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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 CO₂ 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 €/m² net savings, 850-930 kWh/m² reduction in the primary energy consumption and 350-390 kg/m² reduction in the total CO₂ 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 CO₂ emissions.

29 **Keywords – cost-optimal renovation concept; energy performance; greenhouse gas emissions; multi-objective optimi-**
 30 **zation; renewable energy source; primary energy; large panel apartment building**

31

32

33 **1. Introduction**

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

40 According to the similar findings of several recent studies related to renovation and refurbishment of residential apart-
 41 ment buildings, concrete large panel-structured apartment buildings built between the 1960's and 1990's are the most
 42 common apartment building type with significant energy saving potential in many European countries, e.g. the Scandina-
 43 vian countries, Estonia, Russia and numerous Eastern and Northern European countries [1-3,6-9]. Balaras et al. (2005 and
 44 2000), Kuusk & Kalamees (2015), Kuusk et al. (2016) and Bonakdar et al. (2014) all conclude that apartment buildings
 45 built during this era are generally now requiring major renovation and retrofitting measures for both the building envelope
 46 and for the technical systems of the buildings [1-3,8,9]. The recast Energy Performance of Buildings -directive (EPBD)
 47 has come into force to set improved energy performance requirements and standards in both new and existing buildings for
 48 European Union member states [10]. However, studies conducted by Kuusk & Kalamees (2015), Kuusk et al. (2016 and
 49 2014), Csoknyai et al. (2016), Bonakdar et al. (2014) and Balaras et al. (2000) all include similar findings that regardless
 50 of the tightened member state-specific energy performance requirements and the EU 2020 targets to reduce both energy
 51 consumption and greenhouse gas (GHG) emissions, building owners and occupants are typically motivated to conduct
 52 major energy efficiency improving measures, in addition to the minimum mandatory maintenance repairs, in deep renova-
 53 tions only to achieve reasonable energy cost savings with reasonable investment payback period [2-4,7-9]. The findings of
 54 the aforementioned studies and a study conducted by Nemry et al. (2010) all indicate that individual renovation measures
 55 or renovation package concepts with low or even negative return on investment are difficult to be justified for apartment
 56 building owners, regardless of the improvements in energy performance or the reduction in GHG emissions [2-4,7-9,11].
 57 The recast EPBD-directive also encourages to improve the energy performance of existing buildings with technically and

58 economically viable renovation solutions and to utilize renewable energy sources (RES), when they are reasonable to be
59 used [10].

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

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

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

103 Extensive literature reviews regarding life-cycle and CO₂-emission assessments conducted by Atmaca (2015-2016)
104 indicate that there are a limited number of studies related to life-cycle assessment (LCA) of residential buildings and that
105 the more detailed emission analyzes have typically focused mainly on new buildings with various life-cycle assessment
106 periods [15-18]. Furthermore, a common conclusion in Atmaca's (2015-2016) previous studies is that the operation phase
107 of a residential building's life-cycle covers up to 50–95 % of the total energy use and GHG emissions, depending on the
108 climate conditions, energy production technologies and life-cycle period used in the analysis [15-18]. The share of the
109 operation phase from the total energy use and GHG emissions is even more dominant in typical LCC analyzes, where an
110 existing building is cost-effectively renovated and a typically selected life-cycle period of 20-30 years is used in the anal-
111 ysis.

112 The literature review regarding renovation of existing panel-structured apartment buildings indicates that large-scale
113 studies where all realizable renovation measures are studied simultaneously in order to determine the global optimum
114 renovation solutions from both the energy performance and GHG emission perspectives have not been conducted previ-
115 ously [1-3,6-9,11-19]. Furthermore, the literature review also indicates that there are a limited number of studies regarding
116 the utilization of modern heat pump and other renewable energy production technologies as a part of deep renovation of
117 panel-structured apartment buildings located in cold climate conditions, especially where the economic viability and energy

118 performance of the modern RES-based technologies are compared to the more traditional renovation measures regarding
119 the building envelope and other technical systems of the building [1-3,6-9,11-19]. Furthermore, the previous studies related
120 to renovation of apartment buildings have been conducted by using more conventional research methods that are typically
121 always limited to the total number of predefined cases and renovation measures that can be studied.

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

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

- 141 • to determine cost-optimal deep renovation concepts to maximize the primary energy performance of large
142 panel-structured apartment buildings located in cold climate conditions (analysis 1);
- 143 • to determine cost-optimal deep renovation concepts from the total CO₂ emissions perspective, to maximize
144 the environmental impact reduction potential of deep renovations of the studied building type (analysis 2);
- 145 • to study the economic viability of the cost-optimal renovation solutions to reach the proposed national nearly
146 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 CO₂ emission sources, such as embodied CO₂ emissions of construction materials, transportation and delivered energy consumption, on the total CO₂ 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 m² resulting to the heated volume of 7 952 m³. 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 CO₂-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/m²K]	0.55	
Thermal transmittance of roof, [W/m²K]	0.38	
Thermal transmittance of base floor, connected to the ground, [W/m²K]	0.44	
Thermal transmittance of windows, 2-pane structure, [W/m²K]	2.1	g-value: 0.70 ST-value 0.63 Depth of frame: 170 mm Blinds between panes
Integrated window shading		
Thermal transmittance of external doors, [W/m²K]	2.2	
Air-tightness of the building, the q_{50} -value	6.00 m³/(m² 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 CO₂-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 CO₂ 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 CO₂ 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			

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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)

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279

280

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].

291

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

293

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].

297

2.2. Assessment of CO₂ 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 CO₂ 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 CO₂ emissions and that the CO₂ reduction potential of the factors related to the energy performance of buildings is significant

306 compared to the CO₂ reduction potential of construction materials related to the building envelope and infrastructure
307 [6,11,13,32].

308 This study makes use of the key findings of the previous studies and literature and implements an appropriately prac-
309 tical analysis perspective by using the following assumptions and simplifications in the CO₂ emission calculations due to
310 their negligible impact on the total CO₂ emissions of the selected 30-year life-cycle period:

- 311 • the reference point was selected so that the existing building before the renovation was the initial situation:
 - 312 ○ construction materials used in 1973, when the building was originally constructed, and the CO₂
 - 313 emissions of energy consumption before the deep renovation were excluded from the analysis;
- 314 • furthermore, the following details were also excluded from the CO₂ emission analysis:
 - 315 ○ energy and water demand at the building site during the renovation, workmanship related to the
 - 316 installation of the studied HVAC, building services and energy production systems, all fixing-related
 - 317 work, e.g. fastening, sealing, coverings and equivalent thin layer measures, taping, gluing and equiv-
 - 318 alent small details etc., annual maintenances and renewals related to the technical systems of the
 - 319 building, and the network losses of electricity and district heating between the case building and the
 - 320 power plant;
- 321 • as the impact of recycling the demolished materials of the case building, where the demolished materials are
322 replaced with new ones, has a negligible impact on the overall emission analysis, it was also excluded from
323 the analysis.

324 All the CO₂ emissions presented and discussed in this study are the actual CO₂ emissions, not the CO₂ equivalent
325 emissions. After considering different alternative methods to be used in the CO₂ emission assessment, it was determined
326 that by using the described actual CO₂ emission data instead of the CO₂eq data, the results of the study are more universal
327 and can be used for comparison better in future studies related to the assessment of CO₂ emissions of multi-family residen-
328 tial buildings located in different conditions.

329

330 2.2.2 CO₂ emissions of construction materials

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

336 The 360optimi software also includes local material databases to be used for more accurate and detailed emission impact
337 analyzes [33]. The embodied CO₂ emissions for minimum and maximum renovation measures regarding the renovation of
338 the building envelope and the technical systems of the building according to the construction material information of the
339 ICE and 360optimi databases and relevant recent studies regarding the solar-based energy production systems are shown
340 in Table 7 [30,31,33]. Both the ICE and the 360optimi construction material data is shown in Table 7 for reference and
341 comparison, but the local material emission data was used in the analysis.

342

343 **Table 7.** The CO₂ emissions of construction materials according to 360optimi database and ICE database (shown in parentheses).

External wall structure (Fig. 3), material	Embodied CO₂ emission, kg/CO₂/kg	Minimum amount according to selected measure (Fig. 3), kg	Maximum amount according to selected measure (Fig. 3), kg	Total CO₂ emissions according to selected measure, kgCO₂
<i>Mineral wool</i>	0.89 (1.2)	5 550	20 810	4 940 – 18 520
<i>Steel (adjustable fasteners for main thermal insulation layer)</i>	2.34 (1.37)	6 650	15 360	15 560 – 35 940
<i>Wood (frames for outer thermal insulation layer)</i>	0.34 (0.71)	2 660	2 660	900
<i>Brick tiles</i>	0.28 (0.55)	43 690	43 690	12 230
Roof structure (Fig. 3), material	Embodied CO₂ emission, kg/CO₂/kg	Minimum amount according to selected measure (Fig. 3), kg	Maximum amount according to selected measure (Fig. 3), kg	Total CO₂ emissions according to selected measure, kgCO₂
<i>Bitumen</i>	0.65 (0.43)	40	40	26
<i>Concrete</i>	0.11 (0.1)	0	57 410	0 or 6 320
<i>Light gravel</i>	0.25 (0.05)	0	37 440	0 or 9 360
<i>Polyurethane insulation</i>	4.51 (3.5)	0	8 700	0 – 39 240
Windows and external doors, material	Embodied CO₂ emission, kg/CO₂/m²	Minimum amount according to selected measure, m²	Maximum amount according to selected measure, m²	Total CO₂ emissions according to selected measure, kgCO₂
<i>Basic refurbishment, painting, kg/CO₂/kg</i>	1.13 (2.12)	50 (kg)	50 (kg)	60
<i>New windows, argon filled and timber framed</i>	76–107 (50)	0	343	0 – 36 700
<i>New doors, wood + polyurethane</i>	18.5–22 (20.5)	0	79	0 – 1 740
Renewable solar-based energy production systems, includes the materials of the entire system	Embodied CO₂ emission, kg/CO₂/m²	Min. dimensioning of the system	Max. dimensioning of the system	Total CO₂ emissions according to selected measure, kgCO₂
<i>PV-panel modules, monocrystalline - ICE database (average product)</i>	242	0 m ² installed	130 m ² installed	(0 – 31 460)
<i>- 360optimi, average EU product</i>	181			0 – 23 530
<i>Solar thermal collectors, flat-plate - recent studies</i>	160	0 m ² installed	70 m ² installed	(0 – 11 200)
<i>- 360optimi, local (Finnish) product</i>	165			0 – 11 550
Main heating systems (360optimi)	Embodied CO₂ emission, kg/CO₂/system	Min. dimensioning of the system	Max. dimensioning of the system	Total CO₂ emissions according to selected measure, kgCO₂
<i>New DH system substation</i>	140	1, renewed (excl. GSHP)	1, renewed (excl. GSHP)	140
<i>Heat pump systems, includes the entire system with materials and installation equipment</i>				
<i>- GSHP system + electricity aux.</i>	16 kg/kW	10 kW (GSHP concept)	160 kW	160 – 2 560
<i>- A2WHP system</i>	12 kg/kW	10 kW (A2WHP concept)	150 kW	120 – 1 800
<i>- EAHP system</i>	14 kg/kW	30 kW (EAHP concept)	60 kW	420 – 840
Ventilation system (360optimi), the construction material of new ventilation ducts is steel	Embodied CO₂ emission, kg/CO₂/system	Min. dimensioning of the system	Max. dimensioning of the system	Total CO₂ emissions according to selected measure, kgCO₂
<i>Distributed ventilation system for:</i>				
<i>- apartments</i>	10 300	System not installed	System installed	0 or 10 300
<i>- basement floor spaces</i>	1 800	System not installed	System installed	0 or 1 800
<i>Centralized ventilation system for:</i>				

- 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 CO₂ emissions caused by the transportation is approximately 1 % from the embodied CO₂ emissions of the construction materials [33].

2.2.3 CO₂ emissions of energy carriers

The CO₂ 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 CO₂ emissions generated from delivered energy consumption as possible. The CO₂ emissions of energy carriers used in the study were [34]:

- the average CO₂-emission factor for district heating energy produced by combined heat and power (CHP) production is currently 183 kgCO₂/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 kgCO₂/MWh in Finland. The emission factor of electrical energy is an average value of the last five years.

2.2.4 Total CO₂ emissions from materials and energy carriers

The total CO₂ 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: $\sum CO_{2,materials}$ is the overall embodied CO₂ emissions of construction materials, depending on the selected renovation measures related to the building envelope and building services systems; $\sum CO_{2,energy carriers}$ is the overall CO₂ emissions of delivered energy consumption according to different energy carriers (electrical energy and district heating).

373 2.3. Energy performance calculations

374 2.3.1 Calculation of energy performance according to the primary energy consumption

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

- 381
- district heating 0.7
 - 382 • district cooling 0.4
 - 383 • electrical energy 1.7
 - 384 • fossil-based fuels 1.0
 - 385 • renewable-based fuels 0.5 [25].

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

388
389 **Fig. 5.** The energy classes of the EPC and the current proposal for nearly zero-energy apartment buildings [24].

390

391 In Finland, the same energy efficiency and nZEB classifications are applied for both new and existing buildings, even
392 though the nZEB requirements set by the recast EPBD concern only new buildings at the moment [10]. The calculation of
393 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)

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

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 CO₂ 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 CO₂ 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.

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

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

461

462 2.4.2 Selected optimization method

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

472

473 2.4.3 Operation principle of combined simulation and optimization

474 The operation principle of the combined simulation and optimization analysis used in the study is shown in Fig. 6.
475 Further information related to the combined simulation and optimization analyzes and e.g. applications using the MOBO
476 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, €; $\sum I_{0,total}$ is the total investment cost of the studied measures (see Table 5), €; $\sum MR_a$ is the total annual maintenance cost related to the studied renovation measures, €/a; $\sum R_M$ is the total renewal cost related to the studied renovation measures, €; $\sum E_a$ 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 CO₂ emissions of the case building and the NPV of the 30-year LCC. The minimization of the CO₂ 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 CO₂ 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

528 pump systems would be even higher than the presented IRRs, where the escalation rates are not taken into account. The
529 selected reference solution, where other solutions are compared includes the following renovation and retrofitting
530 measures:

- 531 • the external walls are renovated according to Fig. 3, the thermal transmittance of new walls is 0.23 W/m²K;
- 532 • the roof is renovated according to Fig. 3, the thermal transmittance of new roof is 0.13 W/m²K;
- 533 • the original windows are replaced, new windows are: thermal transmittance 0.8 W/m²K and g-value 0.49;
- 534 • the original external doors are replaced, the thermal transmittance of new doors is 0.7 W/m²K;
- 535 • the original district heating substation is renewed;
- 536 • the original ventilation system is not renovated and no renewable energy production systems are installed.

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

- 543 • the external walls are renovated so that the thermal transmittance of new walls is 0.11 W/m²K (280 mm
544 insulation);
- 545 • the roof is renovated so that the thermal transmittance of new roof is 0.07 W/m²K (400 mm insulation);
- 546 • the original windows are replaced, new windows are: thermal transmittance 0.7 W/m²K and g-value 0.42;
- 547 • the original external doors are replaced, the thermal transmittance of new doors is 0.7 W/m²K;
- 548 • the original district heating substation is renewed;
- 549 • 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.

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

<i>Primary energy consumption [kWh/m²,a]</i>	<i>75 (A-class)</i>	<i>80</i>	<i>100 (B-class)</i>	<i>116 (proposal for nZEB)</i>	<i>120</i>	<i>130 (C-class)</i>	<i>158, GOS (minimum requirement)</i>
<i>Recommended main heating system</i>	DH	GSHP	GSHP	EAHP	A2WHP	GSHP	GSHP
<i>NPV of LCC, 30 years [€/m²]</i>	501	427	370	410	407	401	398
<i>Investment cost of studied measures [€/m²]</i>	333	352	294	212	206	227	220
<i>IRR, internal rate of return for the renovation measure package [%/a]</i>	±0.0	2.3	5.2	36.1	86.2	17.8	24.3
<i>Thermal insulation thickness of external walls [mm]</i>	300	280	160	180	180	180	180
<i>Additional thermal insulation thickness of roof or BR [mm]</i>	+400	+400	0, BR	0, BR	0, BR	0, BR	0, BR
<i>Replacement of windows or BR, thermal transmittance and g-value of windows [W/m² K]</i>	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
<i>Replacement of external doors, thermal transmittance of doors [W/m² K]</i>	Yes, 0.7	Yes, 0.7	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
<i>Area of PV-panels [m²]</i>	129	129	128	130	129	129	128
<i>Area of solar thermal collectors [m²]</i>	69	0	0	0	0	0	0
<i>Power output of the heat pump system [kW]</i>	-	67	50	49	41	106	87
<i>Individual renovation of the ventilation system of apartments</i>	Yes, distributed	No	No	No	No	No	No
<i>Individual renovation of the ventilation system of base floor spaces</i>	Yes, distributed	No	No	No	Yes, distributed	No	No
<i>Renovation of the entire ventilation system of the building to centralized system</i>	No	Yes	Yes	No	No	No	No

558
559 **Table 9.** Recommended renovation measures in terms of PE consumption to meet different energy efficiency criteria, new proposed PE
560 weighing factors used in the analysis. GOS and BR stand for Global Optimum Solution and Basic Refurbishment.

<i>Primary energy consumption [kWh/m²,a]</i>	<i>55</i>	<i>60</i>	<i>70</i>	<i>80</i>	<i>90 (new proposal for nZEB)</i>	<i>100</i>	<i>112, GOS (minimum requirement)</i>
<i>Recommended main heating system</i>	GSHP	GSHP	GSHP	EAHP	GSHP	GSHP	GSHP
<i>NPV of LCC, 30 years [€/m²]</i>	482	443	427	410	400	398	398
<i>Investment cost of studied measures [€/m²]</i>	342	323	294	212	227	215	215
<i>IRR, internal rate of return for the renovation measure package [%/a]</i>	1.1	3.5	5.3	36.2	18.1	32.3	32.3
<i>Thermal insulation thickness of external walls [mm]</i>	300	300	180	180	160	180	180
<i>Additional thermal insulation thickness of roof or BR [mm]</i>	+400	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR
<i>Replacement of windows or BR, thermal transmittance and g-value of windows [W/m² K]</i>	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
<i>Replacement of external doors, thermal transmittance of doors [W/m² K]</i>	Yes, 1.0	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
<i>Area of PV-panels [m²]</i>	130	128	128	130	129	129	129
<i>Area of solar thermal collectors [m²]</i>	0	0	0	0	0	0	0
<i>Power output of the heat pump system [kW]</i>	65	79	40	48	85	79	79
<i>Individual renovation of the ventilation system of apartments</i>	Yes, distributed	No	No	No	No	No	No
<i>Individual renovation of the ventilation system of base floor spaces</i>	Yes, distributed	No	No	No	Yes, distributed	No	No
<i>Renovation of the entire ventilation system of the building to centralized system</i>	No	Yes	Yes	No	No	No	No

563 Fig. 8, and Tables 10-11 present the cost-optimal renovation solutions to meet different CO₂ emission criteria using
564 both moderate (2.0 %/a) and high (4.5 %/a) energy price escalation rate scenarios.

565

566

567 **Fig. 8.** Cost-optimal renovation solutions in terms of CO₂ emissions for different main heating systems using a moderate (2.0 %/a)
568 energy price escalation scenario (above) and a high (4.5 %/a) energy price escalation scenario (below) in the analysis.

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

575

576 **Table 10.** Recommended renovation measures in terms of CO₂ emissions to meet different CO₂ emission criteria, moderate energy price
577 escalation (2.0 %/a) scenario. GOS and BR stand for Global Optimum Solution and Basic Refurbishment.

<i>Total CO₂ emissions [kgCO₂/m²,30a]</i>	<i>380</i>	<i>390</i>	<i>410</i>	<i>470</i>	<i>500</i>	<i>530, GOS</i>	<i>560, GOS</i>
<i>Recommended main heating system</i>	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP
<i>NPV of LCC, 30 years [€/m²]</i>	445	439	430	421	397	389	389
<i>Investment cost of studied measures [€/m²]</i>	316	309	293	264	229	212	212
<i>IRR, internal rate of return for the renovation measure package [%/a]</i>	2.6	3.1	4.0	5.8	14.7	37.4	37.4
<i>Thermal insulation thickness of external walls [mm]</i>	230	230	180	280	280	180	180
<i>Additional thermal insulation thickness of roof or BR [mm]</i>	0, BR	0, BR	0, BR	+250	0, BR	0, BR	0, BR
<i>Replacement of windows or BR, thermal transmittance and g-value of windows [W/m² K]</i>	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
<i>Replacement of external doors, thermal transmittance of doors [W/m² K]</i>	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
<i>Area of PV-panels [m²]</i>	126	118	128	125	128	117	117
<i>Area of solar thermal collectors [m²]</i>	0	0	0	0	0	0	0
<i>Power output of the heat pump system [kW]</i>	76	57	39	100	74	66	66
<i>Individual renovation of the ventilation system of apartments</i>	No	No	No	No	No	No	No
<i>Individual renovation of the ventilation system of base floor spaces</i>	No	No	No	Yes, distributed	No	No	No
<i>Renovation of the entire ventilation system of the building to centralized system</i>	Yes	Yes	Yes	No	No	No	No

578

579 **Table 11.** Recommended renovation measures in terms of CO₂ emissions to meet different CO₂ emission criteria, high energy price
580 escalation (4.5 %/a) scenario. GOS and BR stand for Global Optimum Solution and Basic Refurbishment.

<i>Total CO₂ emissions [kgCO₂/m²,30a]</i>	<i>370</i>	<i>380</i>	<i>390</i>	<i>410</i>	<i>470</i>	<i>500</i>	<i>530, GOS</i>
<i>Recommended main heating system</i>	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP
<i>NPV of LCC, 30 years [€/m²]</i>	535	498	494	490	476	466	466
<i>Investment cost of studied measures [€/m²]</i>	365	317	307	298	246	222	216
<i>IRR, internal rate of return for the renovation measure package [%/a]</i>	0.5	2.7	3.1	3.7	8.8	19.1	26.8
<i>Thermal insulation thickness of external walls [mm]</i>	300	280	180	180	280	180	180
<i>Additional thermal insulation thickness of roof or BR [mm]</i>	+150	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR
<i>Replacement of windows or BR, thermal transmittance and g-value of windows [W/m² K]</i>	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
<i>Replacement of external doors, thermal transmittance of doors [W/m² K]</i>	Yes, 0.7	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
<i>Area of PV-panels [m²]</i>	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 CO₂ 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 CO₂ emissions of the reference (bottom left) and the global optimum (bottom right) solutions.

595 According to Fig. 9 and Tables 10-11, no significant additional investments are needed, when the global optimum
596 solutions of both energy price escalation rate analyzes are compared, as the GSHP system delivers excellent cost-effective-
597 ness in an increasing energy price development scenario. However, the higher energy price escalation rate has a significant
598 impact on the LCC of the reference solution, where the main heating system of the building is district heating. According
599 to Fig. 9, the CO₂ emissions caused by the delivered energy consumption are dominant over the transportation and embod-
600 ied CO₂ emissions of the construction materials. In the higher energy price escalation rate scenario, the breakdown of both
601 LCC and CO₂ emissions was similar to the breakdown of LCC and CO₂ emissions of the moderate energy price escalation
602 rate scenario. The share of the energy cost was approximately 9 % higher and the share of the investment cost approximately
603 9 % lower, respectively. The breakdown of the total CO₂ emissions was basically identical in both energy price escalation
604 rate scenarios.

605 4. Discussion

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

619 The cost-optimal energy performance level of the deep renovation was approximately at the minimum energy perfor-
620 mance requirement level (NBCF part D3 (2012)) of new apartment buildings with the GSHP system and close to the
621 initially proposed national nearly zero-energy apartment building level (FlInZEB project, $\text{PE} \leq 116 \text{ kWh}/(\text{m}^2, \text{a})$ with the
622 currently used higher PE weighing factors) with the A2WHP and EAHP systems [48]. According to the analyzes, the new
623 proposed national nZEB requirements ($\text{PE} \leq 90 \text{ kWh}/(\text{m}^2, \text{a})$ with the proposed lower PE weighing factors) of apartment
624 buildings can be more easily and cost-effectively achieved than the initially proposed nZEB requirements ($\text{PE} \leq 116$

625 kWh/(m²,a) with the currently used higher PE weighing factors). The initial nZEB requirement could be achieved by in-
626 vesting approximately 215-220 €/m² with the A2WHP and EAHP systems resulting in approximately 36 % internal rate of
627 return with the EAHP system and approximately 26 % IRR with the A2WHP system, when the investments are compared
628 to the selected reference solution described in chapter 3.1. Approximately 250 €/m² have to be invested with the GSHP
629 system concept to reach the initial nZEB requirement resulting in 9 % IRR compared to the reference solution, respectively.
630 The new proposed nZEB requirement level ($PE \leq 90 \text{ kWh}/(\text{m}^2, \text{a})$ with the proposed lower PE weighing factors) can be
631 cost-effectively achieved with all heat pump systems, resulting in 18 % IRR with the GSHP system, 36 % IRR with the
632 EAHP system and 26 % IRR with the A2WHP system.

633 According to the results, installation of a solar-based electricity production system with PV-panels is a highly recom-
634 mended and cost-effective measure with all studied main heating systems, when primary energy performance is discussed.
635 In addition, a solar-based thermal production system is also recommended to be installed with the district heating system
636 delivering good cost-effectiveness, but it is not recommended to be used with any of the heat pump systems in apartment
637 buildings located in cold climate conditions, as the high energy performance of the modern heat pump systems reduce the
638 cost-effectiveness of the solar thermal system significantly. An essential aspect in the design process of the PV-panel sys-
639 tem in Finland is to dimension the system so that all of the produced electricity can be used on-site. This requires careful
640 matching analysis of the building's electricity production and consumption profiles and loads in the designing process so
641 that the dimensioning of the PV-panel system matches the electricity consumption profile and loads of the building. While
642 the produced electrical energy can also be exported back to the grid and sold to the energy company, it is currently not
643 cost-effective or recommendable for apartment building owners. The maximum area of PV-panels (130 m²) used in the
644 SBMOO analyzes was dimensioned so that all of the produced electricity can be used in the studied building.

645 When primary energy performance is discussed, the optimum combination of renovation measures to reach specific
646 energy performance criteria is a little different with each main heating system, as the same energy performance criteria and
647 cost-effectiveness can be achieved with multiple combination of measures, e.g. by investing more in the heat pump and
648 technical systems, which also require annual maintenance and renewal investments, with the GSHP system or by investing
649 more in the energy performance improving measures related to the building envelope, which don't require annual mainte-
650 nance or renewal investments during the 30-year LCC period, with the EAHP and A2WHP systems. Another essential
651 aspect regarding the cost-effectiveness of the heat pump systems is that the annual basic fee of district heating was assumed
652 to be reduced according to the reduction in peak heating power demand of the building. In general, this means that an
653 EAHP system with 40 kW dimensioning power output reduces the annual peak heating power demand of the district heating
654 system by 40 kW, respectively. Furthermore, as the primary energy weighing factor of district heating is significantly lower

655 than the PE weighing factor of electricity (currently 0.7 for district heating and 1.7 for electricity), the primary energy
656 performance of hybrid energy systems, where a heat pump system with a relatively low dimensioning power output is
657 combined with the district heating system, is typically improved.

658 The additional SBMOO analyzes conducted by using the lower PE weighing factors delivered similar results than the
659 analyzes conducted using the currently used higher PE weighing factors. The global optimum main heating system concept
660 in the additional analyzes using the lower PE weighing factors was the GSHP system, respectively. The major differences
661 between the global optimum solutions of the two analyzes were that the dimensioning power output of the GSHP system
662 was approximately 10 % lower (79 kW vs 87 kW) and the energy efficiency of new windows was a little lower (thermal
663 transmittance 1.0 vs 0.8 W/m²K) in the analyzes conducted using the lower PE weighing factors. According to the results,
664 other measures were practically identical in both analyzes. Due to the fact that the ratio between the PE weighing factors
665 of both the district heating and electricity were decreased equally much (approximately 30 %), the relationships between
666 the energy performance and cost-effectiveness of the renovation measure packages using more district heating or electricity
667 were unchanged.

668 The primary energy performance of the cost-optimal solutions of the district heating system is the highest of all studied
669 main heating systems, but the cost-effectiveness that can be achieved by using the DH system is significantly lower than
670 the cost-effectiveness achievable by investing in cost-optimally dimensioned heat pump systems (see Fig. 7). The cost-
671 optimal solutions of the DH system deliver approximately 12-15 % higher life-cycle costs during the 30-year discount
672 period in both PE weighing factor analyzes than the cost-optimal solutions of the studied heat pump systems. Furthermore,
673 17-21 % lower LCC can be achieved by selecting the cost-optimal solutions of the heat pump systems over the presented
674 reference solutions described in chapter 3.1. These results clearly demonstrate that investments in heat pump and solar-
675 based renewable energy production systems are recommended renovation measures over the energy performance improv-
676 ing measures related to the building envelope, when both the cost-effectiveness and primary energy performance are dis-
677 cussed.

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

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

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

707 The results of the SBMOO analyzes regarding the CO₂ emissions delivered similar conclusions than the optimization
708 results of the PE consumption. Investments in heat pump and technical systems of the building are recommended over the
709 investments in the building envelope and they also deliver significantly better cost-effectiveness and protection against an
710 increasing energy price development. The delivered target energy consumption was used to determine the CO₂ emissions
711 caused by the energy consumption of the building. The major difference between the PE and delivered target energy con-
712 sumption calculation methods is the use of the building. In the PE consumption calculation the energy consumption is
713 calculated by using the standardized internal heat gains and usage profiles, whereas the delivered target energy consumption
714 is calculated by using the real design and operation schedules of the building, which are determined according to the real

715 use of the building. The global optimum solution of the moderate energy price escalation rate scenario was achieved with
716 the GSHP system. The NPV of LCC of the global optimum solution was approximately 12 €/m² lower than the NPV of
717 LCC of the cost optimum solution of the A2WHP system in the moderate energy price escalation rate scenario. The differ-
718 ences to the cost optimum solutions of the EAHP and DH systems were approximately 18 €/m² (EAHP) and 66 €/m² (DH)
719 in the moderate scenario, respectively. When the global optimum solution is compared to the selected reference solution,
720 approximately 89 €/m² savings in the NPV of LCC can be achieved, which equals to a 19 % cost saving potential. The
721 global optimum solution of the moderate energy price escalation scenario consists of a GSHP system with a moderate
722 dimensioning power output (66 kW), 180 mm thermal insulation thickness of external walls (thermal transmittance is 0.17
723 W/m²K), new windows with the thermal transmittance of 0.8 W/m²K and a large area of PV-panels (117 m²).

724 In the higher energy price escalation rate scenario, the global optimum solution consists of the same renovation
725 measures as the global optimum solution of the moderate escalation rate scenario with the exceptions that the optimum
726 dimensioning power output of the GSHP system is increased by approximately 13 % to 76 kW and the optimum area of
727 PV-panels is increased by approximately 10 % to the maximum installable area of 130 m². The LCC saving potential of
728 the global optimum solution is approximately 20 €/m² compared to the A2WHP system, 27 €/m² compared to the EAHP
729 system and 82 €/m² compared to the DH system in the higher energy price escalation rate scenario. The LCC saving po-
730 tential of the global optimum solution is approximately 141 €/m² compared to the selected reference solution in this sce-
731 nario, which equals to a 23 % cost saving potential. It can be concluded that all of the studied heat pump systems provide
732 an excellent protection against the future increase in the delivered energy prices. This conclusion can be made by comparing
733 the global optimum solutions and also the other cost-optimal solutions of the studied main heating systems in both energy
734 price escalation scenarios. The effect of the higher escalation rate on the NPV of LCC is considerably lower with the heat
735 pump systems than with the district heating system. An average increase in the LCC is approximately 19-20 % with the
736 heat pump systems and approximately 27 % with the selected reference solution.

737 As a conclusion from the economic viability point of view, the cost-optimal renovation solutions of the heat pump
738 systems delivered 15-19 % financial savings and a 39-43 % reduction in the total CO₂ emissions compared to the reference
739 solution during the 30-year LCC in a moderate energy price escalation rate (2 %/a) scenario. In a high energy price esca-
740 lation rate (4.5 %/a) scenario, the financial savings were 19-23 % and the reduction in the total CO₂ emissions over the 30-
741 year life-cycle period 40-44 %, respectively. The corresponding figures for the cost-optimal solution of the district heating
742 system were 5 % cost savings and 15 % total CO₂ reduction in the moderate escalation rate scenario and 10 % cost savings
743 and 47 % total CO₂ reduction in the high energy price escalation rate scenario. No external financial support for any of the
744 studied renovation measures was included in the economic calculations used in the optimization analyzes of the study.

745 According to the results, 93-96 % of the total CO₂ emissions are generated from the delivered energy consumption of
746 the building during the 30-year life-cycle period, when the system boundary of the analysis is outlined according to the
747 study. Therefore, renovation measures related to the energy production systems of the building are recommended, as they
748 effectively decrease the delivered energy consumption of the building. When the breakdown of the CO₂ emissions of both
749 the selected reference and the global optimum solutions are compared, the proportion of embodied material emissions is
750 higher in the global optimum solution than in the reference solution. However, the absolute embodied CO₂ emissions of
751 construction materials are actually higher in the reference solution (36 kgCO₂/m²) than in the global optimum solution (34
752 kgCO₂/m²), but as the CO₂ emissions of energy carriers constitute a larger share from the total CO₂ emissions in the refer-
753 ence solution, the relative proportion of the construction materials is lower. In the higher energy price escalation rate sce-
754 nario, the material CO₂ emissions of the global optimum solution increase from 34 kgCO₂/m² to 35 kgCO₂/m², which is
755 mainly coming from the installation of a higher capacity GSHP system (76 kW compared to 66 kW) and a larger area of
756 PV-panels (130 m² compared to 117 m²).

757 The results and limitations of the study also raised the need for future research. While the selected case apartment
758 building was carefully selected after a detailed survey to represent a typical large panel apartment building, additional
759 analyzes are still recommended to be conducted for the studied building type to complement the key findings and conclu-
760 sions derived from this study. Similar analyzes are also recommended to be conducted for deep renovations of large panel
761 apartment buildings located in different techno-economic environments and also in different climate conditions, where the
762 economic level of construction materials, technical systems, labor and energy prices are different. Interesting aspect that is
763 also recommended to be addressed in future research is to study and compare the results of CO₂ emission analyzes, includ-
764 ing applicable heat pump and renewable energy production systems, of apartment buildings located in different climate
765 conditions with different CO₂ emission factors of energy carriers. One of the most important aspects that is recommended
766 to be addressed in future research is to study functional financial support mechanisms and solutions to make it more at-
767 tracting for apartment owners to improve the energy efficiency of the building to the nearly zero-energy level and to further
768 reduce the environmental impact of the existing apartment building stock by reducing the overall CO₂ emissions of the
769 buildings.

770 An important aspect regarding the results and recommended renovation measures of this study is that extensive use of
771 heat pump systems will likely change the energy policy, as the consumption of district heating energy will decrease and
772 the electricity consumption will increase, respectively. According to the current knowledge of the national energy policy,
773 the economic viability of both the exhaust air and the air-to-water heat pump systems used in existing residential apartment
774 buildings will be high in the future as well, as they are typically used as an auxiliary heating system, which is combined

775 with the original, typically district heating, main heating system. However, the economic viability of the ground source
776 heat pump system, which typically uses significantly more electrical energy could change, if the energy policy is drastically
777 changed. This potential scenario requires further research, as the global optimum renovation concepts related to heat pump
778 systems will likely be different in this case.

779 5. Conclusions

780 The objective of the study was to investigate the cost-effectiveness of different energy performance improving
781 measures conducted in deep renovations of typical large panel apartment buildings and to determine the cost-optimal ren-
782 ovation combinations from the studied measures. The cost-effectiveness of the renovation measures was studied from both
783 the primary energy performance and environmental impact reduction potential perspectives by conducting two individual
784 analyzes. A simulation-based multi-objective optimization (SBMOO) analysis was used as the main research method to
785 determine the optimal solutions in both of the analyzes. The cost-optimal renovation concepts were determined from over
786 220 million renovation measure combinations to minimize both the primary energy consumption and the total CO₂ emis-
787 sions of the studied apartment building.

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

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

- 795 • the new proposed national nearly zero-energy apartment building level can be cost-effectively achieved in
796 deep renovations of large panel apartment buildings by investing in the cost-optimal renovation concepts;
- 797 • the studied heat pump systems are highly recommended investments to significantly reduce the total CO₂
798 emissions of multi-family apartment buildings, while also delivering excellent cost-effectiveness at the same
799 time;
- 800 • the CO₂ emissions generated from the delivered energy consumption of the building were dominant in the
801 CO₂ emission assessment, comprising over 90 % of the total CO₂ emissions during the 30-year life-cycle
802 period;

- significant cost savings, improvements in energy performance and reduction in the total CO₂ 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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