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Energy performance and environmental impact analysis of cost-optimal renovation solutions of large panel apartment buildings in Finland

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Abstract

The paper presents energy performance and environmental impact analysis of cost-optimal renovation solutions conducted in deep renovations of typical large panel-structured apartment buildings located in cold climate conditions. The main objective of the study was to determine the cost-optimal renovation concepts from both the primary energy performance and the total CO_2 emission reduction potential perspectives. The cost-optimal solutions for different main heating systems were determined from over 220 million renovation combinations by using a simulation-based multi-objective optimization (SBMOO) analysis as the main research method. The results demonstrate that the proposed national nearly zero-energy apartment building level can be cost-effectively achieved in deep renovations of large panel apartment buildings, delivering approximately 18-36% return on investment. The results also indicate that up to 90-98 €/m^2 net savings, 850-930 kWh/m^2 reduction in the primary energy consumption and 350-390 kg/m^2 reduction in the total CO_2 emissions over the studied 30-year life-cycle period can be achieved simultaneously, when the cost-optimal renovation concepts are selected. Cost-optimally dimensioned heat pump systems deliver significant cost saving and environmental impact reduction potential compared to improving the energy efficiency of the building envelope, as the delivered energy consumption accounts for more than 90% of the total CO_2 emissions.

Keywords – cost-optimal renovation concept; energy performance; greenhouse gas emissions; multi-objective optimization; renewable energy source; primary energy; large panel apartment building

1. Introduction

Several recent studies conducted by Balaras et al. (2005), Kuusk & Kalamees (2015), Kuusk et al. (2016 and 2014) have concluded that the energy and emission saving potential of existing buildings is significant compared to the corresponding potential of new buildings with increasing energy and material efficiency, as the average annual renewal rate of the existing building stock is typically just 1–2 % [1-4]. In addition, recent studies conducted by Kuusk & Kalamees (2015) and Economidou et al. (2011) indicate that the existing residential buildings are the largest single building stock in the EU area with approximately 75 % share of all existing buildings [2,5].

According to the similar findings of several recent studies related to renovation and refurbishment of residential apartment buildings, concrete large panel-structured apartment buildings built between the 1960's and 1990's are the most common apartment building type with significant energy saving potential in many European countries, e.g. the Scandinavian countries, Estonia, Russia and numerous Eastern and Northern European countries [1-3,6-9]. Balaras et al. (2005 and 2000), Kuusk & Kalamees (2015), Kuusk et al. (2016) and Bonakdar et al. (2014) all conclude that apartment buildings built during this era are generally now requiring major renovation and retrofitting measures for both the building envelope and for the technical systems of the buildings [1-3,8,9]. The recast Energy Performance of Buildings -directive (EPBD) has come into force to set improved energy performance requirements and standards in both new and existing buildings for European Union member states [10]. However, studies conducted by Kuusk & Kalamees (2015), Kuusk et al. (2016 and 2014), Csoknyai et al. (2016), Bonakdar et al. (2014) and Balaras et al. (2000) all include similar findings that regardless of the tightened member state-specific energy performance requirements and the EU 2020 targets to reduce both energy consumption and greenhouse gas (GHG) emissions, building owners and occupants are typically motivated to conduct major energy efficiency improving measures, in addition to the minimum mandatory maintenance repairs, in deep renovations only to achieve reasonable energy cost savings with reasonable investment payback period [2-4,7-9]. The findings of the aforementioned studies and a study conducted by Nemry et al. (2010) all indicate that individual renovation measures or renovation package concepts with low or even negative return on investment are difficult to be justified for apartment building owners, regardless of the improvements in energy performance or the reduction in GHG emissions [2-4,7-9,11]. The recast EPBD-directive also encourages to improve the energy performance of existing buildings with technically and economically viable renovation solutions and to utilize renewable energy sources (RES), when they are reasonable to be used [10].

Kuusk & Kalamees (2015), Kuusk et al. (2016), Paiho et al. (2013, 2014 and 2015), Bonakdar et al. (2014), Balaras et al. (2000), Nemry et al. (2010) and Kuusk & Kalamees (2015) have conducted studies to determine the energy performance improving potential and the economic viability of different renovation measures that can be applied in concrete panel-structured apartment buildings located in different climate conditions [2,3,6,8,9,11-14]. However, the aforementioned studies have mainly focused on individual renovation measures or renovation packages regarding the building envelope, the ventilation systems of the buildings and individual renewable energy production systems, such as solar thermal collectors or PV-panel systems. Large-scale studies, where all of the applicable renovation measures, including modern heat pump systems, are studied simultaneously to determine the global cost optimum combination of measures from the energy performance and environmental impact perspectives have not been previously conducted. In addition to the methodology, research perspective and key findings of the aforementioned studies, Atmaca (2015-2016) has recently conducted several studies related to energy performance, life-cycle cost analysis and environmental impact reduction potential of residential buildings located in Turkey [15-18]. A common aspect related to all of the aforementioned studies is that they have focused on individual renovation measures or determined the GHG emissions and environmental impact for specific predefined cases or for specific energy efficiency target levels, such as a minimum requirement level or a proposed nearly zero-energy building (nZEB) level, in new and existing apartment buildings [2,3,6,8,9,11-18].

Niemelä et al. (2016 and 2017) and Häkämies et al. (2014 and 2015) have also studied the performance and economic viability of different heat pump systems as an individual energy performance improving measure in residential buildings located in cold climate conditions [19-22]. All of these studies present similar conclusions indicating that the heat pump systems are profitable investments in many cases, when dimensioned optimally according to the auxiliary heating system used with the heat pump system [19-22]. However, further research is still needed for optimum dimensioning of different heat pump systems, when they are combined with other energy efficiency improving measures and especially for different renovation scenarios applied in different building types with building type-specific main features, e.g. large panel-structured apartment buildings with radiator heating systems and with various façade, building envelope and technical system refurbishment and retrofitting demands. Niemelä et al. (2016 and 2017) and Kuusk et al. (2014) present similar findings in recent studies related to renovation of existing apartment and educational buildings indicating that an energy performance improving renovation of the building envelope is typically not economically viable in brick-structured buildings, if the investment can be used in other more profitable measures, such as applicable heat pump or solar energy systems, at the same time [4,19,20].

However, it is essential to notice that the condition of the outer concrete layer of the panel elements determines the minimum maintenance need in concrete panel apartment buildings. If the outer concrete layer is highly carbonated, this results in the corrosion of the reinforcement structures due to neutralization of concrete and in this case the outer concrete layer is typically demolished along with the original thermal insulation and new thermal insulation and outer layers are installed. Additional thermal insulation is often not applied and it is also not profitable in typical situations, where the outer concrete layer doesn't have to be demolished. The research perspective to determine the cost optimum combination of renovation measures is different in situations, where the outer layer and the original thermal insulation are demolished and renewed. When modern heat pump systems and other RES are compared to additional thermal insulation of external walls, replacement of windows and other more commonly applied renovation measures in this initial situation, there are typically millions of potential renovation combinations. Determining the global optimum renovation concepts for different main heating systems that can be applied in existing residential apartment buildings, from both the energy performance and overall environmental impact perspectives, is impossible without using a modern and sophisticated research method, such as a simulation-based multi-objective optimization analysis. Furthermore, the determined solutions must be technically feasible and functional, e.g. moisture behavior in external walls with thick thermal insulation layers and various climate conditions etc., which must also be taken into account in the analysis in addition to the economic and energy saving aspects.

Extensive literature reviews regarding life-cycle and CO_2-emission assessments conducted by Atmaca (2015-2016) indicate that there are a limited number of studies related to life-cycle assessment (LCA) of residential buildings and that the more detailed emission analyzes have typically focused mainly on new buildings with various life-cycle assessment periods [15-18]. Furthermore, a common conclusion in Atmaca's (2015-2016) previous studies is that the operation phase of a residential building's life-cycle covers up to 50–95 % of the total energy use and GHG emissions, depending on the climate conditions, energy production technologies and life-cycle period used in the analysis [15-18]. The share of the operation phase from the total energy use and GHG emissions is even more dominant in typical LCC analyzes, where an existing building is cost-effectively renovated and a typically selected life-cycle period of 20-30 years is used in the analysis.

The literature review regarding renovation of existing panel-structured apartment buildings indicates that large-scale studies where all realizable renovation measures are studied simultaneously in order to determine the global optimum renovation solutions from both the energy performance and GHG emission perspectives have not been conducted previously [1-3,6-9,11-19]. Furthermore, the literature review also indicates that there are a limited number of studies regarding the utilization of modern heat pump and other renewable energy production technologies as a part of deep renovation of panel-structured apartment buildings located in cold climate conditions, especially where the economic viability and energy performance of the modern RES-based technologies are compared to the more traditional renovation measures regarding the building envelope and other technical systems of the building [1-3,6-9,11-19]. Furthermore, the previous studies related to renovation of apartment buildings have been conducted by using more conventional research methods that are typically always limited to the total number of predefined cases and renovation measures that can be studied.

The main conclusions, findings and limitations of the previous studies regarding the cost-optimal renovation solutions to reduce both the total primary energy use and the environmental impact of existing concrete panel-structured apartment buildings highlight the importance of this paper. As the cost-effective renovation of existing concrete panel-structured residential buildings built during the industrialization period between the 1960's and the 1990's plays a major role to achieve the EU 2020 targets in many countries, cost-optimal renovation concepts, including all applicable renovation measures, with maximum return on investment are needed to encourage apartment building owners to conduct deep renovations including optimal measures to improve the energy efficiency and to reduce the environmental impact of apartment buildings in addition to just conducting the mandatory minimum measures that are needed to operate the building sufficiently.

This study aims to provide economically viable overall renovation solutions for concrete panel-structured apartment buildings located in cold climate by conducting LCC and GHG emission analyzes, where all realizable and applicable measures that can be conducted in the aforementioned building type are studied at the same time. Cost-optimal renovation solutions and their economic viability to meet the proposed national nearly zero-energy (nZEB) apartment building level are also studied and compared to the global optimum solutions of the deep renovation. Furthermore, the study provides a practical research perspective, where the functionality and technical feasibility of the studied measures are carefully evaluated and only technically feasible and functional renovation measures that can be generalized to a large proportion of concrete panel-structured apartment buildings, e.g. the typically used renovation alternatives of the building envelope to provide functional building physical operation, built in cold climates are selected in the analyzes. The aims of this study are:

- to determine cost-optimal deep renovation concepts to maximize the primary energy performance of large panel-structured apartment buildings located in cold climate conditions (analysis 1);
- to determine cost-optimal deep renovation concepts from the total CO_2 emissions perspective, to maximize the environmental impact reduction potential of deep renovations of the studied building type (analysis 2);
- to study the economic viability of the cost-optimal renovation solutions to reach the proposed national nearly zero-energy apartment building requirements (analysis 1);

- to study the effect of different future energy price development scenarios on the cost-optimal deep renovation concepts (analysis 2);
- to study the impact of different CO_2 emission sources, such as embodied CO_2 emissions of construction materials, transportation and delivered energy consumption, on the total CO_2 emissions over a 30-year life-cycle period.

2. Methods

2.1. Case study building

2.1.1 Criteria of case building and main renovation concept design selection

A large panel apartment building located in Kerava, Finland was selected as the studied case building. The selected case building represents a typical panel apartment building built from the late 1960's to the mid 1970's and it is the largest apartment building stock in Finland, as the prefabricated concrete panel production generalized rapidly due to the industrialization during this era. Furthermore, previous studies indicate that the selected apartment building type is the most common multi-family building type in many other European countries located in cold and intermediate climates as well [1-3,6-9]. Generally this building stock also requires considerable renovation measures in the near future and has a significant environmental impact reduction potential, simply due to the age, general condition, energy efficiency and overall solutions conducted in apartment buildings built during this era [1-3,6-9]. The share of the Finnish apartment building stock according to the construction year, total number of buildings and total built floor area is shown in Fig. 1 [23].

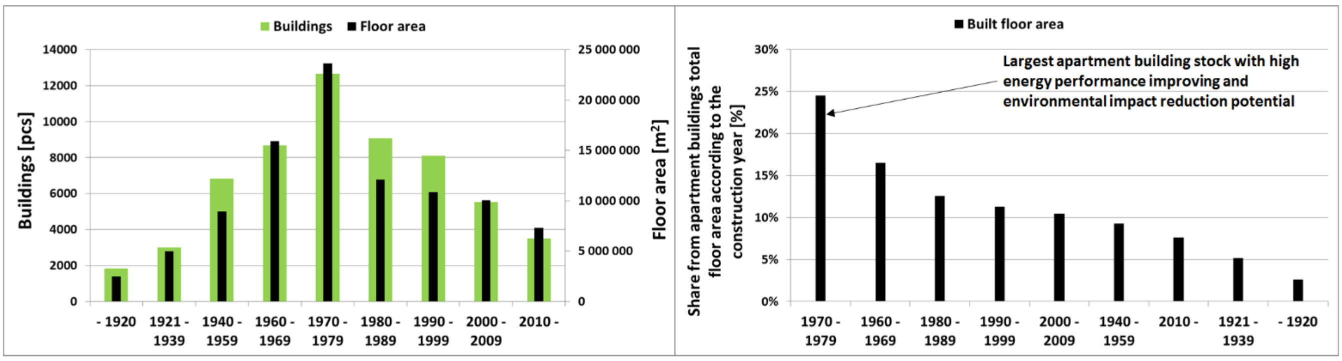

Fig. 1. The built floor area and number of apartment buildings (left) and the share of apartment buildings by the built floor area according to the construction year (right) [23].

A deep renovation process of the case building is studied and the building is in its original condition in the beginning of the analysis. However, to provide as useful and up to date renovation scenarios that can also be used in other cold climate apartment building renovation studies as extensively as possible, the most commonly used refurbishment method of external walls that is applied in Finnish panel-structured apartment buildings, when quality and longevity of the renovation are discussed, is selected to be used as the base concept of the analysis. The detailed survey carried out before the study indicated that the external concrete layer and the original thermal insulation are typically demolished, when the outer concrete layer is showing signs of carbonization, to ensure the best possible quality and longevity for the renovation. Other commonly used and also more cost-effective measure is to install additional thermal insulation on top of the original outer concrete layer to reduce the carbonization process and to stop the potential corrosion of the reinforcement structures. However, the conducted survey indicated that majority of the renovations are conducted by using the demolishing alternative for quality insurance reasons, even though the non-demolishing alternative is more cost-effective, especially when a relatively long but typically used life-cycle period of 20…35 years for the deep renovation process is discussed.

Another disadvantage of the non-demolishing refurbishment alternative is that the windows will be left relatively deep into the external walls structure, if the original wall construction becomes thicker due to the installation of additional thermal insulation and a new outer layer, e.g. a tile or a basic plastering structure, on top of the original concrete outer layer and if the windows are not moved outwards simultaneously with the installation of the additional thermal insulation. In this study, the original windows were supported and left into their original location in cases, where the windows were not replaced. In this scenario, the depth of the outer surface of the original windows is 60…200 mm from the outer surface of the renovated external walls, depending on the selected thermal insulation thickness. In cases where the original windows are replaced with new windows, the windows were installed to their new location in the renovated external walls using a 100 mm recess depth.

2.1.2 Main geometry and structure details

The case apartment building has 5 floors including a base floor and 4 apartment floors. The case building's heated net floor area is 2 898 m^2 resulting to the heated volume of 7 952 m^3. The floor layout of the apartment floors and the geometry of the building are shown in Fig. 2.

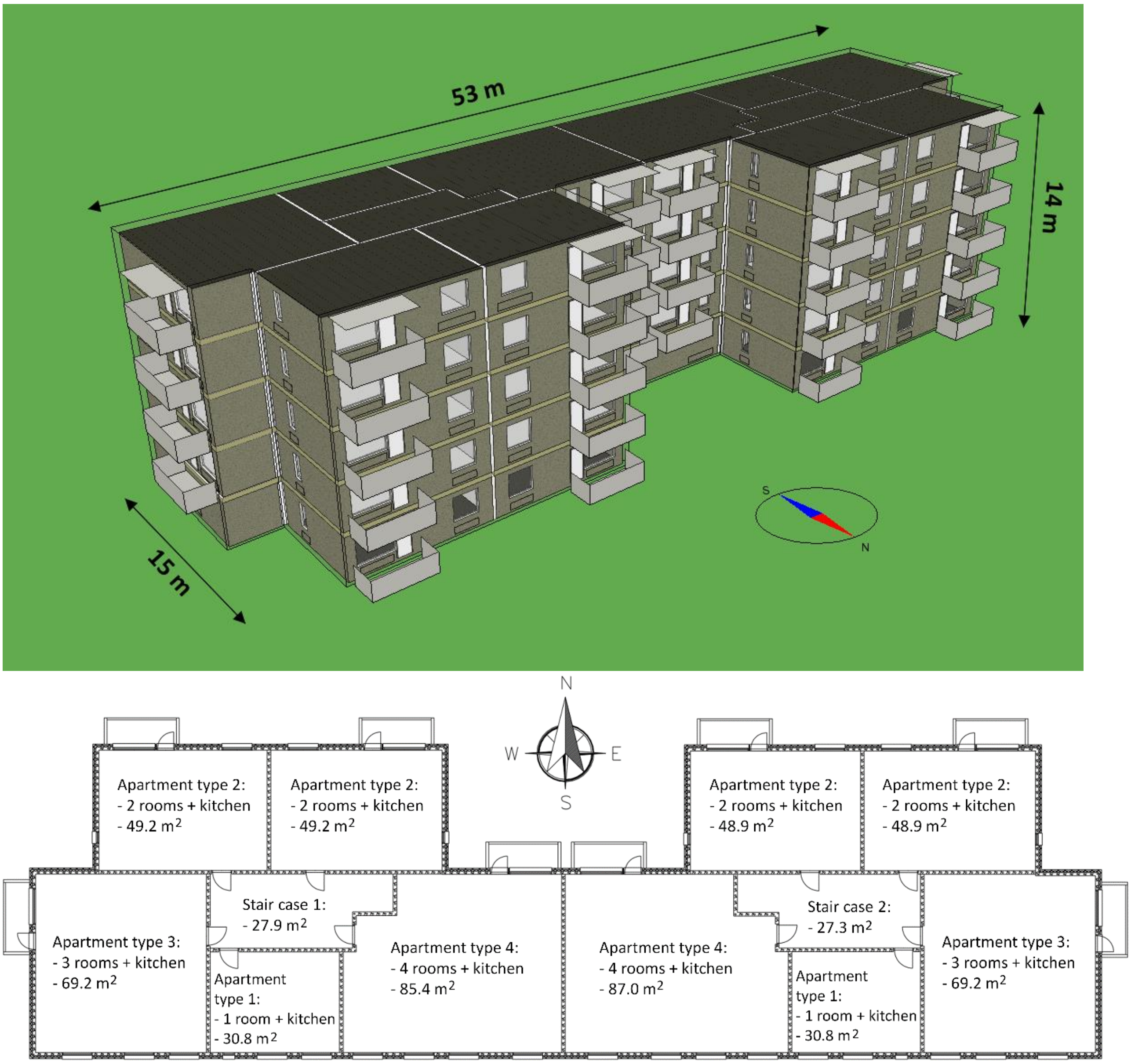

Fig. 2. The floor layout of the apartment floors (below) and the geometry of the studied case building (above).

The basic structure details of external walls and roof according to the selected renovation methods are shown in Fig. 3 with the new and existing structure layers. The shown structure types are also used to determine the embodied energy and CO_2-emission data in the simulation-based optimization analysis, according to the selected structure types and thermal insulation thicknesses of the renovation measures regarding the building envelope. In addition, the thermal transmittances of external structures in the original condition before the renovation are shown in Table 1.

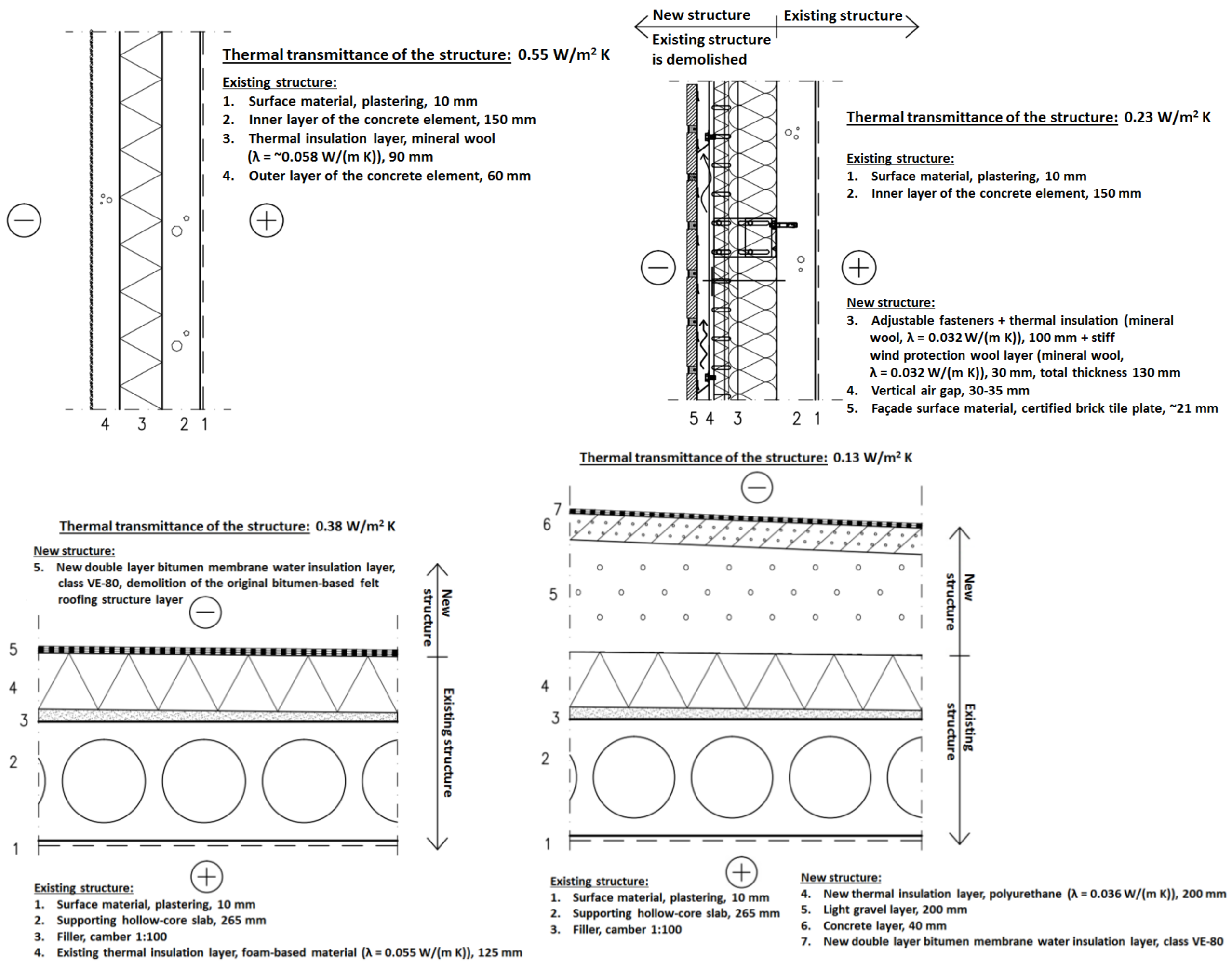

Fig. 3. The structure details of original (above left) and renovated (above right) external walls and the basic refurbishment (below left) and renovated (below right) roof with additional thermal insulation according to the selected renovation methods with the new and existing structure layers presented.

Table 1. The thermal transmittances of external structures.

External structures and air-tightness		
Thermal transmittance of external walls, [W/m^{2}K]	0.55	
Thermal transmittance of roof, [W/m^{2}K]	0.38	
Thermal transmittance of base floor, connected to the ground, [W/m^{2}K]	0.44	
Thermal transmittance of windows, 2-pane structure, [W/m^{2}K]	2.1	g-value: 0.70 ST-value 0.63 Depth of frame: 170 mm
Integrated window shading		Blinds between panes
Thermal transmittance of external doors, [W/m^{2}K]	2.2	
Air-tightness of the building, the q_{50}-value	6.00 m^3/(m^2 h)	According to the Decree for the EPC (176/2013) [24]

2.1.3 Building services systems

The main building services systems of the case building are shown in Table 2. The data shown corresponds to the original state of the building before the studied deep renovation measures with integrated energy efficiency improvements are conducted. There are a total of two individual simulation-based optimization analyzes conducted in the study. The first one was conducted to determine the optimal measures from the primary energy consumption's perspective and the second one from the delivered energy consumption's perspective, which represents the estimated real use of the studied case building. The main differences in the building services systems between these two analyzes are shown in Table 2. The conducted analyzes 1 and 2 are described in more detail in chapter 2.2.

Table 2. The building services systems of the case apartment building.

Building services systems	
Analysis 1: Calculation of PE consumption according to the standardized use of the building (NBCF D3 (2012))	
Ventilation system	Mechanical exhaust ventilation system, no heat recovery system
Operation schedule of the ventilation system	Monday-Sunday, 24 h/day, ventilation system is always on
Exhaust air flow rate	0.5 $dm^3/(s, m^2)$, constant air volume (CAV) system
The specific fan power of the ventilation system (SFP-value)	1.50 $kW/(m^3/s)$
Heat distribution system	Hydronic radiator heating system
Dimensioning temperatures of the heat distribution system	80/60 °C
Room temperature set point for heating	21.0 °C (all room spaces)
Space heating control system	Supply water temperature control according to the outdoor temperature
Domestic hot water (DHW) consumption	0.5 $m^3/(m^2,a)$
DHW circulation system	58/55 °C (designing temperatures) 0.11 dm^3/s (designing water flow rate)
Analysis 2: Calculation of delivered target energy consumption according to the actual use of the case building	
Exhaust air flow rate	0.4 $dm^3/(s, m^2)$, CAV system
Room temperature set point for heating	21.0 °C (apartments), 18.0 °C (stair cases and base floor spaces)
DHW consumption	50 dm^3/(occupant per day), total number of occupants in the building is 88
Other building services systems and design values	The same as in the analysis 1

2.1.4 Internal gains and profiles

Table 3 shows the internal gains from occupants, household equipment and lighting that were used in the dynamic energy simulations of the SBO analyzes conducted in the study. Furthermore, the average occupancy and usage profiles of the internal gains used in the first SBO analysis are also shown in Table 3. The standardized specific internal gains according to the National Building Code of Finland (NBCF) part D3 (2012) were used in the first SBO analysis (see Table 3), where the energy performance improving measures were assessed from the primary energy consumption's perspective, as the PE consumption of buildings must be calculated according to the NBCF part D3 (2012) in Finland [25].

The second SBO analysis consists of a little different specific internal gains and usage profiles, which were selected according to the actual use of the case apartment building after the initial survey conducted prior to the study. The second SBO analysis was conducted to determine the CO_2-emissions of a selected life-cycle period according to the actual use and estimated delivered energy consumption of the case building. The internal gains of the second SBO analysis are shown in Table 3 and the occupancy and usage profiles in Fig. 4, respectively. They were determined to represent the actual real use of the case building more accurately than the internal gains and simplified profiles of the NBCF part D3 (2012).

Table 3. The internal gains for dynamic energy simulations from occupants, lighting and household equipment.

Internal heat gains from occupants, lighting and household equipment	
Analysis 1: Calculation of PE consumption according to the standardized use of the building (NBCF D3 (2012))	
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, internal gain from occupants equals to 15.8 kWh/(m^2,a) with an average occupancy rate of 0.6
Lighting	Average gain 11.0 W/m^2, internal gain from lighting equals to 9.6 kWh/(m^2,a) with an average usage rate of 0.1
Household equipment	Average gain 4.0 W/m^2, internal gain from household equipment equals to 21.0 kWh/(m^2,a) with an average usage rate of 0.6
Analysis 2: Calculation of delivered target energy consumption according to the actual use of the case building	
Occupants	Average sensible gain 3.0 W/m^2 (only in apartments), which equals to 1 occupant per 28 m^2 with activity level of 1.2 met, internal gain from occupants equals to 15.3 kWh/(m^2,a) with an average occupancy profile shown in Fig. 4
Lighting	Average gain 3.5 W/m^2 in apartments and 11.0 W/m^2 in stair cases and equivalent spaces, internal gain from lighting equals to 9.4 kWh/(m^2,a) in apartments and 24.1 kWh/(m^2,a) in stair cases and equivalent spaces with the average usage profiles shown in Fig. 4
Household equipment	Average gain 9.0 W/m^2 (only in apartments), internal gain from household equipment equals to 29.8 kWh/(m^2,a) with an average usage profile shown in Fig. 4

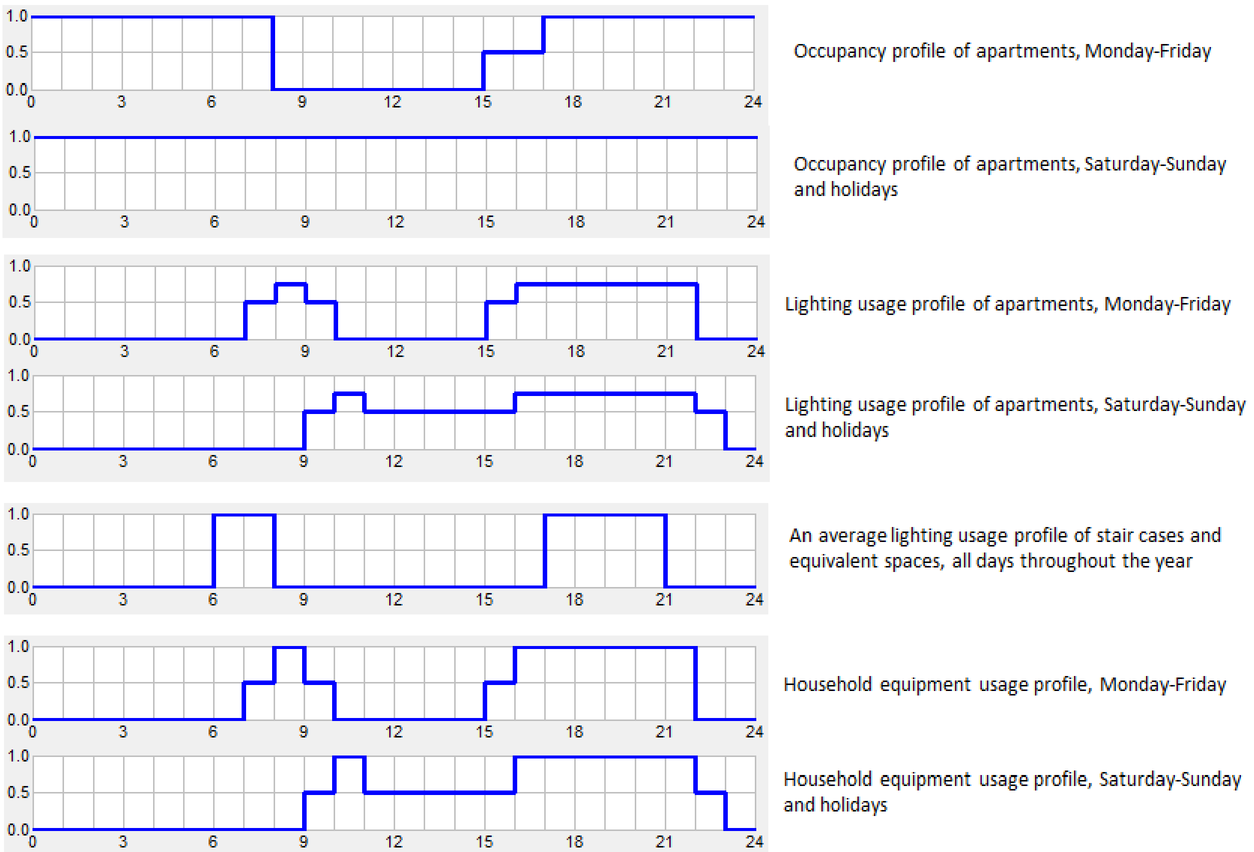

Fig. 4. The occupancy and usage profiles used in the dynamic energy simulations of delivered energy consumption in optimization analysis 2. The hours of the day are shown on the x-axis and the occupancy or usage rate is shown on the y-axis (0 = 0 % occupancy or usage rate, 1 = 100 % occupancy or usage rate).

2.1.5 Weather data and indoor climate conditions

Finland is classified into cold climate zone according to the Köppen-Geiger climate classification and also into four individual country-specific climate zones (I-IV) according to the NBCF [25,26]. Kerava is located in the Southern Finland

and belongs to the climate zone I [25,27]. The updated test reference year 2012 (TRY2012) weather data of zone I, which must also be used for all calculations of PE consumption to classify and compare the energy efficiency of buildings according to the NBCF part D3 (2012) in Finland [25], was used for the both SBO analyzes 1 and 2 conducted in the study. For comparison of the main climate condition features of similar studies conducted in different climates, the average annual ambient temperature of the used weather data is +5.6 °C and the annual degree day number S17 is 3 952 Kd. Further details of the used weather data are presented in a recent study conducted by Kalamees et al. (2012) [27].

The dynamic energy simulations of the study were conducted so that the indoor climate conditions before and after the deep renovation fulfill the minimum indoor climate requirements of the current Finnish building regulations regarding residential apartment buildings. At the minimum requirement level, the indoor air temperature of apartments is approximately 21…22 °C during the heating season and the CO_2 concentration of the indoor air of apartments is less than 1000 ppm at all times. The survey conducted prior to the study indicated that the indoor thermal conditions of the original Finnish large-panel apartment buildings built during the 1970's are approximately at the selected level during the heating season and in some cases the indoor air temperatures of apartments are even higher than the recommended temperature level of 21…22 °C.

2.1.6 Studied measures and cost data

Simulation-based multi-objective optimization (SBMOO) analysis was used as the main research method in the study. The optimized measures, which are studied in the SBO analysis are shown in Table 4. All applicable measures, such as commonly applied measures regarding the building envelope and also modern renewable energy production technologies, were taken into account to provide as detailed and versatile results as possible. Main heating system-specific concepts were studied (see Table 4) to provide cost-efficient renovation packages to meet different energy efficiency targets for buildings equipped with different main heating systems. The total number of renovation combinations included in both the PE consumption (analysis 1) and the combined delivered energy consumption and CO_2 emission (analysis 2) analyzes is shown in Table 4. Table 5 shows the construction costs related to the studied measures [28]. The current 24 % Finnish VAT is excluded from the cost data shown in Table 5.

Table 4. Studied measures (design variables) and energy production systems.

Air-to-water heat pump system, A2WHP concept	Min. measure	Max. measure	Variable

- Dimensioning power output of the heat pump system, kW	10	150	Continuous
- Dimensioning of solar-based electricity system, area of PV-panels, m^2	0	130	Continuous
- Renovation of the ventilation system, 6 alternative methods: - original exhaust air ventilation system is preserved for entire building - centralized ventilation system with heat recovery for apartments - centralized ventilation system with heat recovery for base floor spaces - distributed ventilation system with heat recovery for apartments - distributed ventilation system with heat recovery for base floor spaces - centralized ventilation system with heat recovery for entire building	No renovation	Centralized for entire building	Discrete, 6 options
- Thermal insulation thickness of external walls shown in Fig. 3, mm	80	300	Discrete, 8 options
- Additional thermal insulation thickness of roof shown in Fig. 3 or just the basic refurbishment (renewal of the water insulation layer), mm	0, basic refurbishment	400	Discrete, 10 options
- Renovation of windows by using the following alternative methods: - original windows are repaired, painted and re-sealed, the windows are also supported to the inner concrete layer of the original external walls due to the selected renovation method of ext. walls (see Fig. 3) - original windows are removed and new windows are installed with the thermal transmittance of 1.0, 0.8, 0.7 or 0.6 W/(m^2 K)	Repair, original	New, 0.6 W/(m^2 K)	Discrete, 5 options
- Renovation of external doors as follows: - no measures, original doors are preserved - original doors are removed and new doors are installed with the thermal transmittance of 1.0 or 0.7 W/(m^2 K)	No measures	New, 0.7 W/(m^2 K)	Discrete, 3 options
District heating system, DH concept	**Min. measure**	**Max. measure**	**Variable**
- Dimensioning of solar-based thermal system, area of solar collectors, m^2	0	70	Continuous
- Dimensioning of solar-based electricity system, area of PV-panels, m^2	0	130	Continuous
- Renovation of the ventilation system, see the A2WHP concept	No renovation	Centralized for entire building	Discrete, 6 options
- Renovation of external walls, see the A2WHP concept	80	300	Discrete, 8 options
- Renovation of roof, see the A2WHP concept	0, basic refurbishment	400	Discrete, 10 options
- Renovation of windows, see the A2WHP concept	Repair, original	New, 0.6 W/(m^2 K)	Discrete, 5 options
- Renovation of external doors, see the A2WHP concept	No measures	New, 0.7 W/(m^2 K)	Discrete, 3 options
Exhaust air heat pump system, EAHP concept	**Min. measure**	**Max. measure**	**Variable**
- Dimensioning power output of the heat pump system, kW	30	60	Continuous
- Dimensioning of solar-based electricity system, area of PV-panels, m^2	0	130	Continuous
- Renovation of external walls, see the A2WHP concept	80	300	Discrete, 8 options
- Renovation of roof, see the A2WHP concept	0, basic refurbishment	400	Discrete, 10 options
- Renovation of windows, see the A2WHP concept	Repair, original	New, 0.6 W/(m^2 K)	Discrete, 5 options
- Renovation of external doors, see the A2WHP concept			Discrete, 3 options
Ground source heat pump system concept, GSHP concept	**Min. measure**	**Max. measure**	**Variable**
- Dimensioning power output of the heat pump system, kW	10	160	Continuous
- Dimensioning of solar-based electricity system, area of PV-panels, m^2	0	130	Continuous
- Renovation of the ventilation system, see the A2WHP concept	No renovation	Centralized for entire building	Discrete, 6 options
- Renovation of external walls, see the A2WHP concept	80	300	Discrete, 8 options
- Renovation of roof, see the A2WHP concept	0, basic refurbishment	400	Discrete, 10 options
- Renovation of windows, see the A2WHP concept	Repair, original	New, 0.6 W/(m^2 K)	Discrete, 5 options
- Renovation of external doors, see the A2WHP concept	No measures	New, 0.7 W/(m^2 K)	Discrete, 3 options
Total number of renovation combinations in the studied concepts			
- A2WHP concept: ~72 000 000			
- DH concept: ~72 000 000			
- EAHP concept: ~12 000 000			
- GSHP concept: ~72 000 000			
- Total number of studied combinations: ~228 000 000			

Table 5. Construction costs of studied renovation measures (the Finnish VAT (24 %) excluded), including installation costs related to the measures [28].

Renovation measure	Investment cost
Solar-based electricity production system with PV-panels, €/panel-m^2	232 (1.45 €/W$_p$)
Solar-based thermal production system with solar collectors, €/collector-m^2	615
Renovation of external walls according to the structure details shown in Fig. 3, also includes the necessary supporting structures of the original windows and additional costs regarding the foundations and eaves of the building, depending on the total thickness of the structure, €/ex.wall-m^2	
- demolition of outer concrete layer and thermal insulation, new thermal insulation thickness is 80 mm	252
- as previous, but the new thermal insulation thickness is: 130 mm	259
- 160 mm	263
- 180 mm	266
- 230 mm (requires measures for foundations and eaves)	286
- 260 mm (requires measures for foundations and eaves)	291
- 280 mm (requires measures for foundations and eaves)	295
- 300 mm (requires measures for foundations and eaves)	298
Renovation of roof according to the structure details shown in Fig. 3, also includes the additional costs regarding the eaves of the building, depending on the total thickness of the structure, €/roof-m^2	
- renewal of the original water insulation layer, no further measures	40
- demolition of top structure layer and thermal insulation, new thermal insulation thickness is 50 mm	99
- as previous, but the new thermal insulation thickness is: 100 mm	103
- 125 mm	107
- 150 mm	111
- 200 mm	115
- 250 mm	119
- 300 mm	123
- 400 mm	132
Renovation of windows according to different alternative methods, also includes all installation, supporting, demolition/removal and additional costs related to the measure, €/window-m^2	
- original windows are repaired, painted and re-sealed, the windows are also supported to the inner concrete layer of the original ext. walls due to the selected renovation method of ext. walls (see Fig. 3)	123
- original windows are removed and new windows are installed, the thermal transmittance of new windows is 1.0 W/(m^2 K) and the g-value is 0.50	251
- as previous, but new windows are: thermal transmittance 0.8 W/(m^2 K) and g-value 0.49	270
- thermal transmittance 0.7 W/(m^2 K) and g-value 0.42	296
- thermal transmittance 0.6 W/(m^2 K) and g-value 0.39	312
Renovation of external doors, also includes removal and installation costs, €/door-m^2	
- no measures, original doors are preserved	0
- original doors are removed and new doors are installed, the thermal transmittance of new doors is 1.0 W/(m^2 K)	465
- as previous, but the thermal transmittance of new doors is 0.7 W/(m^2 K)	537
Renovation of the ventilation system by using different methods, also includes installation and construction related costs, €/floor-m^2	
- no measures, the original exhaust air ventilation system is preserved for the entire building	0
- centralized ventilation system with heat recovery (temperature efficiency 85 %) for: base floor spaces	142
- apartments	98
- the entire building	91
- distributed ventilation system with heat recovery (temperature efficiency 80 %) for: base floor spaces	60
- apartments	70
Heat pump systems, also includes installation costs, €/kW	
- air-to-water (640 + 15 000 €)	
- exhaust air (110 + 76 000 €)	
- ground source (1050 + 15 000 €)	
Renewal of the original district heating system substation and control automation, €/floor-m^2	7 (20 000 €)
Renewal of approximately 15 radiators to low-temperature radiators in the top floor of the building (GSHP system), €	3 000
Installation of new main electricity connection cable and new main electricity substation (GSHP system), €	12 500
Balancing of the original 80/60 °C radiator heating system to 65/55 °C dimensioning temperatures, €	18 800 (6.5 €/floor-m^2)

The heat recovery (temperature) efficiency of the renovated centralized ventilation systems is 86 % and the heat recovery efficiency of the distributed ventilation systems is 80 %, respectively. The air filters of new AHUs (distributed and centralized) are assumed to be replaced two times per year. The basic refurbishment method of the original windows is repair, painting and resealing. It is estimated that this measure extends the technical operation time of the original windows for 15 years and must be conducted again after that and this has also been taken into account in the economic calculations. If the original windows are preserved, they must also be supported to the inner concrete layer of the original external walls so that they don't fall off, when the outer concrete layer and thermal insulation of the original walls are demolished (see Fig. 3).

The cost data used in the study (Table 5) was determined by a group of experts [28]. Cost data of relevant recent studies regarding refurbishment of existing apartment buildings was also used in addition to the more detailed and specific cost estimations determined by the group of experts [19,22,29]. Table 6 presents the maintenance and renewal costs of different measures during the selected 30-year life-cycle period that were taken into account in the analyzes [19,22,28].

Table 6. Maintenance and renewal costs of different measures (the 24 % VAT excluded) [19,22,28].

Renovation measure	Annual maintenance cost	Renewal cost
DH system concept	None	7 €/floor-m^2, after 25 years
EAHP system concept (hybrid system)	0.75 % from the investment cost	218 €/kW, after 15 years
A2WHP system concept (hybrid system)	0.75 % from the investment cost	200 €/kW, after 15 years
GSHP system concept (non-hybrid system)	0.5 % from the investment cost	186 €/kW, after 15 years
Solar thermal collector system	3.0 % from the investment cost	175 €/collector-m^2, after 20 years
Solar electricity system (PV-panels)	2.0 % from the investment cost	None
Distributed ventilation system (apartments)	4 400 €/a	None
Distributed ventilation system (base floor spaces and stair cases)	300 €/a	None
Centralized ventilation system	200 €/a	None
Basic refurbishment of original windows	None	123 €/window-m^2, after 15 years

It is assumed that other systems and equipment can be operated without significant renewal or maintenance costs for the 30-year life-cycle period used in the LCC analyzes of the study. Furthermore, the residual value of the studied measures is not taken into account in the LCC analyzes due to its low impact on the results of the LCC analysis [19,22,28,29].

2.2. Assessment of CO_2 emissions

2.2.1 System boundary and assumptions

Previous studies and extensive literature reviews have concluded that the operation period of a building is dominant over the building's life-cycle even in new buildings, when the total CO_2 emissions are discussed [15-18,30,31]. Furthermore, several recent studies related to studying the energy, material and emission efficiency of existing concrete-structured apartment buildings located in cold climate conditions have concluded that the energy efficiency, delivered energy consumption and the energy production systems of existing apartment buildings are the key factors to minimize the total CO_2 emissions and that the CO_2 reduction potential of the factors related to the energy performance of buildings is significant compared to the CO_2 reduction potential of construction materials related to the building envelope and infrastructure [6,11,13,32].

This study makes use of the key findings of the previous studies and literature and implements an appropriately practical analysis perspective by using the following assumptions and simplifications in the CO_2 emission calculations due to their negligible impact on the total CO_2 emissions of the selected 30-year life-cycle period:

- the reference point was selected so that the existing building before the renovation was the initial situation:
  - construction materials used in 1973, when the building was originally constructed, and the CO_2 emissions of energy consumption before the deep renovation were excluded from the analysis;
- furthermore, the following details were also excluded from the CO_2 emission analysis:
  - energy and water demand at the building site during the renovation, workmanship related to the installation of the studied HVAC, building services and energy production systems, all fixing-related work, e.g. fastening, sealing, coverings and equivalent thin layer measures, taping, gluing and equivalent small details etc., annual maintenances and renewals related to the technical systems of the building, and the network losses of electricity and district heating between the case building and the power plant;
- as the impact of recycling the demolished materials of the case building, where the demolished materials are replaced with new ones, has a negligible impact on the overall emission analysis, it was also excluded from the analysis.

All the CO_2 emissions presented and discussed in this study are the actual CO_2 emissions, not the CO_2 equivalent emissions. After considering different alternative methods to be used in the CO_2 emission assessment, it was determined that by using the described actual CO_2 emission data instead of the CO_2eq data, the results of the study are more universal and can be used for comparison better in future studies related to the assessment of CO_2 emissions of multi-family residential buildings located in different conditions.

2.2.2 CO_2 emissions of construction materials

One commonly used and internationally proven method to determine the embodied energy and emission data of construction materials is to use the Inventory of Carbon & Energy (ICE) database [15-18,30,31]. Furthermore, also more efficient and automated calculation software with detailed material databases and features suitable to be used by consultancy companies have been developed to estimate the GHG emissions of different construction materials and measures related to the building envelope and the technical systems of buildings, e.g. the 360optimi developed by Bionova Oy [33].

The 360optimi software also includes local material databases to be used for more accurate and detailed emission impact analyzes [33]. The embodied CO_2 emissions for minimum and maximum renovation measures regarding the renovation of the building envelope and the technical systems of the building according to the construction material information of the ICE and 360optimi databases and relevant recent studies regarding the solar-based energy production systems are shown in Table 7 [30,31,33]. Both the ICE and the 360optimi construction material data is shown in Table 7 for reference and comparison, but the local material emission data was used in the analysis.

Table 7. The CO_2 emissions of construction materials according to 360optimi database and ICE database (shown in parentheses).

External wall structure (Fig. 3), material	**Embodied CO_2 emission, kg/CO_2/kg**	**Minimum amount according to selected measure (Fig. 3), kg**	**Maximum amount according to selected measure (Fig. 3), kg**	**Total CO_2 emissions according to selected measure, kgCO_2**
Mineral wool	0.89 (1.2)	5 550	20 810	4 940 – 18 520
Steel (adjustable fasteners for main thermal insulation layer)	2.34 (1.37)	6 650	15 360	15 560 – 35 940
Wood (frames for outer thermal insulation layer)	0.34 (0.71)	2 660	2 660	900
Brick tiles	0.28 (0.55)	43 690	43 690	12 230
Roof structure (Fig. 3), material	**Embodied CO_2 emission, kg/CO_2/kg**	**Minimum amount according to selected measure (Fig. 3), kg**	**Maximum amount according to selected measure (Fig. 3), kg**	**Total CO_2 emissions according to selected measure, kgCO_2**
Bitumen	0.65 (0.43)	40	40	26
Concrete	0.11 (0.1)	0	57 410	0 or 6 320
Light gravel	0.25 (0.05)	0	37 440	0 or 9 360
Polyurethane insulation	4.51 (3.5)	0	8 700	0 – 39 240
Windows and external doors, material	**Embodied CO_2 emission, kg/CO_2/m^2**	**Minimum amount according to selected measure, m^2**	**Maximum amount according to selected measure, m^2**	**Total CO_2 emissions according to selected measure, kgCO_2**
Basic refurbishment, painting, kg/CO_2/kg	1.13 (2.12)	50 (kg)	50 (kg)	60
New windows, argon filled and timber framed	76–107 (50)	0	343	0 – 36 700
New doors, wood + polyurethane	18.5–22 (20.5)	0	79	0 – 1 740
Renewable solar-based energy production systems, includes the materials of the entire system	**Embodied CO_2 emission, kg/CO_2/m^2**	**Min. dimensioning of the system**	**Max. dimensioning of the system**	**Total CO_2 emissions according to selected measure, kgCO_2**
PV-panel modules, monocrystalline		0 m^2 installed	130 m^2 installed	
- ICE database (average product)	242			(0 – 31 460)
- 360optimi, average EU product	181			0 – 23 530
Solar thermal collectors, flat-plate		0 m^2 installed	70 m^2 installed	
- recent studies	160			(0 – 11 200)
- 360optimi, local (Finnish) product	165			0 – 11 550
Main heating systems (360optimi)	**Embodied CO_2 emission, kg/CO_2/system**	**Min. dimensioning of the system**	**Max. dimensioning of the system**	**Total CO_2 emissions according to selected measure, kgCO_2**
New DH system substation	140	1, renewed (excl. GSHP)	1, renewed (excl. GSHP)	140
Heat pump systems, includes the entire system with materials and installation equipment				
- GSHP system + electricity aux.	16 kg/kW	10 kW (GSHP concept)	160 kW	160 – 2 560
- A2WHP system	12 kg/kW	10 kW (A2WHP concept)	150 kW	120 – 1 800
- EAHP system	14 kg/kW	30 kW (EAHP concept)	60 kW	420 – 840
Ventilation system (360optimi), the construction material of new ventilation ducts is steel	**Embodied CO_2 emission, kg/CO_2/system**	**Min. dimensioning of the system**	**Max. dimensioning of the system**	**Total CO_2 emissions according to selected measure, kgCO_2**
Distributed ventilation system for:				
- apartments	10 300	System not installed	System installed	0 or 10 300
- basement floor spaces	1 800	System not installed	System installed	0 or 1 800
Centralized ventilation system for:				

- apartments	6 850	System not installed	System installed	0 or 6 850
- basement floor spaces	1 600	System not installed	System installed	0 or 1 600
- entire building	8 100	System not installed	System installed	0 or 8 100

The average EU product data of the PV-panel system and the local Finnish product data of the solar thermal collector system shown in Table 7 were used in the analysis. The overall average transportation distance of construction materials to the construction site was assumed to be approximately 300 km by using a conventional truck [33]. These assumptions result in a situation, where the average proportion of the CO_2 emissions caused by the transportation is approximately 1 % from the embodied CO_2 emissions of the construction materials [33].

2.2.3 CO_2 emissions of energy carriers

The CO_2 emissions of different energy carriers have been determined by using the delivered energy consumption of the studied case apartment building. The dynamic energy simulation to determine the delivered energy consumption were conducted according to the estimated real use of the case building to provide as accurate estimations of CO_2 emissions generated from delivered energy consumption as possible. The CO_2 emissions of energy carriers used in the study were [34]:

- the average CO_2-emission factor for district heating energy produced by combined heat and power (CHP) production is currently 183 kgCO_2/MWh in Finland. The emission factor of district heating is an average value of the last three years;
- the average emission factor for electrical energy is currently 209 kgCO_2/MWh in Finland. The emission factor of electrical energy is an average value of the last five years.

2.2.4 Total CO_2 emissions from materials and energy carriers

The total CO_2 emissions generated from materials used in the deep renovation of the case apartment building and from delivered energy consumption of different energy carriers during the selected life-cycle period of 30 years is calculated by Eq. (1)

$$CO_{2,total} = \sum CO_{2,materials} + \sum CO_{2,energy\ carriers} \quad (1)$$

where: $\Sigma CO_{2,materials}$ is the overall embodied CO_2 emissions of construction materials, depending on the selected renovation measures related to the building envelope and building services systems; $\Sigma CO_{2,energy\ carriers}$ is the overall CO_2 emissions of delivered energy consumption according to different energy carriers (electrical energy and district heating).

2.3. Energy performance calculations

2.3.1 Calculation of energy performance according to the primary energy consumption

According to the recast EPBD, the energy efficiency classifications of the energy performance certificates (EPCs) are defined according to the primary energy consumption of buildings [10]. Furthermore, the energy performance requirements of nearly zero-energy buildings are also defined according to the PE consumption by using the guidelines of the EPBD. The primary energy weighing factors of different energy carriers are typically country-specific and they are determined by each member state depending on the energy production infrastructure and other features related to the energy consumption of buildings [10]. The PE weighing factors currently used in Finland are as follows:

- district heating 0.7
- district cooling 0.4
- electrical energy 1.7
- fossil-based fuels 1.0
- renewable-based fuels 0.5 [25].

The energy efficiency classes (A-G) of the EPC and the current proposal for nZEB for apartment buildings is defined according to the PE consumption as shown in Fig. 5 in Finland.

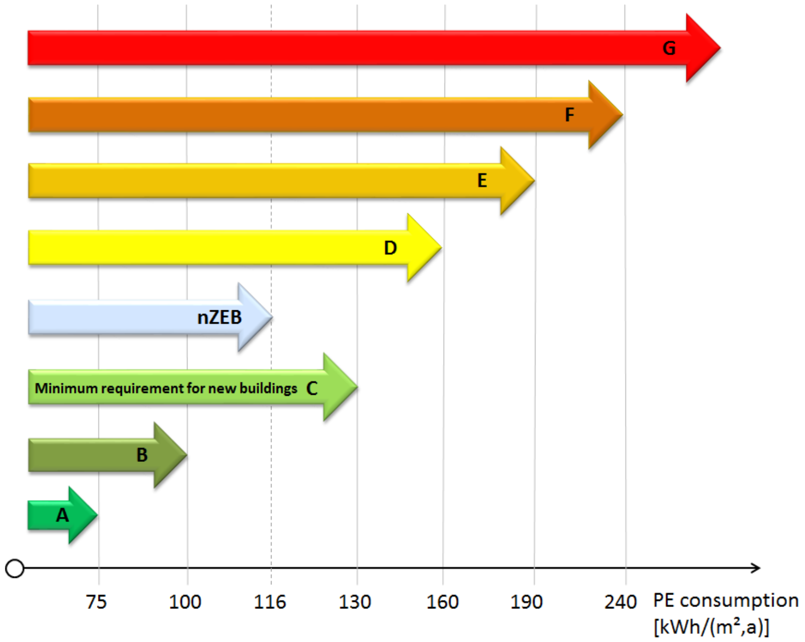

Fig. 5. The energy classes of the EPC and the current proposal for nearly zero-energy apartment buildings [24].

In Finland, the same energy efficiency and nZEB classifications are applied for both new and existing buildings, even though the nZEB requirements set by the recast EPBD concern only new buildings at the moment [10]. The calculation of the PE consumption takes into account heating and cooling energy used by spaces, ventilation and air-conditioning systems, heating of domestic hot water, and electricity used by household and other electrical equipment, lighting and HVAC systems of a building, including fans, pumps and auxiliary equipment of building services systems. In addition, efficiencies of operation of different technical systems, e.g. losses of the heating and cooling distribution and control systems, are also taken into account in the calculation of the PE consumption. The PE consumption is calculated by Eq. (2)

$$PE_{consumption} = \frac{\sum_i (E_i \cdot f_i)}{A_{net}} \tag{2}$$

where: f_i is the PE weighing factor of energy carrier i, -; A_{net} is the heated net floor area of the building, m^2 and E_i is the annual delivered energy of energy carrier i, kWh/a [25].

There are also national requirements for improving the energy performance of existing buildings in deep renovations, where major renovation measures are conducted for the building envelope or for the technical systems [35]. One of the more practical methods to demonstrate the overall improvement in energy performance is to reduce the PE consumption of the building below a predefined level set by the building regulations [35]. This method is also applied for the studied building to set the minimum requirement level for the deep renovation. The predefined energy efficiency improvement level of existing apartment buildings is to reduce the PE consumption of the building to 85 % from the reference situation before the deep renovation is conducted [35]. The reference PE consumption of the studied building prior to the renovation is 186 kWh/(m^2,a) resulting to a requirement, where the minimum reduction of the PE consumption must be the aforementioned 15 % to 158 kWh/(m^2,a) after the renovation measures are conducted [35].

The study also includes an additional sensitivity analysis, where different primary energy weighing factors are used to compare the cost optimum combination of renovation measures between an analysis conducted by using the current national PE weighing factors presented earlier in this chapter and an analysis conducted by using lower PE weighing factors. The PE weighing factors used in the additional sensitivity analysis are as follows:

- district heating 0.5
- district cooling 0.28
- electrical energy 1.2
- fossil-based fuels 1.0 (same as the currently used weighing factor)
- renewable-based fuels 0.5 (same as the currently used weighing factor).

The effect of the lower PE weighing factors on the cost optimum renovation solutions was studied, as the currently used PE weighing factors are under consideration to be changed to the lower weighing factor values by the Finnish Ministry of the Environment. The maximum PE consumption limits of nZEBs for different building types would also decrease in the same proportion, according to the new proposed PE weighing factor values.

2.3.2 Calculation of energy performance and CO_2 emissions according to the delivered energy consumption

Analysis 2 conducted in the study was carried out by assessing and comparing the energy efficiency of different renovation measures using the delivered total energy consumption of different energy carrier. In this analysis, the delivered energy consumption was calculated according to the estimated real use of the studied apartment building. The delivered energy consumption differs from the calculation of the PE consumption, as the energy consumption is calculated without using the PE factors of different energy carriers. Furthermore, no standardized building type-specific internal gains or usage profiles are used, as the calculation is based on the estimated real use and occupancy of the building. Typically, the selection of economically viable renovation solutions should be based on the delivered energy consumption calculated according to the estimated real use of a building. However, the economic viability of different energy efficiency improving measures must be estimated and determined according to the PE consumption of the building as well, as the energy efficiency classifications of the EPC and the energy performance requirements of nZEBs are defined based on the PE consumption of buildings. The environmental impact and CO_2 emission analyzes were conducted by using the delivered energy consumption energy calculation method, as it was estimated to represent the real environmental effects caused by the energy consumption of the building better.

2.4. Simulation-based optimization analysis

2.4.1 Selected simulation method

The energy performance calculations of the SBO analyzes were conducted by using a fully dynamic energy simulation method. The selected simulation tool was IDA Indoor Climate and Energy (IDA-ICE), version 4.7. IDA-ICE has been proved to be an accurate and reliable dynamic simulation tool in several previous studies [36-42]. The performance of IDA-ICE has been validated by using field testing and measurements and the accuracy of IDA-ICE has also been compared to other established dynamic simulation tools used in energy performance and indoor climate simulations of buildings [36-42]. The performance of the studied heat pump and solar-based energy production systems was simulated by using the Early Stage Building Optimization (ESBO) Plant model integrated in the current version of IDA-ICE. Various renewable energy production technologies can be simulated as a part of dynamic energy and indoor comfort simulations of buildings by applying the ESBO Plant model extension, resulting to more versatile and detailed building performance analyzes including the dimensioning of RES.

The studied heat pump models were calibrated by applying a detailed calibration methodology developed in a recent study related to dynamic simulation of heat pump systems, carried out by Niemelä et al. (2016) [43], where the simulation model validation and comparison to real measured energy performance data of different heat pump systems is presented and described in detail. The average overall COP error margins of all rating conditions (e.g. 7/45 °C for the A2WHP system or 0/35 °C for the GSHP system) after the calibration process were:

- A2WHP system, 6 different rating conditions: average COP error margin +2.7 %;
- EAHP system, 4 different rating conditions: average COP error margin +0.4 %;
- GSHP system, 4 different rating conditions: average COP error margin -1.8 %.

2.4.2 Selected optimization method

The selected optimization method used in the SBO analyzes was the relatively new Multi-Objective Building Optimization (MOBO) tool, version 0.3b, developed by VTT Technical Research Centre of Finland and Aalto University [44]. MOBO is equipped with a graphical user interface (GUI) and it is mainly developed for building performance optimization problems where multiple conflicting objectives are optimized simultaneously, but it can also be used to solve one-dimensional optimization problems [44]. The optimization algorithm utilized in the study was the Pareto-Archive NSGA-II algorithm, which is an advanced genetic algorithm developed to solve multi-dimensional optimization problems. Even though being a relatively new optimization software, the performance and features of MOBO have already been tested and compared to other established optimization methods with good success [44,45]. A more detailed description and the main features of MOBO are presented in a recent study conducted by Palonen et al. (2013) [44].

2.4.3 Operation principle of combined simulation and optimization

The operation principle of the combined simulation and optimization analysis used in the study is shown in Fig. 6. Further information related to the combined simulation and optimization analyzes and e.g. applications using the MOBO software with other simulation platforms is presented in several previous SBO related studies [19,20,44,45].

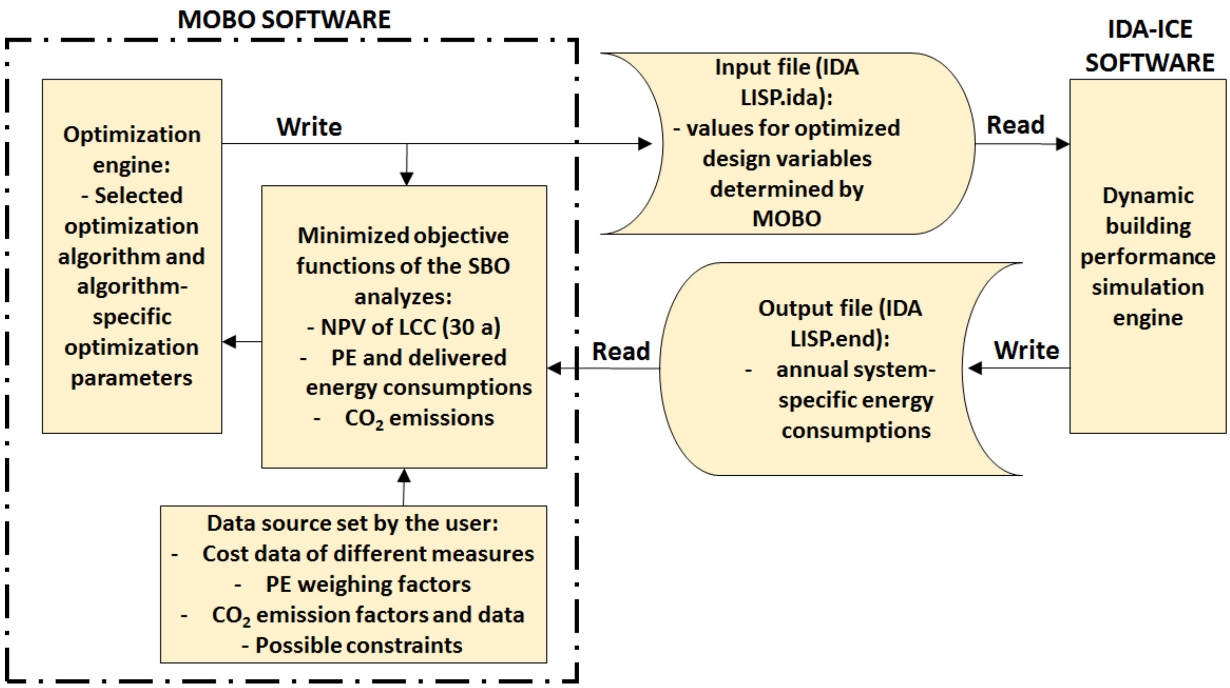

Fig. 6. The operation principle of combined simulation and optimization analysis.

2.5. Life-cycle cost calculations

The economic viability of the studied renovation measures was assessed by determining the net present value (NPV) of life-cycle cost (LCC) over a 30-year life-cycle period. The essential and mandatory maintenance repair measures were also taken into account in the LCC analysis, as described in chapter 2.1.6. The NPV of LCC over the selected life-cycle period is calculated by Eq. (3)

$$NPV_{LCC,30a} = \sum I_{0,total} + \sum MR_a \frac{1-(1+r)^{-n}}{r} + \sum R_M \frac{1}{(1+r)^k} + \sum E_a \frac{1-(1+r_e)^{-n}}{r_e} \quad (3)$$

where: $NPV_{LCC,30a}$ is the net present value of the LCC over the selected 30-year life-cycle period, €; $\Sigma I_{0,total}$ is the total investment cost of the studied measures (see Table 5), €; ΣMR_a is the total annual maintenance cost related to the studied renovation measures, €/a; ΣR_M is the total renewal cost related to the studied renovation measures, €; ΣE_a is the total annual energy cost of the studied apartment building, €/a; r is the real interest rate used in the life-cycle cost calculations; r_e is the escalated real interest rate used in the life-cycle cost calculations with an estimated energy price escalation rate scenario included; n is the selected life-cycle period of the analysis (30 a), a; k is the year from the start of the LCC analysis, when a specific renewal or retrofitting measure is carried out.

The following energy prices (the 24 % VAT is excluded from the prices) were used in the life-cycle cost calculations of the study [46,47]:

- 84 €/MWh for electrical energy;

- 53.3 €/MWh for district heating energy;
- the annual basic fee of district heating was calculated according to the calculation instructions of the local district heating company (Keravan Energia) [46]. The annual basic fee is 5 730 €/a in the initial "as built" condition prior to the deep renovation and it is reduced according to the selected measures that reduce the peak heating power demand of the case building.

The other main calculation parameters used in the life-cycle cost analysis were:

- real interest rate: 3.0 % [4,19,22,29];
- estimated escalation rate of energy price: +2.0 %/a for electrical energy and district heating [4,19,22,29].

3. Results

The study consists of 8 individual SBO analyzes. First four analyzes were conducted to minimize the PE consumption and the NPV of the 30-year LCC and the final four analyzes were conducted to minimize the CO_2 emissions of the case building and the NPV of the 30-year LCC. The minimization of the CO_2 emissions was conducted according to the calculation methodology and system boundaries presented in chapter 2.2. Over 7 000 individual energy simulations were performed in the study to determine the cost-optimal solutions for different main heating systems to meet different energy performance and CO_2 emission criteria.

3.1. Cost-optimal solutions in terms of PE consumption

Fig. 7 and Tables 8 and 9 present the cost-optimal renovation solutions to meet different energy efficiency criteria in terms of the PE performance in the studied building. Fig. 7 and Tables 8 and 9 present the cost-optimal solutions using both the current and the new proposed PE weighing factors described in chapter 2.3.1. Furthermore, the nearly zero-energy apartment building PE consumption limits for both weighing factor scenarios are also shown in Fig. 7. The PE consumption limits of different energy classes of the EPC are only shown for the analysis using the current PE weighing factors, as the PE consumption requirements of new energy classes of the EPC using the lower PE weighing factors have not been determined yet. The minimized objectives of the SBO analyzes were the PE consumption, calculated according to Eq. (2), and the NPV of the 30-year LCC, calculated according to Eq. (3). The internal rate of return (IRR) for the cost-optimal renovation packages to meet different energy performance criteria is also shown in Tables 8 and 9. The IRR is calculated for the cost-optimal solutions, which are compared to a selected reference solution also shown in Fig. 7. The presented IRRs are calculated without taking the escalation rates of energy prices into account for a simpler comparison of different solutions. If the escalation rates of the energy carrier prices were taken into account, the IRRs of the solutions including heat pump systems would be even higher than the presented IRRs, where the escalation rates are not taken into account. The selected reference solution, where other solutions are compared includes the following renovation and retrofitting measures:

- the external walls are renovated according to Fig. 3, the thermal transmittance of new walls is 0.23 W/m^2K;
- the roof is renovated according to Fig. 3, the thermal transmittance of new roof is 0.13 W/m^2K;
- the original windows are replaced, new windows are: thermal transmittance 0.8 W/m^2K and g-value 0.49;
- the original external doors are replaced, the thermal transmittance of new doors is 0.7 W/m^2K;
- the original district heating substation is renewed;
- the original ventilation system is not renovated and no renewable energy production systems are installed.

Furthermore, the following reference solution (Reference solution 2) was also studied and compared to the selected reference solution described above to determine, if it is cost-effective to maximize the energy performance of the building envelope in a deep renovation. The motivation to determine this renovation scenario is because the building envelope is renovated extensively due to its poor condition and the energy performance improving measures related to the envelope can be cost-effectively combined with the mandatory maintenance measures improving the general condition of the building envelope. The additional reference solution 2 includes the following renovation and retrofitting measures:

- the external walls are renovated so that the thermal transmittance of new walls is 0.11 W/m^2K (280 mm insulation);
- the roof is renovated so that the thermal transmittance of new roof is 0.07 W/m^2K (400 mm insulation);
- the original windows are replaced, new windows are: thermal transmittance 0.7 W/m^2K and g-value 0.42;
- the original external doors are replaced, the thermal transmittance of new doors is 0.7 W/m^2K;
- the original district heating substation is renewed;
- the original ventilation system is not renovated and no renewable energy production systems are installed.

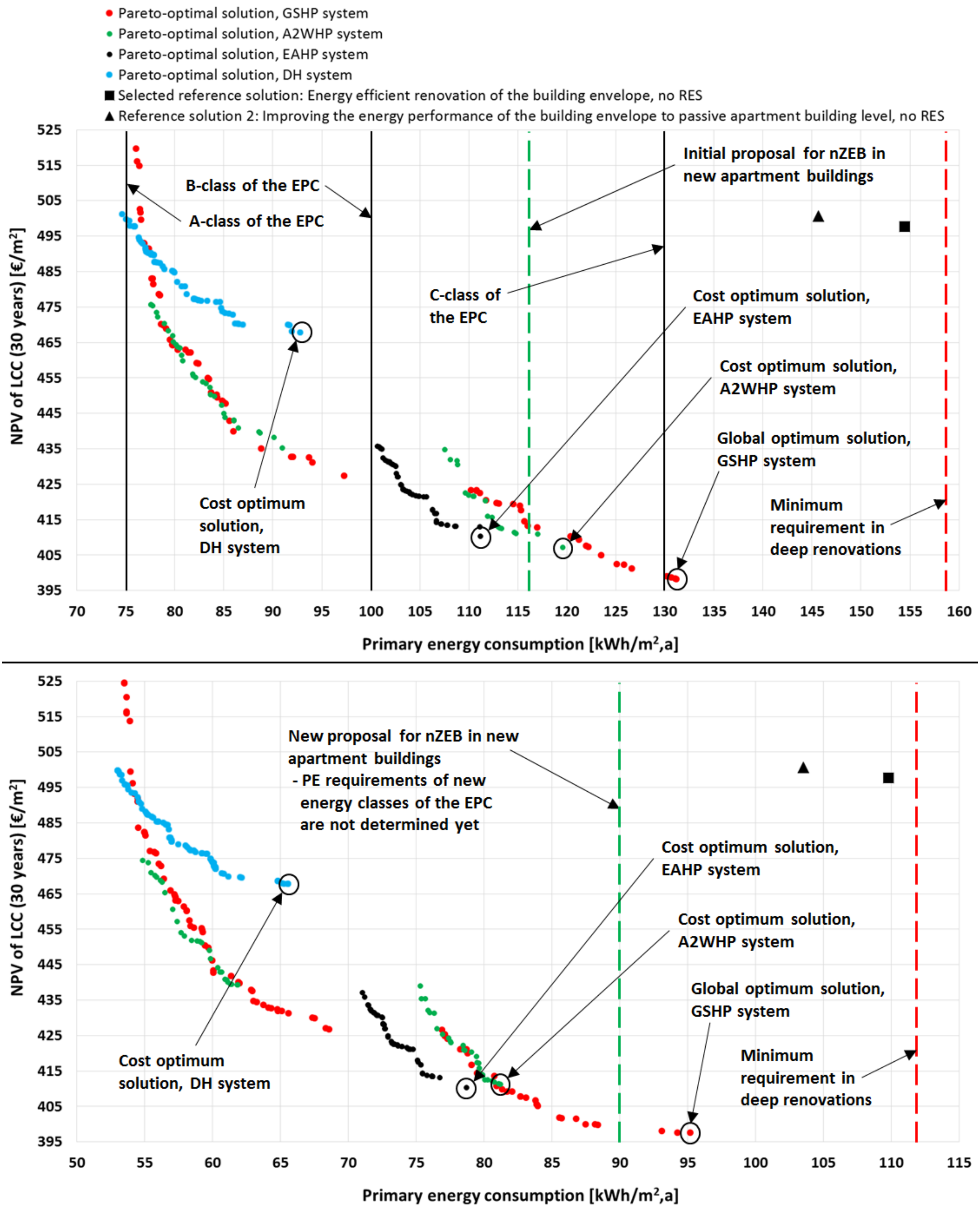

Fig. 7. Cost-optimal renovation solutions in terms of PE consumption for different main heating systems using the current PE weighing factors (above) and new proposed weighing factors (below) in the analysis.

Table 8. Recommended renovation measures in terms of PE consumption to meet different energy efficiency criteria, current PE weighing factors used in the analysis. GOS and BR stand for Global Optimum Solution and Basic Refurbishment.

Primary energy consumption [kWh/m^2,a]	*75 (A-class)*	*80*	*100 (B-class)*	*116 (proposal for nZEB)*	*120*	*130 (C-class)*	*158, GOS (minimum requirement)*
Recommended main heating system	DH	GSHP	GSHP	EAHP	A2WHP	GSHP	GSHP
NPV of LCC, 30 years [€/m^2]	501	427	370	410	407	401	398
Investment cost of studied measures [€/m^2]	333	352	294	212	206	227	220
IRR, internal rate of return for the renovation measure package [%/a]	±0.0	2.3	5.2	36.1	86.2	17.8	24.3
Thermal insulation thickness of external walls [mm]	300	280	160	180	180	180	180
Additional thermal insulation thickness of roof or BR [mm]	+400	+400	0, BR	0, BR	0, BR	0, BR	0, BR
Replacement of windows or BR, thermal transmittance and g-value of windows [W/m^2 K]	Yes, 0.60, g-value 0.39	Yes, 0.8, g-value 0.49	Yes, 1.0, g-value 0.50	Yes, 0.8, g-value 0.49	Yes, 1.0, g-value 0.50	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49
Replacement of external doors, thermal transmittance of doors [W/m^2 K]	Yes, 0.7	Yes, 0.7	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
Area of PV-panels [m^2]	129	129	128	130	129	129	128
Area of solar thermal collectors [m^2]	69	0	0	0	0	0	0
Power output of the heat pump system [kW]	-	67	50	49	41	106	87
Individual renovation of the ventilation system of apartments	Yes, distributed	No	No	No	No	No	No
Individual renovation of the ventilation system of base floor spaces	Yes, distributed	No	No	No	Yes, distributed	No	No
Renovation of the entire ventilation system of the building to centralized system	No	Yes	Yes	No	No	No	No

Table 9. Recommended renovation measures in terms of PE consumption to meet different energy efficiency criteria, new proposed PE weighing factors used in the analysis. GOS and BR stand for Global Optimum Solution and Basic Refurbishment.

Primary energy consumption [kWh/m^2,a]	*55*	*60*	*70*	*80*	*90 (new proposal for nZEB)*	*100*	*112, GOS (minimum requirement)*
Recommended main heating system	GSHP	GSHP	GSHP	EAHP	GSHP	GSHP	GSHP
NPV of LCC, 30 years [€/m^2]	482	443	427	410	400	398	398
Investment cost of studied measures [€/m^2]	342	323	294	212	227	215	215
IRR, internal rate of return for the renovation measure package [%/a]	1.1	3.5	5.3	36.2	18.1	32.3	32.3
Thermal insulation thickness of external walls [mm]	300	300	180	180	160	180	180
Additional thermal insulation thickness of roof or BR [mm]	+400	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR
Replacement of windows or BR, thermal transmittance and g-value of windows [W/m^2 K]	Yes, 0.7, g-value 0.42	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 1.0, g-value 0.50	Yes, 1.0, g-value 0.50
Replacement of external doors, thermal transmittance of doors [W/m^2 K]	Yes, 1.0	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
Area of PV-panels [m^2]	130	128	128	130	129	129	129
Area of solar thermal collectors [m^2]	0	0	0	0	0	0	0
Power output of the heat pump system [kW]	65	79	40	48	85	79	79
Individual renovation of the ventilation system of apartments	Yes, distributed	No	No	No	No	No	No
Individual renovation of the ventilation system of base floor spaces	Yes, distributed	No	No	No	Yes, distributed	No	No
Renovation of the entire ventilation system of the building to centralized system	No	Yes	Yes	No	No	No	No

3.2. Cost-optimal solutions in terms of CO_2 emissions

Fig. 8, and Tables 10-11 present the cost-optimal renovation solutions to meet different CO_2 emission criteria using both moderate (2.0 %/a) and high (4.5 %/a) energy price escalation rate scenarios.

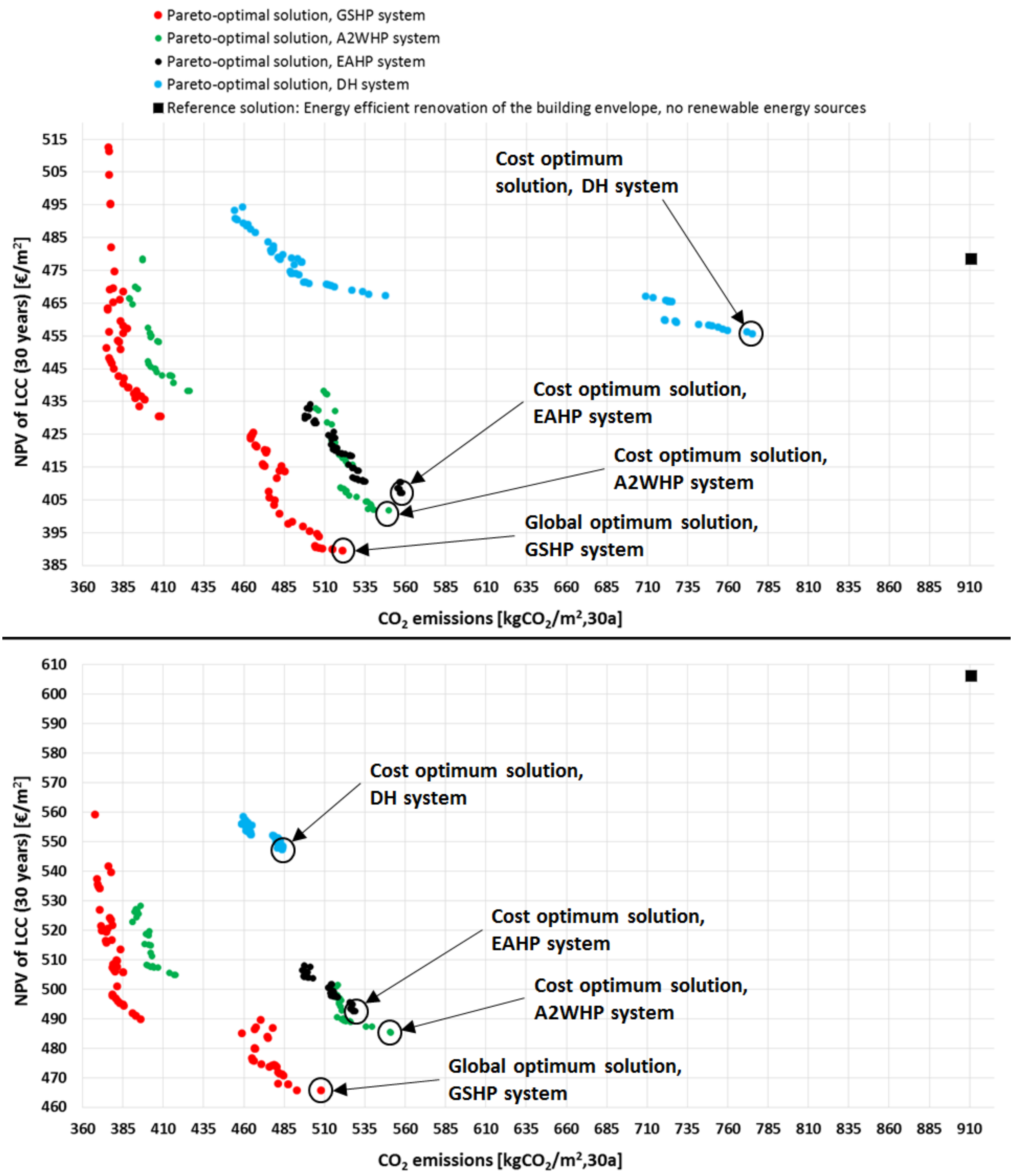

Fig. 8. Cost-optimal renovation solutions in terms of CO_2 emissions for different main heating systems using a moderate (2.0 %/a) energy price escalation scenario (above) and a high (4.5 %/a) energy price escalation scenario (below) in the analysis.

The presented CO2 emissions include the embodied emissions of the construction materials, transportation of the materials to the construction site and the CO2 emissions caused by the delivered energy consumption according to the actual use of the studied case building. The minimized objectives of the SBO analyzes were the total CO2 emissions, calculated according to Eq. (1), and the NPV of the 30-year LCC, calculated according to Eq. (3). The internal rate of return (IRR) shown in Tables 10 and 11 is calculated by comparing the presented cost-optimal renovation package to the selected reference solution described in chapter 3.1.

Table 10. Recommended renovation measures in terms of CO_2 emissions to meet different CO_2 emission criteria, moderate energy price escalation (2.0 %/a) scenario. GOS and BR stand for Global Optimum Solution and Basic Refurbishment.

Total CO_2 emissions [$kgCO_2/m^2$,30a]	***380***	***390***	***410***	***470***	***500***	***530, GOS***	***560, GOS***
Recommended main heating system	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP
NPV of LCC, 30 years [€/m²]	445	439	430	421	397	389	389
Investment cost of studied measures [€/m²]	316	309	293	264	229	212	212
IRR, internal rate of return for the renovation measure package [%/a]	2.6	3.1	4.0	5.8	14.7	37.4	37.4
Thermal insulation thickness of external walls [mm]	230	230	180	280	280	180	180
Additional thermal insulation thickness of roof or BR [mm]	0, BR	0, BR	0, BR	+250	0, BR	0, BR	0, BR
Replacement of windows or BR, thermal transmittance and g-value of windows [W/m² K]	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49
Replacement of external doors, thermal transmittance of doors [W/m² K]	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
Area of PV-panels [m²]	126	118	128	125	128	117	117
Area of solar thermal collectors [m²]	0	0	0	0	0	0	0
Power output of the heat pump system [kW]	76	57	39	100	74	66	66
Individual renovation of the ventilation system of apartments	No	No	No	No	No	No	No
Individual renovation of the ventilation system of base floor spaces	No	No	No	Yes, distributed	No	No	No
Renovation of the entire ventilation system of the building to centralized system	Yes	Yes	Yes	No	No	No	No

Table 11. Recommended renovation measures in terms of CO_2 emissions to meet different CO_2 emission criteria, high energy price escalation (4.5 %/a) scenario. GOS and BR stand for Global Optimum Solution and Basic Refurbishment.

Total CO_2 emissions [$kgCO_2/m^2$,30a]	***370***	***380***	***390***	***410***	***470***	***500***	***530, GOS***
Recommended main heating system	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP
NPV of LCC, 30 years [€/m²]	535	498	494	490	476	466	466
Investment cost of studied measures [€/m²]	365	317	307	298	246	222	216
IRR, internal rate of return for the renovation measure package [%/a]	0.5	2.7	3.1	3.7	8.8	19.1	26.8
Thermal insulation thickness of external walls [mm]	300	280	180	180	280	180	180
Additional thermal insulation thickness of roof or BR [mm]	+150	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR
Replacement of windows or BR, thermal transmittance and g-value of windows [W/m² K]	Yes, 0.60, g-value 0.39	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49	Yes, 0.8, g-value 0.49
Replacement of external doors, thermal transmittance of doors [W/m² K]	Yes, 0.7	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
Area of PV-panels [m²]	128	130	130	130	129	130	130

Area of solar thermal collectors [m^2]	0	0	0	0	0	0	0
Power output of the heat pump system [kW]	97	66	76	53	97	93	76
Individual renovation of the ventilation system of apartments	No	No	No	No	No	No	No
Individual renovation of the ventilation system of base floor spaces	No	No	No	No	Yes, distributed	No	No
Renovation of the entire ventilation system of the building to centralized system	Yes	Yes	Yes	Yes	No	No	No

3.3. Comparison of global optimum solutions

Fig. 9 presents the breakdown of LCC and CO_2 emissions of both the global optimum solution, highlighted in Fig. 8 and described in Table 10, and the selected reference solution, described in chapter 3.1, in the moderate energy price escalation rate (2.0 %/a) scenario. The global optimum solution shown in Fig. 9 is achieved by selecting the GSHP system with a moderate dimensioning power output (approximately 66 kW, see Table 10) as the main heating system and by producing the auxiliary heating energy with electricity. The reference solution presented in Fig. 9 is considered as a baseline renovation measure package, where the energy efficiency of the building envelope is improved to a good level using practical renovation measures, which also meet the minimum requirements of the current national building regulations.

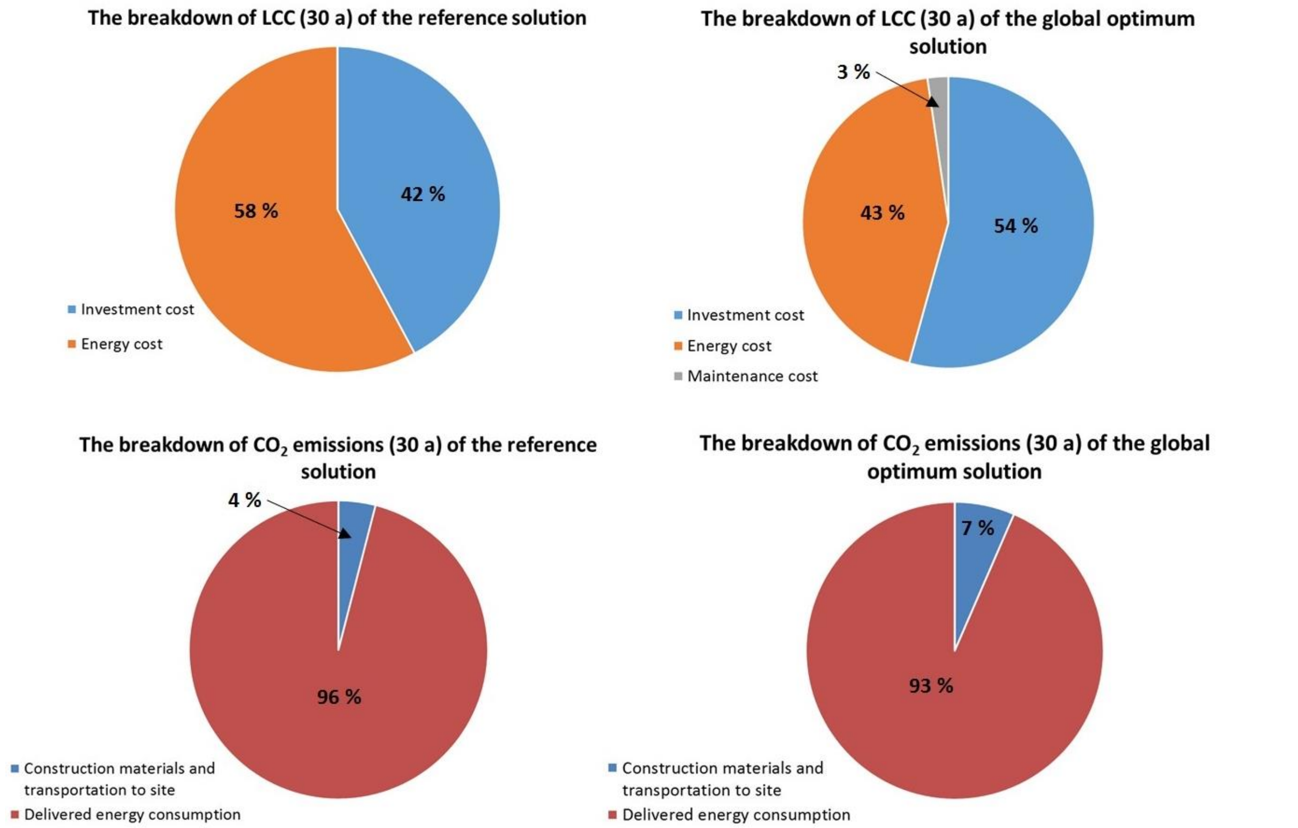

Fig. 9. The breakdown of LCC analysis (2.0 %/a escalation rate) of the selected reference (top left) and the global optimum (top right) solutions and the breakdown of CO_2 emissions of the reference (bottom left) and the global optimum (bottom right) solutions.

According to Fig. 9 and Tables 10-11, no significant additional investments are needed, when the global optimum solutions of both energy price escalation rate analyzes are compared, as the GSHP system delivers excellent cost-effectiveness in an increasing energy price development scenario. However, the higher energy price escalation rate has a significant impact on the LCC of the reference solution, where the main heating system of the building is district heating. According to Fig. 9, the CO_2 emissions caused by the delivered energy consumption are dominant over the transportation and embodied CO_2 emissions of the construction materials. In the higher energy price escalation rate scenario, the breakdown of both LCC and CO_2 emissions was similar to the breakdown of LCC and CO_2 emissions of the moderate energy price escalation rate scenario. The share of the energy cost was approximately 9 % higher and the share of the investment cost approximately 9 % lower, respectively. The breakdown of the total CO_2 emissions was basically identical in both energy price escalation rate scenarios.

4. Discussion

According to the results of the SBMOO analyzes regarding the PE performance, investments in heat pump systems deliver significant cost savings during the selected 30-year life-cycle period compared to the district heating system or extensive renovation of the building envelope. The global optimum solution is achieved with the ground source heat pump system, but the air-to-water and exhaust air heat pump systems also deliver excellent energy performance and cost-effectiveness. In fact, the cost-optimum solutions of the A2WHP and EAHP systems deliver higher internal rate of return (IRR) percentage, up to 86 % with the A2WHP system, than the GSHP system, when the solutions are compared to the selected reference solution. However, while the actual IRR-percentage isn't as high with the GSHP system, the higher absolute savings make it the global optimum main heating system concept in the 30-year LCC analysis. According to the results, the NPV of LCC of the GSHP system is approximately 2 % (~9 €/m^2) lower than the NPV of LCC of the A2WHP system and approximately 3 % (~12 €/m^2) lower than the NPV of LCC of the EAHP system, respectively. While the GSHP system delivers the global optimum solution, the EAHP system is the cost-optimal main heating system concept to reach the initial PE consumption requirement of the proposed national nearly zero-energy apartment buildings, delivering up to 36 % internal rate of return, when it is compared to the aforementioned reference solution.

The cost-optimal energy performance level of the deep renovation was approximately at the minimum energy performance requirement level (NBCF part D3 (2012)) of new apartment buildings with the GSHP system and close to the initially proposed national nearly zero-energy apartment building level (FInZEB project, PE $\leq$ 116 kWh/(m^2,a) with the currently used higher PE weighing factors) with the A2WHP and EAHP systems [48]. According to the analyzes, the new proposed national nZEB requirements (PE $\leq$ 90 kWh/(m^2,a) with the proposed lower PE weighing factors) of apartment buildings can be more easily and cost-effectively achieved than the initially proposed nZEB requirements (PE $\leq$ 116 kWh/(m^2,a) with the currently used higher PE weighing factors). The initial nZEB requirement could be achieved by investing approximately 215-220 €/m^2 with the A2WHP and EAHP systems resulting in approximately 36 % internal rate of return with the EAHP system and approximately 26 % IRR with the A2WHP system, when the investments are compared to the selected reference solution described in chapter 3.1. Approximately 250 €/m^2 have to be invested with the GSHP system concept to reach the initial nZEB requirement resulting in 9 % IRR compared to the reference solution, respectively. The new proposed nZEB requirement level (PE $\leq$ 90 kWh/(m^2,a) with the proposed lower PE weighing factors) can be cost-effectively achieved with all heat pump systems, resulting in 18 % IRR with the GSHP system, 36 % IRR with the EAHP system and 26 % IRR with the A2WHP system.

According to the results, installation of a solar-based electricity production system with PV-panels is a highly recommended and cost-effective measure with all studied main heating systems, when primary energy performance is discussed. In addition, a solar-based thermal production system is also recommended to be installed with the district heating system delivering good cost-effectiveness, but it is not recommended to be used with any of the heat pump systems in apartment buildings located in cold climate conditions, as the high energy performance of the modern heat pump systems reduce the cost-effectiveness of the solar thermal system significantly. An essential aspect in the design process of the PV-panel system in Finland is to dimension the system so that all of the produced electricity can be used on-site. This requires careful matching analysis of the building's electricity production and consumption profiles and loads in the designing process so that the dimensioning of the PV-panel system matches the electricity consumption profile and loads of the building. While the produced electrical energy can also be exported back to the grid and sold to the energy company, it is currently not cost-effective or recommendable for apartment building owners. The maximum area of PV-panels (130 m^2) used in the SBMOO analyzes was dimensioned so that all of the produced electricity can be used in the studied building.

When primary energy performance is discussed, the optimum combination of renovation measures to reach specific energy performance criteria is a little different with each main heating system, as the same energy performance criteria and cost-effectiveness can be achieved with multiple combination of measures, e.g. by investing more in the heat pump and technical systems, which also require annual maintenance and renewal investments, with the GSHP system or by investing more in the energy performance improving measures related to the building envelope, which don't require annual maintenance or renewal investments during the 30-year LCC period, with the EAHP and A2WHP systems. Another essential aspect regarding the cost-effectiveness of the heat pump systems is that the annual basic fee of district heating was assumed to be reduced according to the reduction in peak heating power demand of the building. In general, this means that an EAHP system with 40 kW dimensioning power output reduces the annual peak heating power demand of the district heating system by 40 kW, respectively. Furthermore, as the primary energy weighing factor of district heating is significantly lower than the PE weighing factor of electricity (currently 0.7 for district heating and 1.7 for electricity), the primary energy performance of hybrid energy systems, where a heat pump system with a relatively low dimensioning power output is combined with the district heating system, is typically improved.

The additional SBMOO analyzes conducted by using the lower PE weighing factors delivered similar results than the analyzes conducted using the currently used higher PE weighing factors. The global optimum main heating system concept in the additional analyzes using the lower PE weighing factors was the GSHP system, respectively. The major differences between the global optimum solutions of the two analyzes were that the dimensioning power output of the GSHP system was approximately 10 % lower (79 kW vs 87 kW) and the energy efficiency of new windows was a little lower (thermal transmittance 1.0 vs 0.8 W/m^2K) in the analyzes conducted using the lower PE weighing factors. According to the results, other measures were practically identical in both analyzes. Due to the fact that the ratio between the PE weighing factors of both the district heating and electricity were decreased equally much (approximately 30 %), the relationships between the energy performance and cost-effectiveness of the renovation measure packages using more district heating or electricity were unchanged.

The primary energy performance of the cost-optimal solutions of the district heating system is the highest of all studied main heating systems, but the cost-effectiveness that can be achieved by using the DH system is significantly lower than the cost-effectiveness achievable by investing in cost-optimally dimensioned heat pump systems (see Fig. 7). The cost-optimal solutions of the DH system deliver approximately 12-15 % higher life-cycle costs during the 30-year discount period in both PE weighing factor analyzes than the cost-optimal solutions of the studied heat pump systems. Furthermore, 17-21 % lower LCC can be achieved by selecting the cost-optimal solutions of the heat pump systems over the presented reference solutions described in chapter 3.1. These results clearly demonstrate that investments in heat pump and solar-based renewable energy production systems are recommended renovation measures over the energy performance improving measures related to the building envelope, when both the cost-effectiveness and primary energy performance are discussed.

According to the results of the SBMOO analyzes regarding the primary energy performance, both the A2WHP and EAHP systems are cost-effective alternatives for the GSHP system in deep renovations of existing large panel apartment buildings, where initial setting and the objective of the renovation are similar to the situation presented in this study. Furthermore, the risks involved in the installation of both the A2WHP and EAHP are typically considerable lower than the risks in the installation of the GSHP system, as there are always risks involved in the drilling of boreholes successfully and cost-effectively (e.g. the depth and quality of the bedrock etc.), whereas the risks involved in the installation of the A2WHP and EAHP systems are easily predicted and monitored.

When the economic viability of the renovation of the ventilation system is discussed, it is important to acknowledge that there are also essential quality aspects related to the renovation of the original system, regardless whether the renovated ventilation system is distributed or centralized. Typically the renovated ventilation system improves both the indoor air quality (IAQ) and thermal comfort conditions of existing apartment buildings originally equipped with mechanical exhaust air ventilation system by reducing unwanted draught and improving the ventilation efficiency. These important quality aspects are difficult to be measured in the LCC analyzes by using only economic indicators. Instead they should always be carefully considered and taken into account from multiple perspectives (e.g. indoor environment quality, economic and environmental impacts), when deep renovations of large panel apartment buildings are planned.

According to the results and key findings of the study and other similar studies conducted recently, the initial setting and the system boundary of the renovation analysis have a relatively significant impact on the recommended renovation measures [3,4,6,13,14,19,20]. The initial setting and the system boundary of the analyzes conducted in the study were selected so that the building envelope, including the external walls, windows and roof, is facing deep renovation measures and must be refurbished. Furthermore, the renovation method of external walls was selected so that the original exterior concrete and thermal insulation layers are demolished due to their poor condition, as it was determined to be a commonly used method to renovate the external walls of large panel apartment buildings. In this setting, the cost-effectiveness of the renovation measures related to improving the energy efficiency of the building envelope is significantly better than in an initial setting, where the exterior construction layers of external walls are not required to be demolished. As the minimum renovation requirement is to demolish the exterior structure layers and to install new thermal insulation and exterior surface regardless, it is not as significant investment to install a thicker thermal insulation layer in this scenario as it is in a scenario, where the exterior structures of external walls are not required to be demolished due to their better condition. According to the analyzes, the selected initial setting and the system boundary are the main reasons, why the energy performance and cost-effectiveness of the studied heat pump systems are so close to each other.

The results of the SBMOO analyzes regarding the CO_2 emissions delivered similar conclusions than the optimization results of the PE consumption. Investments in heat pump and technical systems of the building are recommended over the investments in the building envelope and they also deliver significantly better cost-effectiveness and protection against an increasing energy price development. The delivered target energy consumption was used to determine the CO_2 emissions caused by the energy consumption of the building. The major difference between the PE and delivered target energy consumption calculation methods is the use of the building. In the PE consumption calculation the energy consumption is calculated by using the standardized internal heat gains and usage profiles, whereas the delivered target energy consumption is calculated by using the real design and operation schedules of the building, which are determined according to the real use of the building. The global optimum solution of the moderate energy price escalation rate scenario was achieved with the GSHP system. The NPV of LCC of the global optimum solution was approximately 12 €/m^2 lower than the NPV of LCC of the cost optimum solution of the A2WHP system in the moderate energy price escalation rate scenario. The differences to the cost optimum solutions of the EAHP and DH systems were approximately 18 €/m^2 (EAHP) and 66 €/m^2 (DH) in the moderate scenario, respectively. When the global optimum solution is compared to the selected reference solution, approximately 89 €/m^2 savings in the NPV of LCC can be achieved, which equals to a 19 % cost saving potential. The global optimum solution of the moderate energy price escalation scenario consists of a GSHP system with a moderate dimensioning power output (66 kW), 180 mm thermal insulation thickness of external walls (thermal transmittance is 0.17 W/m^2K), new windows with the thermal transmittance of 0.8 W/m^2K and a large area of PV-panels (117 m^2).

In the higher energy price escalation rate scenario, the global optimum solution consists of the same renovation measures as the global optimum solution of the moderate escalation rate scenario with the exceptions that the optimum dimensioning power output of the GSHP system is increased by approximately 13 % to 76 kW and the optimum area of PV-panels is increased by approximately 10 % to the maximum installable area of 130 m^2. The LCC saving potential of the global optimum solution is approximately 20 €/m^2 compared to the A2WHP system, 27 €/m^2 compared to the EAHP system and 82 €/m^2 compared to the DH system in the higher energy price escalation rate scenario. The LCC saving potential of the global optimum solution is approximately 141 €/m^2 compared to the selected reference solution in this scenario, which equals to a 23 % cost saving potential. It can be concluded that all of the studied heat pump systems provide an excellent protection against the future increase in the delivered energy prices. This conclusion can be made by comparing the global optimum solutions and also the other cost-optimal solutions of the studied main heating systems in both energy price escalation scenarios. The effect of the higher escalation rate on the NPV of LCC is considerably lower with the heat pump systems than with the district heating system. An average increase in the LCC is approximately 19-20 % with the heat pump systems and approximately 27 % with the selected reference solution.

As a conclusion from the economic viability point of view, the cost-optimal renovation solutions of the heat pump systems delivered 15-19 % financial savings and a 39-43 % reduction in the total CO_2 emissions compared to the reference solution during the 30-year LCC in a moderate energy price escalation rate (2 %/a) scenario. In a high energy price escalation rate (4.5 %/a) scenario, the financial savings were 19-23 % and the reduction in the total CO_2 emissions over the 30-year life-cycle period 40-44 %, respectively. The corresponding figures for the cost-optimal solution of the district heating system were 5 % cost savings and 15 % total CO_2 reduction in the moderate escalation rate scenario and 10 % cost savings and 47 % total CO_2 reduction in the high energy price escalation rate scenario. No external financial support for any of the studied renovation measures was included in the economic calculations used in the optimization analyzes of the study.

According to the results, 93-96 % of the total CO_2 emissions are generated from the delivered energy consumption of the building during the 30-year life-cycle period, when the system boundary of the analysis is outlined according to the study. Therefore, renovation measures related to the energy production systems of the building are recommended, as they effectively decrease the delivered energy consumption of the building. When the breakdown of the CO_2 emissions of both the selected reference and the global optimum solutions are compared, the proportion of embodied material emissions is higher in the global optimum solution than in the reference solution. However, the absolute embodied CO_2 emissions of construction materials are actually higher in the reference solution (36 $kgCO_2/m^2$) than in the global optimum solution (34 $kgCO_2/m^2$), but as the CO_2 emissions of energy carriers constitute a larger share from the total CO_2 emissions in the reference solution, the relative proportion of the construction materials is lower. In the higher energy price escalation rate scenario, the material CO_2 emissions of the global optimum solution increase from 34 $kgCO_2/m^2$ to 35 $kgCO_2/m^2$, which is mainly coming from the installation of a higher capacity GSHP system (76 kW compared to 66 kW) and a larger area of PV-panels (130 m^2 compared to 117 m^2).

The results and limitations of the study also raised the need for future research. While the selected case apartment building was carefully selected after a detailed survey to represent a typical large panel apartment building, additional analyzes are still recommended to be conducted for the studied building type to complement the key findings and conclusions derived from this study. Similar analyzes are also recommended to be conducted for deep renovations of large panel apartment buildings located in different techno-economic environments and also in different climate conditions, where the economic level of construction materials, technical systems, labor and energy prices are different. Interesting aspect that is also recommended to be addressed in future research is to study and compare the results of CO_2 emission analyzes, including applicable heat pump and renewable energy production systems, of apartment buildings located in different climate conditions with different CO_2 emission factors of energy carriers. One of the most important aspects that is recommended to be addressed in future research is to study functional financial support mechanisms and solutions to make it more attracting for apartment owners to improve the energy efficiency of the building to the nearly zero-energy level and to further reduce the environmental impact of the existing apartment building stock by reducing the overall CO_2 emissions of the buildings.

An important aspect regarding the results and recommended renovation measures of this study is that extensive use of heat pump systems will likely change the energy policy, as the consumption of district heating energy will decrease and the electricity consumption will increase, respectively. According to the current knowledge of the national energy policy, the economic viability of both the exhaust air and the air-to-water heat pump systems used in existing residential apartment buildings will be high in the future as well, as they are typically used as an auxiliary heating system, which is combined with the original, typically district heating, main heating system. However, the economic viability of the ground source heat pump system, which typically uses significantly more electrical energy could change, if the energy policy is drastically changed. This potential scenario requires further research, as the global optimum renovation concepts related to heat pump systems will likely be different in this case.

5. Conclusions

The objective of the study was to investigate the cost-effectiveness of different energy performance improving measures conducted in deep renovations of typical large panel apartment buildings and to determine the cost-optimal renovation combinations from the studied measures. The cost-effectiveness of the renovation measures was studied from both the primary energy performance and environmental impact reduction potential perspectives by conducting two individual analyzes. A simulation-based multi-objective optimization (SBMOO) analysis was used as the main research method to determine the optimal solutions in both of the analyzes. The cost-optimal renovation concepts were determined from over 220 million renovation measure combinations to minimize both the primary energy consumption and the total CO_2 emissions of the studied apartment building.

The global optimum main heating system in all of the conducted SBMOO analyzes was the ground source heat pump system. However, the cost-effectiveness and energy performance of the exhaust air and air-to-water heat pump systems were close to the performance of the GSHP system especially, when primary energy performance is discussed. The results demonstrated that the energy performance of the cost-optimal renovation solutions was at the minimum requirement level of new apartment buildings with the ground source heat pump system and close to the proposed nearly zero-energy apartment building level with the exhaust air and air-to-water heat pump systems.

Based on the results of this study, the following conclusions can be made:

- the new proposed national nearly zero-energy apartment building level can be cost-effectively achieved in deep renovations of large panel apartment buildings by investing in the cost-optimal renovation concepts;
- the studied heat pump systems are highly recommended investments to significantly reduce the total CO_2 emissions of multi-family apartment buildings, while also delivering excellent cost-effectiveness at the same time;
- the CO_2 emissions generated from the delivered energy consumption of the building were dominant in the CO_2 emission assessment, comprising over 90 % of the total CO_2 emissions during the 30-year life-cycle period;

- significant cost savings, improvements in energy performance and reduction in the total CO_2 emissions can be achieved by investing in modern renewable energy production and HVAC systems instead of the energy performance improving measures related to the building envelope;
- the results of this study can be generalized to similar cold climate conditions and techno-economic environments, when deep renovations of large panel apartment buildings are conducted.

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