a proposal was made for a cost-effective and reasonable nZEB level for different building types. The nZEB definition of different building types was defined by the total primary energy consumption of the building type. The total primary energy consumption requirement level is 116 $\text{kWh}_E/(\text{m}^2,\text{a})$ or less for new apartment buildings [39].

Even though the results of the FInZEB project only concern new buildings, and they will come into force in 2020 according to the current information [39,40], the same energy performance target levels are applied to existing buildings as well, if the objective of a deep renovation is to renovate an existing building to a nearly zero-energy building.

2.2. Simulation and optimisation

2.2.1 Simulation method

Dynamic energy simulations were carried out by using IDA Indoor Climate and Energy (IDA ICE), version 4.6.1, simulation software. IDA ICE's performance, accuracy and reliability as a dynamic simulation tool has been validated and proved in numerous studies before, such as tests against measurements and several independent inter-model comparisons [41-47]. Furthermore, the implementation of the ESBO Plant model in IDA ICE makes the modelling of renewable energy production systems, such as the heat pump systems, micro-CHP plants and solar-based energy production systems, as a part of the dynamic energy simulation of buildings possible.

2.2.2 Optimisation method

The optimisation method used in the SBO analysis was MOBO (Multi-Objective Building Performance Optimisation), version 0.3b. MOBO is a new software developed by Aalto University and VTT Technical Research Centre of Finland for building performance optimisation [21]. MOBO can be combined with many different simulation platforms, and it can solve one- and multi-dimensional optimisation problems [21,22]. MOBO includes multiple types of optimisation algorithms to be used in various optimisation problems [21]. The optimisation algorithm used in the simulation-based optimisation analyses of the study was the Pareto-Archive NSGA-II genetic algorithm, which is an advanced and highly efficient algorithm to be used in multi-objective optimisation analyses [21,22]. A graphical user interface is used to feed the input data to MOBO. It is also possible to carry out parallel simulation with MOBO to increase the effectiveness and reduce the simulation time of the SBO analysis [21]. Recent studies indicate that the SBO analysis is an effective method to determine the optimal solutions in multi-objective building performance analyses [22]. Nguyen et al. states that "On the building optimisation point of view, the free tool MOBO shows promising capabilities and may become the major optimisation engine in coming years." [22]

2.2.3 Operation of simulation-based optimisation

Fig. 3 presents the main components and their relationships for the SBO analysis. The operation of the simulation-based optimisation analysis, with the simulation and optimisation methods used in the study, is presented in Fig. 4.

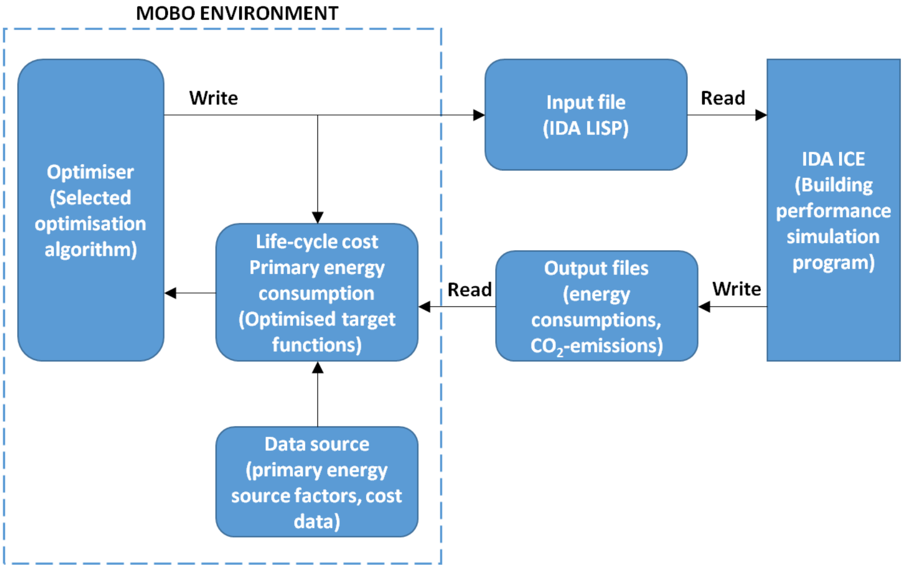

Fig. 3. The main components and their relationships in the simulation-based optimisation analysis of the study.

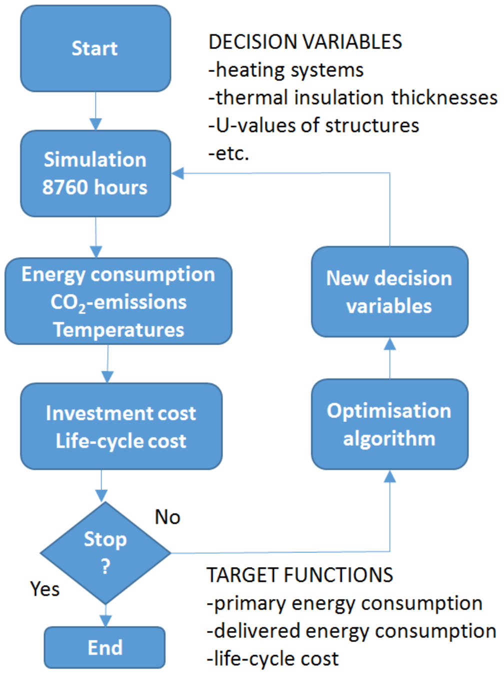

Fig. 4. Operation of the simulation-based optimisation analysis.

2.3. Calibration of heat pump models

In IDA ICE, the energy performance of different heat pump systems can be simulated with the ESBO Plant model. However, the default heat pump models of the ESBO Plant should be calibrated to match the performance of real heat pump systems before the energy simulations. After the heat pump models are calibrated to correspond to the performance of real heat pump systems, they can be used as a part of the dynamic energy simulation. This makes the whole simulation process more reliable, because the dynamic simulation of energy production systems is integrated to the dynamic energy simulation of the building. All of the heat pump models used in this study were modified and calibrated by the first author. No default heat pump models of the ESBO Plant were used in the energy simulations. The exhaust air heat pump model used in the study was designed and constructed by the first author.

Table 7 presents the performance of real heat pump systems and the performance of the simulated heat pump models used in this study. According to Table 7, the accuracy and performance of the calibrated heat pump models are very close to the performance of the real heat pump systems. This means that the results of the analysis are reliable and accurate and correspond to the real energy performance and differences of the studied heat pump systems. According to a recent study, the heat pump models of the ESBO Plant can be calibrated to correspond to any real heat pump system on the market [48]. When accurate COP-values of the heat pump systems in different operating points are used, accurate and realistic SPF-values are obtained, making the simulation of the heat pump systems more reliable.

Table 7. Energy performance of real heat pump systems and the calibrated heat pump models used in the energy simulations.

A2WHP system			
Operating point (inlet ambient air temperature/outlet water temperature to the heating system), according to EN 14511	Measured COP of the real system (NIBE F2300), measured according to the EN 14511 by manufacturer	COP of the calibrated heat pump model	Error margin between the measured COP according to the EN 14511 standard and the calibrated heat pump model
-15/55 °C	1.93	1.93	±0 %
-15/45 °C	2.18	2.06	-5.4 %
-15/35 °C	2.50	2.29	-8.2 %
-7/45 °C	2.62	2.46	-6.1 %
-7/35 °C	3.05	2.81	-8.0 %
2/55 °C	2.67	3.00	+12.3 %
2/45 °C	3.15	3.29	+4.3 %
2/35 °C	3.68	3.70	+0.5 %
7/55 °C	3.07	3.27	+6.4 %
7/45 °C	3.52	3.65	+3.8 %
7/35 °C	4.14	4.19	+1.2 %
10/35 °C	4.75	4.53	-4.6 %
15/35 °C	4.97	5.05	+1.6 %
Average error margin of all operating points			***-0.2 %***

GSHP system			
Operating point (inlet brine temperature/outlet water temperature to the heating system), according to EN 14511	Measured COP of the real system (NIBE F1345), measured according to the EN 14511 by manufacturer	COP of the calibrated heat pump model	Error margin between the measured COP according to the EN 14511 standard and the calibrated heat pump model
0/35 °C	4.30	4.27	-0.7 %
0/45 °C	3.52	3.60	+2.4 %
10/35 °C	5.08	5.04	-0.9 %
10/45 °C	4.15	3.81	-8.3 %
Average error margin of all operating points			***-1.9 %***

The IDA ICE ESBO Plant doesn't include an EAHP model by default. To simulate the EAHP system, a functional EAHP model has to be constructed manually in the ESBO Plant. A GSHP or an A2WHP system model can be used in the simulation of the EAHP system. The GSHP implementation is the more commonly used method to utilise the EAHP system in real renovation projects carried out in existing apartment buildings. The easiest way to model the GSHP implementation is to use the default A2WHP unit as a base system and to construct the actual heat pump system using the A2WHP unit and a few correction factors in the heat pump model. The EAHP model was developed and extensively tested in the study by the first author. Numerous test simulations carried out in the study indicated that the energy performance of the simulated EAHP model was very close to the energy performance of a real operating EAHP system (see Table 7, calibration results of the A2WHP and GSHP systems, which were used to simulate the EAHP system).

2.4. Economic calculations

The minimum life-cycle cost was used to assess the cost effectiveness of different renovation measures. The maintenance repairs were also taken into account to prevent decay of the building and also to prevent the increase of renovation debt. The discount period of the calculations was 25 years, which is one of the typical discount periods used in the economic calculations of apartment building renovations in Finland [10,33,35]. The global life-cycle cost was calculated by Eq. (2).

$$LCC_{25a} = \sum I_{0,tot} + \sum M_{tot} + \sum R_{tot} + \sum E_{tot} - \sum Res_{tot} \qquad (2)$$

where: LCC_{25a} is the present value of the life-cycle cost of the building during the 25-year discount period, €; $\Sigma I_{0,tot}$ is the total investment cost of the energy performance renovation measures, €; ΣM_{tot} is the total maintenance cost of the energy performance renovation measures, €; ΣR_{tot} is the total renewal cost of the energy performance renovation measures, €; ΣE_{tot} is the total energy cost, €; ΣRes_{tot} is the total residual value of the energy performance renovation measures, €.

The total maintenance cost of the renovation measures was calculated by Eq. (3)

$$\sum M_{tot} = \frac{1-(1+r)^{-n}}{r} \times M_a \qquad (3)$$

where: r is the real interest rate; n is the discount period of the LCC calculation, a; M_a is the annual maintenance cost of the renovation measures, €/a.

The total energy cost of the renovation measures was calculated by Eq. (4)

$$\sum E_{tot} = \frac{1-(1+r_e)^{-n}}{r_e} \times E_a \qquad (4)$$

where: r_e is the escalated real interest rate; n is the discount period of the LCC calculation, a; E_a is the annual energy cost, €/a.

The total renewal cost of the renovation measures was calculated by Eq. (5)

$$\sum R_{tot} = \frac{1}{(1+r)^{k_i}} \times R_M \qquad (5)$$

where: r is the real interest rate; k_i is the year from the start, when the renewal is carried out; R_M is the renewal cost of the renovation measure, €. ΣR_{tot} consists of the sum of individual renewal costs of different renovation measures.

The total residual value is the sum of residual values of individual renovation measures and the total investment cost is the sum of individual investment costs of different renovation measures. The energy prices used in the economic calculations were 101.6 €/MWh for electricity and 61.1 €/MWh for district heating [49,50]. The basic fee of the district heating system was 8 870 €/a in the initial "as built" condition [49]. The basic fee was reduced according to the energy saving potential of different renovation measures to correspond to the real situation [49]. The presented energy prices also include all taxes, such as the Finnish V.A.T., which is 24 % in 2015.

The real interest rate used in the calculations was 3.0 %, which is a typical interest rate used in economic calculations regarding both new and existing residential apartment buildings [1,35,36,39]. The escalation rate of the energy prices was 2.0 % in the calculations for both electricity and district heating [1,35,36,39]. An additional sensitivity analysis was also carried out by using a real interest rate of 7.0 %. Furthermore, the effect of the escalation rate of energy prices was also analysed and discussed after the original optimisation analysis.

3. Results

The results presented in this chapter include the main results of the simulation-based optimisation analysis. A total of four SBO analyses were carried out in the original analysis. The optimised concepts were the district heating system, the ground source heat pump system, the exhaust air heat pump system and the air-to-water heat pump system. Only the Pareto-optimal solutions of each optimisation analysis are presented in the results. In addition, a few sensitivity analyses were carried out with the ground source heat pump system to determine the effect of different economic calculation parameters and optimisation method on the results and the recommendable renovation measures of the SBO analysis.

3.1. Cost-optimal renovation solutions

Fig. 5 presents the cost-optimal energy performance improving solutions in the studied brick apartment building. Fig. 6 presents the investment cost of these solutions. The objective functions of the optimisation analysis were the present value of a 25-year life-cycle cost (Eq. (2)) and the total primary energy consumption (Eq. (1)) of the studied apartment building. The decision variables of the optimisation analysis (see Table 4) for different main heating system concepts were the studied energy performance renovation measures. All of the Pareto-optimal solutions of the studied main heating systems are also presented in Figs. 5-6 to determine the cost-effectiveness of the renovation solutions to reach different energy performance target levels. The global optimum solution is the cost-optimal solution of the ground source heat pump system.

A typical reference solution, where no energy performance improving measures are carried out during the renovation, is also presented in the figures. The different energy performance classes of the EPC for new apartment buildings, proposed primary energy consumption for new nearly zero-energy apartment buildings and the minimum energy performance target level in renovations are presented as a reference.

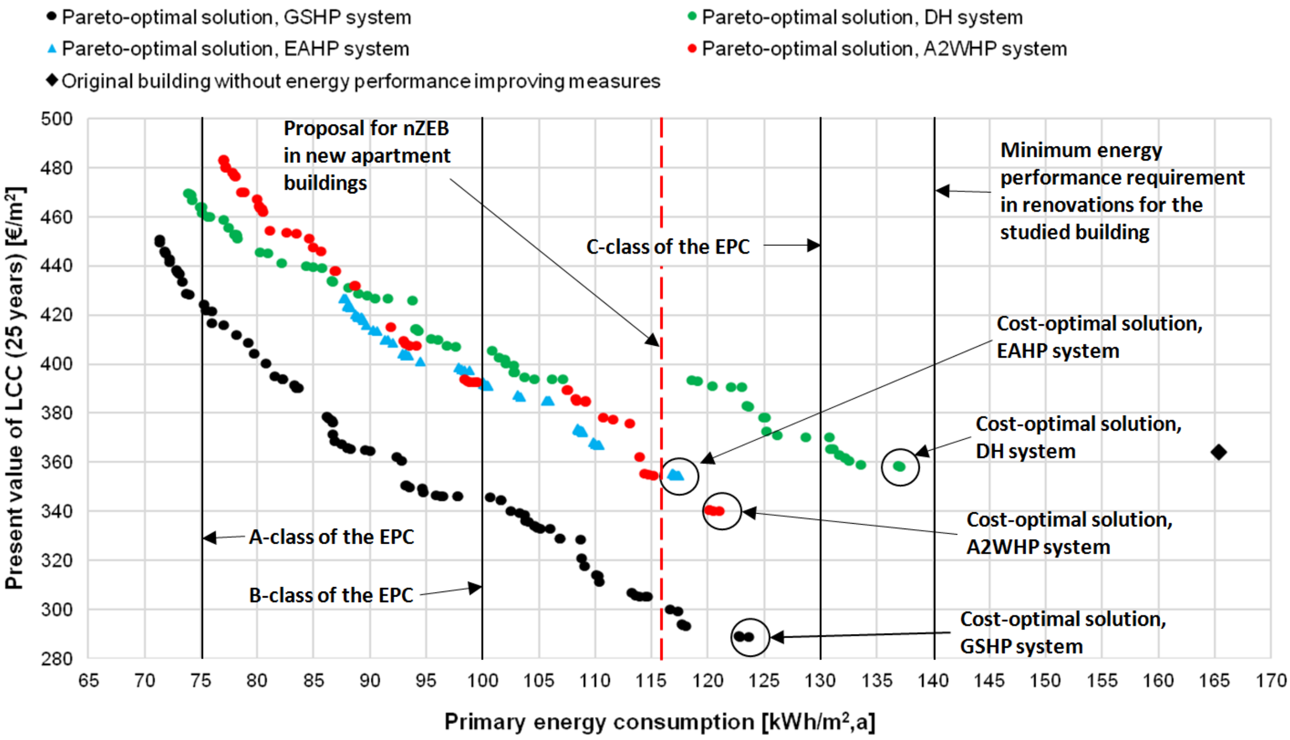

Fig. 5. Cost-optimal energy performance improving solutions for different main heating systems, present value of net LCC presented.

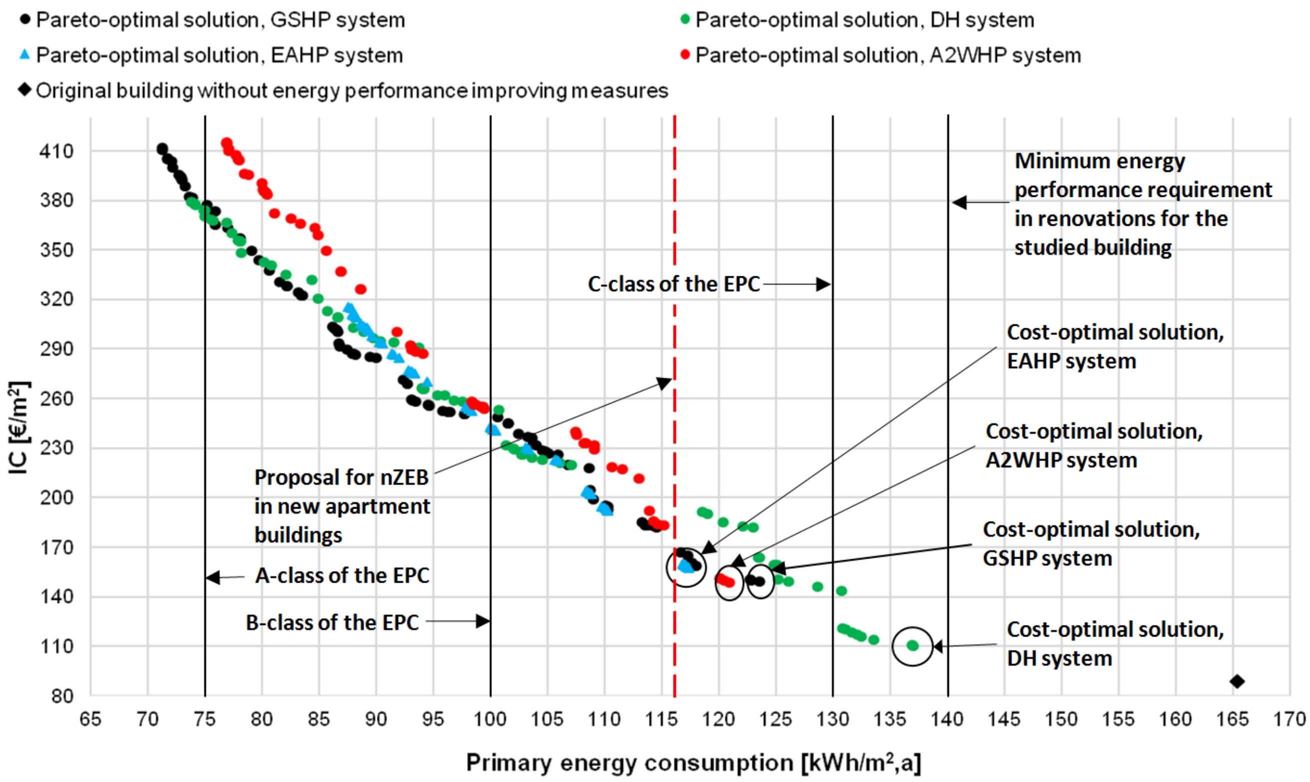

Fig. 6. Cost-optimal energy performance improving solutions for different main heating systems, IC presented.

The investment cost of the renovation measures is an important factor in the deep renovations of apartment buildings, because the renovations are typically financed by loans [1,33,34]. The maximum amount of the loan is typically limited as is the maximum loan period. This means that the maximum investment cost of the renovation measures have to be monitored, depending on the terms of the loan and on the energy performance target level of the renovation. Fig. 6 presents the minimum investment cost to reach different energy performance target levels and helps to choose the loan terms and details according to the energy performance criteria of the renovation measures.

The effect of the renovation measures on the energy performance of the studied building can be seen from the difference between the life-cycle cost of different solutions (Fig. 5), not from the difference between the investment cost of the solutions.

3.2. Cost-effective energy performance improving measures

Tables 8-11 present the cost-effective energy performance improving measures for different main heating systems in the studied apartment building. The tables include the recommendable measures of the studied decision variables depending on the energy performance target level. The recommendable measures form a combination of energy performance improving measures to meet different energy performance criteria (objective function 1) with the lowest life-cycle costs (objective function 2) possible. The tables also include the investment and the net present value of life-cycle costs of the combination of the energy performance improving measures. The recommendable measures depend heavily on the energy performance target level of the renovation and on the selected main heating system. Typically, the renovation measures that meet the minimum requirement level or the cost-optimal level are selected, because the investment cost of the measures to meet the higher classes of the EPC are relatively high [1,33-35].

Table 8. Cost-effective energy performance improving measures with the GSHP to reach different energy performance criteria.

Energy class of the EPC, primary energy consumption [kWh/m²,a]	Power output of the heat pump system [kW]	Area of PV-panels [m²]	External walls ins [mm]	Roof ins [mm]	Windows, U-value [W/m² K]	Ventilation system	NPV of LCC [€/m²]	IC [€/m²]
75 (A-class)	70	170	+150	+350	1.0 (new)	Renovated	428	383
90	73	170	0	+250	1.0 (new)	Renovated	366	288
100 (B-class)	70	160	0	+150	2.5 (original)	Renovated	346	251
110	150	170	0	+350	1.0 (new)	Original	318	199
120	130	160	0	+400	2.5 (original)	Original	294	161
130 (C-class)	94	170	0	+250	2.5 (original)	Original	289	150
140 (minimum requirement)	94	170	0	+250	2.5 (original)	Original	289	150

Table 9. Cost-effective energy performance improving measures with the EAHP to reach different energy performance criteria.

Energy class of the EPC, primary energy consumption [kWh/m²,a]	Power output of the heat pump system [kW]	Area of PV-panels [m²]	External walls ins [mm]	Roof ins [mm]	Windows, U-value [W/m² K]	Exhaust air temperature after the evaporator [°C]	NPV of LCC [€/m²]	IC [€/m²]
75 (A-class)	-	-	-	-	-	-	-	-
90	39	170	+150	+400	0.8 (new)	-2.1	416	298
100 (B-class)	39	170	+150	+500	2.5 (original)	-2.3	398	255
110	39	170	0	+500	1.0 (new)	-4.0	368	195
120	39	170	0	+250	2.5 (original)	-2.1	354	158
130 (C-class)	39	170	0	+250	2.5 (original)	-2.1	354	158
140 (minimum requirement)	39	170	0	+250	2.5 (original)	-2.1	354	158

Table 10. Cost-effective energy performance improving measures with the A2WHP to reach different energy performance criteria.

Energy class of the EPC, primary energy consumption [kWh/m^2,a]	Power output of the heat pump system [kW]	Area of PV-panels [m^2]	External walls ins [mm]	Roof ins [mm]	Windows, U-value [W/m^2 K]	Ventilation system	NPV of LCC [€/m^2]	IC [€/m^2]
75 (A-class)	-	-	-	-	-	-	-	-
90	45	170	+50	+450	2.5 (original)	Renovated	432	327
100 (B-class)	53	170	0	+500	2.5 (original)	Renovated	394	258
110	63	167	+100	+450	2.5 (original)	Original	386	233
120	70	170	0	+100	2.5 (original)	Original	340	149
130 (C-class)	70	170	0	+100	2.5 (original)	Original	340	149
140 (minimum requirement)	70	170	0	+100	2.5 (original)	Original	340	149

Table 11. Cost-effective energy performance improving measures with the DH system to reach different energy performance criteria.

Energy class of the EPC, primary energy consumption [kWh/m^2,a]	Area of solar thermal collectors [m^2]	Area of PV-panels [m^2]	External walls ins [mm]	Roof ins [mm]	Windows, U-value [W/m^2 K]	Ventilation system	NPV of LCC [€/m^2]	IC [€/m^2]
75 (A-class)	90	170	+200	+450	1.0 (new)	Renovated	470	380
90	56	170	+100	+250	2.5 (original)	Renovated	429	301
100 (B-class)	60	160	0	+350	1.0 (new)	Renovated	407	259
110	40	170	0	+300	2.5 (original)	Renovated	394	221
120	34	170	0	+300	2.5 (original)	Renovated	394	220
130 (C-class)	66	170	0	+300	1.0 (new)	Original	373	151
140 (minimum requirement)	34	170	0	+300	2.5 (original)	Original	358	111

3.3. The main results of the sensitivity analyses

The main results of the essential sensitivity analyses are presented in Fig. 7. The real interest rate of the economic calculations was 7.0 % in the SBO analysis presented in Fig. 7. The Pareto-optimal solutions of the original SBO analysis with the 3.0 % real interest rate are also presented in the Fig. 7. The sensitivity analyses of the study were only carried out for the ground source heat pump system, as it was the cost-optimal main heating system concept of the study. A more detailed description and the detailed results of all the sensitivity analyses carried out in the study are presented in the references [35]. More Pareto-optimal solutions at the cost-optimal level can be determined with the higher real interest rate (see Fig. 7). The main difference between these solutions is the recommendable area of the PV-panels (170 m^2/3.0%, 85 m^2/7.0 %) and the additional thermal insulation thickness of the roof (+250 mm/3.0 %, +100 mm/7.0 %), which have both been decreased from the recommendable solutions of the original optimisation analysis with the 3.0 % real interest rate. Furthermore, the optimal dimensioning power output of the ground source heat pump system is also a little bit lower (94 kW/3.0 %, 83 kW/7.0 %), when the real interest rate of the life-cycle cost calculation is 7.0 %.

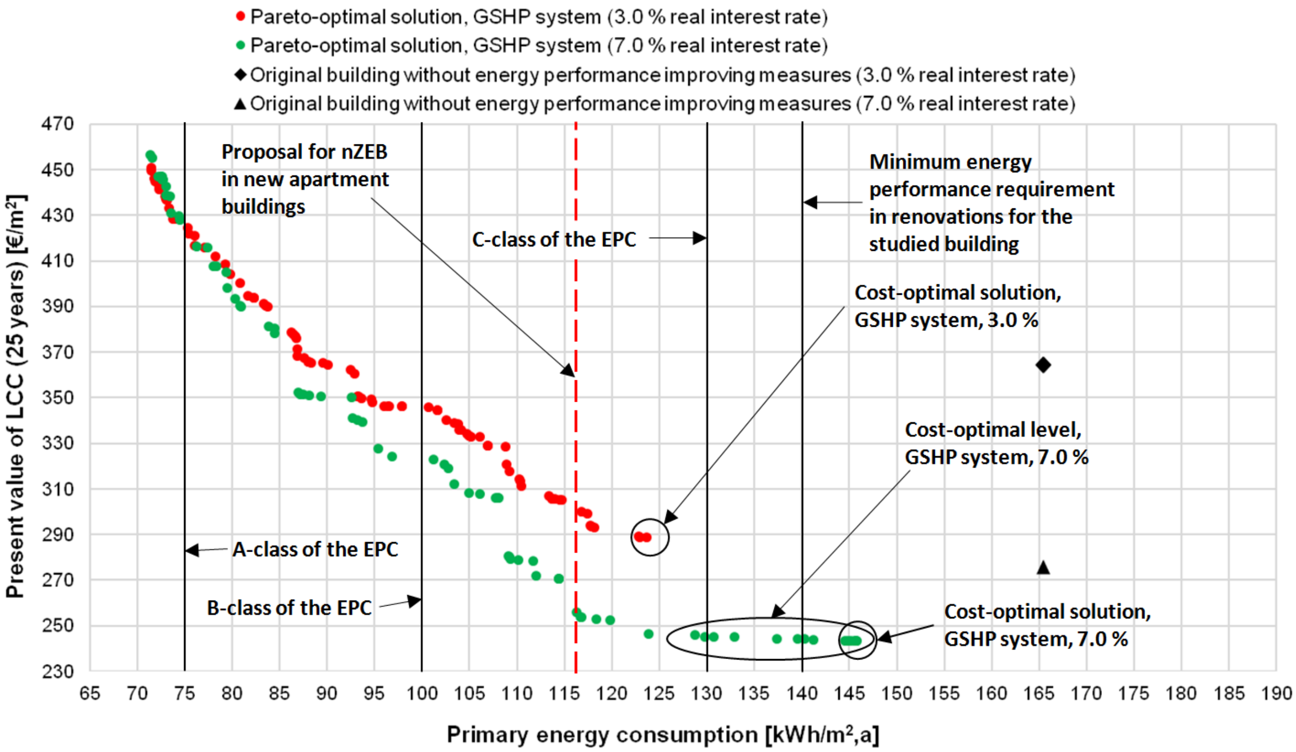

Fig. 7. Cost-optimal energy performance improving solutions for the ground source heat pump system with different real interest rates of the life-cycle cost calculations, present value of net LCC presented.

4. Discussion

The ground source heat pump system delivers the best energy performance improvements when cost-optimality is discussed. However, in many cases, the GSHP system cannot be selected as the main heating system in dense urban areas, because the plot size of the building is often too small for drilling a sufficient number of boreholes or installation of sufficient amount of horizontal plane heat collector pipes. According to the results, the air-to-water heat pump system also seems to deliver excellent energy performance and cost-effectiveness in the climate of Southern Finland. The modern air-to-water heat pump systems are functioning well in cold climates and also delivering good energy performance at the same time. In addition, the investment cost of the air-to-water heat pump system is typically considerably lower than the investment cost of the ground source heat pump system, for example, making the A2WHP system a cost-effective solution to improve the energy performance of residential buildings. Furthermore, the results of the recent heat pump study provide similar conclusions [10].

All of the studied heat pump systems deliver better energy performance and cost-effectiveness than the district heating system. The results indicate that major improvements in energy performance can be achieved by investing in the heat pump systems and in solar electricity production system. The main reasons for this are that the studied modern heat pump systems are operating at a high energy efficiency level, and the investment cost of the solar electricity systems has decreased substantially over the past few years. Another important aspect is the fact that it is favourable to produce solar-based electricity on-site as it decreases the imported electrical energy. The primary energy factor for electricity is 1.7 in Finland, so any savings in the delivered electricity energy use provide high gains in the total primary energy consumption of the building. According to the results, the cost optimum level of the energy performance renovation measures in a brick apartment building was close to the energy efficiency requirements of new apartment buildings.

In this study, the maximum area of PV-panels used in the optimisation analysis was dimensioned so that all of the produced electricity can be used on-site, when the standardised usage profiles of the Finnish building regulations are used [27]. However, it is important to notice that if real usage profiles of an apartment building were used, the total amount of PV-electricity that could be utilised in the building would probably be less, because the usage of lighting and electricity appliances in residential buildings is typically focused on times when the production rate of the PV-electricity system is lower.

The results indicate that the additional thermal insulation of external walls is not a cost-effective renovation measure in the Finnish brick apartment buildings. As an individual measure, the additional thermal insulation of the external walls improves the energy efficiency and decreases the delivered energy need of a brick apartment building considerably, but it seems to be a reasonable and cost-effective option only at the higher energy performance target levels, when other more cost-effective options have already been used. According to the optimisation analysis, additional thermal insulation of the roof seems to be a recommendable renovation measure in brick apartment buildings, where the additional insulation can be installed without any structural alterations of the roof. Replacement of windows seems to be a reasonable renovation measure, and in many cases, the windows of an existing apartment building are replaced to improve both the thermal comfort level and the energy efficiency.

The solar thermal system proved to be a cost-effective alternative to be used with the district heating system. It is important to notice that the profitability of the solar-based energy production system depends heavily on the price of the energy it replaces. Typically, this is the main reason why the solar thermal collectors are a recommendable solution when the district heating system is used, but are seldom profitable when a heat pump system is used as the main heating system of an apartment building.

According to the results, the complete renovation of the ventilation system is not a profitable solution in a typical Finnish brick apartment building when the cost-effectiveness is discussed. This is due to the high initial investment cost of the renovation. Even though the annual energy savings of the measure are high, the investment cost of the renovated system is too high to make it a profitable investment in economic calculations. However, there are always significant quality aspects related to the renovation of the ventilation system. Residents of the brick apartment buildings can often experience draught and uneven thermal comfort levels because of the original mechanical exhaust ventilation system. Typically, the indoor air quality, thermal comfort level and energy efficiency are all improved when the original ventilation system is renovated to a new mechanical supply and exhaust ventilation system. These quality aspects of the renovation cannot be directly measured by economic calculations, but they should still be taken into account when planning the renovation of the ventilation system. The quality aspects of any renovation measure should always be taken into account in addition to the energy performance improvement potential, because buildings are built for use according to their purpose; they are not built to mainly save energy.

Several sensitivity analyses indicated that the interest rate used in the economic calculations and the expected return on investment have a relatively high impact on the optimal renovation measures. When a high interest rate is selected, more profit is expected from the investment. Typically, relatively modest interest rates are used in the economic calculations of energy performance improving investments of existing apartment buildings. Sensitivity analyses indicated that the present value of the life-cycle cost of the ground source heat pump system’s cost-optimal level was approximately 45 €/m^2 lower than in the original optimisation analysis. In addition, the total investment cost was also approximately 20 €/m^2 lower in the cost-optimal solution of the sensitivity analysis. The real interest rates used in the economic calculations were 3.0 % in the original analysis and 7.0 % in the additional sensitivity analysis. In recommendable renovation measures, this means that the optimal dimensioning power output of the heat pumps system is approximately 20 % lower, the optimal area of PV-panels is approximately 85 m^2 compared to the 170 m^2 of the original analysis, and the additional thermal insulation of the roof is +100 mm compared to the +250 mm of the original analysis. It is also important to note that the cost-optimal solution of the optimisation analysis, with the 7.0 % real interest rate, didn’t meet the minimum energy performance improving requirements of the building regulations.

According to the sensitivity analyses, increasing the escalation rate of the energy price, without increasing the interest rate of economic calculations, affects the profitability of the higher investment cost measures, such as the renovation of the ventilation system and the additional thermal insulation of external walls. The escalation rate of the energy price means the average annual increase in the price of delivered energy. The higher the used escalation rate is, the better the overall profitability of the high investment measures will be, providing that the expensive measures deliver a certain improvement in the energy performance of the building. When an unrealistically high energy price escalation rate is used, such as 20-25 %/a, the results will be different. The optimisation analysis delivers recommendable renovation measures to meet the new situation, where maximum energy savings and minimum energy consumption of the building are required. In this case, the cost-optimal solutions will also include high investment cost measures, such as the renovation of the ventilation system and additional thermal insulation of external walls, as they provide significant energy savings. They also become profitable in the economic calculations when the average annual increase of the energy price is high enough. A small increase (2-4 %) in the escalation rate of the energy prices doesn't make a significant difference in the recommendable and cost-effective energy performance renovation measures.

According to the study, the minimum investment cost for maintenance repairs is approximately 90 €/m^2 in a brick apartment building. The cost-optimal renovation solutions of different heat pump systems require approximately 150-160 €/m^2 investments. According to the economic calculations, to reach the proposed nearly zero-energy apartment building target level as cost effectively as possible in brick apartment building renovations, the average annual community fee will decrease by approximately 3.0 €/m^2 with the ground source heat pump system, 1.0 €/m^2 with the air-to-water heat pump system and 0.4 €/m^2 with the exhaust air heat pump system compared to the reference, minimum investment cost, solution. The average annual community fee will increase by approximately 0.4 €/m^2 with the district heating system.

It is important to note that the energy performance certificate classes of the EPC and the primary energy consumption of buildings used in the EPC are always calculated values. They represent the energy performance of a building in a standard situation and in standard use. The actual energy consumption and energy costs of buildings are typically always a little different than the calculated primary energy consumption, because the users of the building have a significant impact on the real energy performance of existing buildings. However, the building regulations require that the primary energy consumption and the energy class of the EPC have to be calculated for every new and existing building. In addition, the nearly zero-energy buildings are defined in Finland using the standardised primary energy consumption. For this reason, it is important to determine cost-optimal energy efficiency concepts to meet the energy performance requirements of the building regulations. According to the results of this study, a cost-effective proposal for an energy performance target level of existing nearly zero-energy apartment buildings would be 130 kWh/(m^2,a), which is the minimum energy performance requirement level of new apartment buildings in Finland.

The cost-optimal energy performance improving measures presented in this study do not include any external financial support from the government or from any other source, excluding the solar-based electricity production system (PV-panels), where a 30 % financial support granted by the Finnish Ministry of Employment and the Economy is applied. The 30 % financial support from the total investment cost of the solar electricity system will be granted to any building, existing or new, considering the installation of the solar-based electricity production system in Finland. Possible other financial support and grants for different renovation measures would also effect the results of the optimisation analyses and the recommendable renovation measures, depending on the measure and on the amount of financial support. This would make the more expensive and extensive deep renovation measures, such as the additional thermal insulation of external walls or renovation of the ventilation system, more cost-effective and feasible.

When deep renovations are carried out, it is also important to recognise that the community fees will always be higher in the beginning of the loan period, which will increase the economic risks of the apartment owners and discourage the occupants from carrying out deep renovation measures.

If it is assumed that the studied case building represents the entire Finnish brick apartment building stock built in the 1960’s and all buildings of the building stock are facing a deep renovation with similar renovation and retrofitting demands as the studied case building in the initial situation, preliminary calculations indicate that up to 1.2 billion euros and 16.1 TWh of primary energy could be saved simultaneously in the Finnish brick apartment building stock alone over a 25-year life-cycle period in this scenario, if global optimum renovation solutions presented in this study were conducted. Or if similar assumptions were made from the maximum energy saving potential perspective, up to 27 TWh of primary energy could be saved over the same period of time without any increase in life-cycle cost. This would equal to 25 % potential savings in primary energy consumption and approximately 21 % potential financial savings in the 25-year life-cycle cost simultaneously. Or in the aforementioned maximum energy saving potential scenario, up to 42 % potential savings in primary energy consumption could be achieved during the 25-year life-cycle period without any increase in the LCC.

There are still interesting issues that remained to be resolved in future research. One key aspect is to determine competitive external financial solutions for apartment owners to conduct deep renovations that exceed the cost optimum level, as the main motivation of apartment owners to conduct energy performance improving measures is typically cost savings. To determine external financial solutions and support mechanisms would encourage apartment owners to conduct deep renovations to potentially meet the energy performance requirements of new low energy and nearly zero-energy apartment buildings by lowering the economic risks of the apartment owners. Furthermore, this study was outlined to focus on determining the cost-optimal energy efficiency measures for apartment owners from the primary energy consumption perspective by minimising the PE consumption in addition to the net present value of LCC. Future research is still required to study the effect of different energy performance improving measures on the CO_2-emissions perspective and to provide assessment of other commonly used environmental impact indicators. However, this study complements the existing body of literature and current knowledge regarding cost-effective renovation of apartment buildings by providing economically viable and technically feasible renovation measures and packages to meet different energy performance criteria according to the recast EPBD-directive as cost-effectively as possible.

Future research is also required to determine and compare the cost-optimal renovation measures from both the primary and the delivered target energy consumption perspectives in brick- and panel-structured apartment buildings located in different climate conditions, possibly by conducting similar analyses as presented in this study. In addition, the economic viability, technical feasibility, functionality and performance of modern renewable energy production systems in different climates and operating conditions still require further research and validation.

5. Conclusions

The studied brick apartment building represents a typical Finnish apartment building built in the first half of the 1960's. The objective was to study and determine the cost-optimal renovation measures to decrease both delivered and primary energy consumption of the building. The performance and cost optimality of the modern heat pump systems were also studied.

Results of the optimisation analysis indicated that the cost-optimal level for the renovation of Finnish brick apartment buildings was close to the minimum energy performance requirements of new apartment buildings (130 kWh/(m^2,a)). According to the results of this study, this energy performance target level could be proposed to a nearly zero-energy building target level for existing apartment buildings in Finland. This would mean a 10-15 % increase in the energy performance requirements of the building regulations compared to the current state.

According to the results, the heat pump systems deliver the best economic viability and the largest improvement in the energy performance of a brick apartment building, when energy efficiency and cost effectiveness are discussed. The ground source heat pump system proved to be the global cost optimum main heating system concept. However, both exhaust air and air-to-water heat pump system concepts also provided significant improvements in energy efficiency and cost-effectiveness. Furthermore, the solar-based energy production systems also proved to be cost-effective alternatives to improve the energy performance of the studied building. The PV-electricity production system was an especially recommendable measure with practically maximum installable panel area in every main heating system concept optimisation. According to this study, the renovation of the ventilation system and the additional thermal insulation of external walls are not cost-effective renovation measures, even though they provide significant energy efficiency improvements.

According to the study, the energy saving potential of HVAC and energy production systems is substantial compared to the energy saving potential of the building envelope. The studied renewable energy productions systems are economically viable and recommendable investments. The research method used in the study proved to be extremely effective and also versatile, as global optimum solutions cannot be determined by conventional methods, where a few individual energy efficiency measures or concepts are simulated and compared, as deep renovations of buildings typically include thousands or even millions of potential solution combinations. The results, conclusions and the recommended energy performance improving measures of this study can be generalised to similar climates and techno-economic environments, when deep renovations of brick apartment buildings are planned to be carried out.

Future research is still required to determine competitive financial solutions to encourage apartment owners to carry out deep renovations that improve the energy performance of apartment buildings beyond the cost optimum level by decreasing the economic risks of the apartment owners. Similar analyses are also needed for other apartment building types built in different decades, e.g. the panel-structured apartment buildings built in the late 1960’s and in the 1970’s and 1980’s. Cost-optimal renovation studies are also needed for different building types located in different climate conditions. Furthermore, further research and validation regarding economic viability, technical feasibility, functionality and performance in different operating conditions are also still needed for the modern and developing renewable energy production systems.

Acknowledgements

This study has been carried out as a spin-off project of the “Heat pumps in energy and cost efficient nearly zero energy buildings in Finland” -project. The study was financially supported by Tekes – the Finnish Funding Agency for Innovation and the following companies: Ensto, Fidelix, Gebwell, Mestariasunnot, Kaukomarkkinat, Suomen Lämpöpumpputekniikka, NIBE, Oilon, Rettig and Scanoffice. The Finnish Heat Pump Association SULPU and Green Net Finland also provided an important contribution to this study.

References

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

[2] Balaras, C.A., Droutsa, K., Argiriou, A.A., Asimakopoulos, D.N. Potential for energy conservation in apartment buildings. Energy and Buildings 31 (2000) 143-154.

[3] Koiv, T.-A., Toode, A. Heat energy and water consumption in apartment buildings. Proceedings of the Estonian Academy of Sciences. Engineering 7 (September (3)) (2001) 235, 7 pp.

[4] Martinot, E. Investments to Improve the Energy Efficiency of Existing Residential Buildings in Countries of the Former Soviet Union. Studies of Economies in Transformation No. 24. World Bank, Washington DC, 1997.

[5] Matrosov, Y. The experience of developing the complex of building energy standard for Russian Federation, in: Symposium on Indoor Air Quality and Building Physics. Symposium Materials, Tallinn Technical University, 2000.

[6] Paiho, S., Sepponen, M., Abdurafikov, R., Nystedt, A., Kouhia, I., Meinander, M., Hoang, M. Feasibility on upgrading Moscow apartment buildings for energy efficiency, in: 7th International Cold Climate HVAC Conference, Calgary, Alberta, Canada. 12-14 November, 2012, pp. 126-134.

[7] Kuusk, K., Kalamees, T. The analysis of renovation cost effectiveness of apartment buildings. Building Research & Information 00 (2015).

[8] 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).

[9] Häkämies, S., Jokisalo, J., Paiho, S., Hirvonen, J. State-of-the-art and developments of heat pumps and nZEB in Finland. IEA HPP Annex 40, 2014. 11th IEA Heat Pump Conference. Country report IEA HPP Annex 40 Task 1 Finland: State-of-the-Art Analysis of Nearly Zero Energy Buildings. Finland, 2014. Available at: http://www.annex40.net/fileadmin/user_upload/annex40.net/publications/HPC_NSERC_Annex40_WS_FI.pdf

[10] Häkämies, S., Hirvonen, J., Jokisalo, J., Knuuti, A., Kosonen, R., Niemelä, T., Paiho, S., Pulakka, S. Heat pumps in energy and cost efficient nearly zero energy buildings in Finland. Project HP4NZEB. VTT Technical Research Centre of Finland Ltd, Espoo, Finland, 2015. Available at: http://www.vtt.fi/inf/pdf/technology/2015/T235.pdf

[11] Atmaca, A. and Atmaca, N. Life cycle energy (LCEA) and carbon dioxide emissions (LCCO$_2$A) assessment of two residential buildings in Gaziantep, Turkey. Energy and Buildings 102 (2015): 417–431.

[12] Atmaca, A. and Atmaca, N. Comparative life cycle energy and cost analysis of post-disaster temporary housings. Applied Energy 171 (2016): 429–443.

[13] Atmaca, A. Life cycle assessment and cost analysis of residential buildings in south east of Turkey: part 1 – review and methodology. The International Journal of Life Cycle Assessment, 21 (6) (2016): 831–846.

[14] Atmaca, A. Life cycle assessment and cost analysis of residential buildings in South East of Turkey: part 2 – a case study. The International Journal of Life Cycle Assessment, (2016). DOI: 10.1007/s11367-016-1051-7.

[15] Paiho, S., Hedman, Å., Abdurafikov, R., Hoang, H., Sepponen, M., Kouhia, I., Meinander, M. Energy saving potentials of Moscow apartment buildings in residential districts. Energy and Buildings 66 (2013), pp. 706–713.

[16] Csoknyai, T., Hrabovszky-Horváth, S., Georgiev, Z., Jovanovic-Popovic, M., Stankovic, B., Villatoro, O., Szendrö, G. Building stock characteristics and energy performance of residential buildings in Eastern-European countries. Energy and Buildings (2016). DOI: 10.1016/j.enbuild.2016.06.062.

[17] Bonakdar, F., Dodoo, A., Gustavsson, L. Cost-optimum analysis of building fabric renovation in a Swedish multi-story residential building. Energy and Buildings 84 (2014), pp. 662–673.

[18] Kuusk, K., Kalamees, T. nZEB Retrofit of a Concrete Large Panel Apartment Building. Energy Procedia 78 (2015), pp. 985–990.

[19] Paiho, S., Hoang, H., Hedman, Å., Abdurafikov, R., Sepponen, M., Meinander, M. Energy and emission analyses of renovation scenarios of a Moscow residential district. Energy and Buildings 76 (2014), pp. 402–413.

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

[21] Palonen, M., Hamdy, M., Hasan, A. MOBO a new software for multi-objective building performance optimization. Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28. Aalto University and VTT Technical Research Centre of Finland, Espoo, Finland, 2013. Available at: http://www.ibpsa.org/proceedings/BS2013/p_1489.pdf

[22] Nguyen, A-T., Reiter, S., Rigo, P. A review on simulation-based optimization methods applied to building performance analysis. Applied Energy 113 (2014): 1043–1058.

[23] Statistics Finland. The statistics of accommodation in Finland, 2011. Available at: http://pxweb2.stat.fi/database/StatFin/databasetree_fi.asp (in Finnish)

[24] Helsingin Energia. The statistics of specific heat energy consumption of building stocks built in different decades that are connected to the Helsingin Energia's district heating network. Helsinki, 2007. Available at: http://www.omataloyhtio.fi/artikkelit/7091/tiilirakenne_on_energiateknisesti.htm%20-%20.VJ038F4ilI (in Finnish)

[25] Mäkiö, E., Malinen, M., Neuvonen, P., Vikström, K., Mäenpää, R., Saarenpää, J., Tähti, E. Apartment Buildings 1960–1975. Rakennustietosäätiö RTS, Rakennustieto Oy, Helsinki. Tammer-Paino Oy 1994, Tampere. ISBN 951-682-279-7. (in Finnish)

[26] Neuvonen, P. Apartment Buildings 1880-2000: Architecture, construction technology, renovation. Rakennustietosäätiö RTS, Rakennustekniikan keskus -säätiö ja Museovirasto. Tammer-Paino Oy 2006, Tampere. ISBN 978-951-682-794-3. (in Finnish)

[27] NBCF, National Building Code of Finland. Part D3, Energy management in buildings, regulations and guidelines 2012. Ministry of the Environment, Helsinki. Available at: http://www.finlex.fi/data/normit/37188-D3-2012_Suomi.pdf (in Finnish)

[28] Peel M, Finlayson B, McMahon T. Updated world map of the Köpper–Geiger climate classification. Hydrology and Earth System Science Discussions 2007: 439–72.

[29] National Building Code of Finland. Part D5, Calculation of power and energy needs for heating of buildings, guidelines 2012. Ministry of the Environment, Helsinki. Available at: http://www.finlex.fi/data/normit/41189-D5-17-5-2013-final-su.pdf

[30] Kalamees, T., Jylhä, K., Tietäväinen, H., Jokisalo, J., Ilomets, S., Hyvönen, R., Saku, S. Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. Energy and Buildings 47 (2012): 53–60.

[31] Holopainen, R., Hekkanen, M., Hemmilä, K., Norvasuo, M. The energy performance renovation measures and saving potentials of Finnish buildings. VTT Technical Research Centre of Finland 2007, Espoo, Finland. ISBN 978-951-38-6908-3. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2007/T2377.pdf

[32] Kouhia, I., Nieminen, J., Pulakka, S. The energy renovations of the building’s envelope. VTT Research Report VTT-R-04017-10. VTT Technical Research Centre of Finland 2010, Espoo, Finland. Available at: http://www.vtt.fi/inf/julkaisut/muut/2010/VTT-R-04017-10.pdf

[33] Häkkinen, T., Ruuska, A., Vares, S., Pulakka, S., Kouhia, I., Holopainen, R. Methods and concepts for sustainable renovation of buildings. VTT Technical Research Centre of Finland 2012, Espoo, Finland. ISBN 978-951-38-7841-2. Available at: http://www.vtt.fi/inf/pdf/technology/2012/T26.pdf

[34] Vainio, T., Airaksinen, M., Saari, A., Hasan, A., Vihola, J., Heljo, J., Jokisalo, J., Sirén, K., Pulakka, S., Nissinen, K., Möttönen, V., Vuolle, M., Niemelä, J., Kalliomäki, P., Kauppinen J., Haakana, M. Calculation of cost-optimal levels of minimum energy performance requirements. The notice to the European Commission according to the Energy Performance of Buildings Directive (2010/31/EC) Article 5.
Available at: http://ec.europa.eu/energy/efficiency/buildings/implementation_en.htm

[35] Niemelä, T. Cost Optimal Renovation Solutions in the 1960s Apartment Buildings. Master’s Thesis. Aalto University, School of Engineering, Department of Energy Technology, HVAC 2015, Espoo, Finland. Available at: https://aaltodoc.aalto.fi/handle/123456789/15959

[36] FInZEB project. FInZEB project life-cycle cost calculations for apartment and office buildings. FInZEB project, Optiplan Oy 2014, Helsinki, Finland. Available at FInZEB project’s homepage: http://finzeb.fi/wp-content/uploads/2014/11/FinZEB_kustannusten-muodostuminen_asuinkerrostalo-ja-toimisto.pdf

[37] Decree on Improving Energy Performance in Renovations 2013/4. Helsinki 2013: Ministry of the Environment. Available at: http://www.ym.fi/download/noname/%7B924394EF-BED0-42F2-9AD2-5BE3036A6EAD%7D/31396

[38] Decree on EPC 2013. Helsinki, Finland 2013: Ministry of the Environment.
Available at: http://www.ym.fi/download/noname/%7B27BAFE2B-E645-4464-AFB8-CBFB162B5ADC%7D/31591

[39] FInZEB project. The final report and the appendix 1 of the FInZEB project. FInZEB project, Granlund Oy 2015, Helsinki, Finland. Available at: http://finzeb.fi/wp-content/uploads/2015/04/FInZEB_loppuraportti.pdf

[40] Ministry of the Environment. Nearly Zero-Energy Buildings, timetable for the implementation of the EPBD 2010/31/EU -directive. Helsinki, Finland 2015: Ministry of the Environment 2015. Available at: http://www.ym.fi/download/noname/%7BAB94FA45-537C-4264-A5CF-81BD5AA33C37%7D/108422

[41] Sahlin, P. Modelling and Simulation Methods for Modular Continuous Systems in Buildings. Doctoral Dissertation. Department of Building Sciences, Division of Building Services Engineering, Royal Institute of Technology 1996, Stockholm, Sweden. ISSN 0284-141X. Available at: http://www.equa.se/dncenter/thesis.pdf

[42] Björsell, N., Bring, A., Eriksson, L., Grozman, P., Lindgren, M., Sahlin, P., Shapovalov, A., Vuolle, M. IDA indoor climate and energy 1999, Proceedings of the IBPSA Building Simulation ‘99 conference, Kyoto, Japan.

[43] Moinard, S. and Guyon, G., editors. Empirical validation of EDF ETNA and GENEC test-cell models. Subtask A.3. A Report of IEA Task 22. Building Energy Analysis Tools, 1999.

[44] Travesi, J., Maxwell, G., Klaassen, C., Holtz, M. Empirical validation of Iowa energy resource station building energy analysis simulation models. IEA Task 22, Subtask A, 2001.

[45] Achermann, M., Zweifel, G. RADTEST – Radiant heating and cooling test cases. Subtask C. A Report of IEA Task 22. Building Energy Analysis Tools, 2003.

[46] Kropf, S. and Zweifel, G. Validation of the building simulation program IDA-ICE according to CEN 13791 'Thermal performance of buildings – calculation of internal temperatures of a room in summer without mechanical cooling – general criteria and validation procedures', Luzern, 2001.

[47] Loutzenhiser, P., Manz, H., Maxwell, G. Empirical Validations of Shading / Daylighting / load Interactions in building energy simulation tools, A Report for the International Energy Agency SHC Task 34, ECBCS Annex 43 Project C, 2007.

[48] Niemelä T, Vuolle M, Kosonen R, Jokisalo J, Salmi W, Nisula M. Dynamic simulation methods of heat pump systems as a part of dynamic energy simulation of buildings, In: Proceedings of BSO2016: 3th conference of international building performance simulation association England, Newcastle, England, September 12–14, 2016. Paper number 1146.

[49] Vantaan Energia Oy. Vantaan Energia Oy's online district heating and electricity price list, November 2014. Available online at: http://www.vantaanenergia.fi/lampo/hinnastot-ja-ehdot/

[50] Energia 247 Oy. Energia 247 Oy's online electricity price list, November 2014. Available online at: https://www.energia247.fi/tuotteet