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Towards the EU emissions targets of 2050: Optimal energy renovation measures of Finnish apartment buildings

Janne Hirvonen[a]*, Juha Jokisalo[a], Juhani Heljo[b], Risto Kosonen[a,c]

[a]*Department of Mechanical Engineering, Aalto University, Espoo, Finland;*

[b]*Department of Civil Engineering, Tampere University of Technology, Tampere, Finland*

[c]*College of Urban Construction, Nanjing Tech University, Nanjing, P.R. China*

* Department of Mechanical Engineering, Aalto University, PO Box 14400, FI-00076 AALTO, janne.p.hirvonen@aalto.fi , +35850 431 5780

Towards the EU emissions targets of 2050: Optimal energy renovation measures of Finnish apartment buildings

Member countries of the European Union have released targets to reduce carbon dioxide emissions by 80% by the year 2050. Energy use in buildings is a major source of these emissions, which is why this study focused on the cost-optimal renovation of Finnish apartment buildings. Apartment buildings from four different construction years (pre-1976, 1976-2002, 2003-2009 and post-2010) were modelled, using three different heating systems: district heating, ground-source heat pump and exhaust air heat pump. Multi-objective optimization was utilized to find the most cost-effective energy renovation measures.

Most cost-effective renovation measures were ground-source heat pumps, demand-based ventilation and solar electricity. Additional thermal insulation of walls was usually too expensive. By performing only the cost-effective renovations, the emissions could be reduced by 80, 82, 69 and 68%, from the oldest to the newest buildings, respectively. This could be done with the initial investment cost of 296, 235, 115 and 104 €/m^2, respectively.

Keywords: Cost-optimal renovation, Energy performance, Multi-objective optimization, Greenhouse gas emissions, Apartment building

1. Introduction

Avoiding the worst effects of climate change is one of the major objectives of the European Union (EU). Therefore, the EU has made a decision to significantly reduce greenhouse gas emissions. Two significant milestones for the EU are the goal to reduce greenhouse gas emissions by 40% relative to 1990 levels by the year 2030 (European Commission, 2018) and by 80% by the year 2050 (European Commission, 2018). Most emissions are produced by energy generation and 40% of European total energy consumption happens in buildings (The European Parliament and the Council of the

European Union, 2010), which is why reducing the energy consumption of buildings is an important sub-objective for the decarbonization challenge. For this reason, the EU has implemented the Energy Performance of Buildings Directive (EPBD) (The European Parliament and the Council of the European Union, 2010), which declares that all new buildings should be nearly zero energy buildings by the end of the year 2020. As a result, construction standards have tightened and new buildings use significantly less energy than old buildings (Saari, et al., 2012). However, most of the building stock consists of old, low performance buildings. For example, in Greece 70% of buildings have been built before the implementation of energy performance regulations (Chadiarakou & Santamouris, 2014). Similarly in Finland, 43% of the housing stock has been built in the 1950s, -60s and -70s (Holopainen, et al., 2016). To significantly reduce the emissions caused in the building sector, the old buildings need to be renovated to higher standards. Due to the importance of the topic, many studies have been made on different aspects of energy renovations. General methodology to support decision making for building energy renovation has been presented in (Mora, et al., 2018) and the technical, social and environmental feasibility of renovation solutions have been examined for different countries in (Holopainen, et al., 2016). While energy renovations can be uneconomical, they can also increase the value of the building, as well as improve the quality of the indoor air.

Since different types of buildings have different use patterns, they also require solutions tailored to that specific building type. Case studies showing the results in different situations are important. Energy retrofit designs have been done on daycare centers (Jradi, et al., 2018), office buildings (Gustafsson, et al., 2017), educational buildings (Niemelä, et al., 2016) and museums (Zannis, et al., 2006). Historical buildings typical in the Mediterranean area (Gagliano, et al., 2016) require different treatment than residential buildings in the Nordic region (Niemelä, et al., 2017).

Decarbonization of national energy systems is an important goal. Such plans have been studied before, such as in a German study which examined how 100% of German energy use could be covered by renewable energy (Henning & Palzer, 2014). However, in that study, the improvements in the building sector were modeled in a simplified way, without taking into account any specific energy renovation measures. Conversely, in this study, the specifics of the building sector are examined in more detail, as a precursor for a later study on the whole national energy system. As it is not individual buildings, but the whole building stock that determines the importance of the performance improvements, it is imperative to know the age distribution of different types of buildings existing in a nation. This affects their structural and HVAC solutions, determining the energy performance of the building stock. When this is known, energy renovations can be prioritized according to the emission reduction potential available. There are different methods to find out the energy consumption of buildings. Probabilistic energy consumption models were studied in (Barkhudaryan, et al., 2016). Increasingly common, however, is the use of dynamic building simulation software such as EnergyPlus, TRNSYS or IDA-ICE (Nageler, et al., 2018). Typically, studies on optimal building designs and retrofitting have been done by calculating the performance of a set amount of pre-defined design packages, such as in (Ferreira, et al., 2016). However, this limits the number of possible options and may not provide the truly optimal solution. It is becoming increasingly common to combine simulation software with optimization algorithms to provide more accurate design information (Nguyen, et al., 2014).

In Finland, apartment buildings and single family houses are the most significant segments of buildings. This study focuses on apartment buildings, which make up 21% of the total floor area of buildings in Finland (Statistics Finland, 2017) and are responsible for 26% of the energy consumption in the residential sector. The main topic is the energy renovation of apartment buildings in a cold climate, using dynamic building simulations and multi-objective optimization as tools in determining cost-optimal solutions. In an effort to cover the whole apartment building stock, several age categories of buildings were chosen and optimized separately. Earlier studies have found great potential to reduce energy demand and emissions in old residential buildings. Heating demand reduction of 68% was possible in Moscowian residential districts (Paiho, et al., 2013). In Estonia, it was found that old apartment buildings could be cost-effectively renovated close to the current efficiency standard (Kuusk, et al., 2014).

Energy efficiency in Finland is typically measured through delivered or primary energy consumption, using constant primary energy factors. This study examines cost-effective CO_2 emission reduction over 25 year, using variable CO_2 emission factors, which has not been done before. This gives a stronger emphasis on energy consumption in the heating season and provides a more realistic estimate of the benefits of solar energy. The novelty of this study is in examining all the age classes of Finnish apartment buildings, for which cost-optimal energy retrofit solutions are determined with respect to reductions in carbon dioxide emissions for the first time. Multi-objective optimization is used to find the tradeoff between cost and emissions. The study presents new information on how effective different methods are in reducing emissions in buildings of different ages, how much different retrofit levels affect life cycle costs and how much upfront investments are needed to reduce emissions. It shows the role that building retrofitting can play when reaching for the EU emission targets for 2050.

2. Methods

2.1. Simulation setup

The study was made using dynamic simulations and multi-objective optimization, as shown in Figure 1. To find the hourly energy demand in the building, simulations were carried out with the IDA-ICE simulation software (EQUA Simulation AB, 2018), which has been validated according to CEN standards (EQUA Simulation AB, 2010). The calculations were done for the climate of Southern Finland, using the Finnish test reference year (TRY2012), which has been shown to describe the current Finnish climatic conditions (Kalamees, et al., 2012). The simulation results from a single year were then used in MATLAB to perform additional energy system performance and life cycle cost (LCC) calculations.

Multi-objective optimization was performed with MOBO software, utilizing the NSGA-II genetic algorithm and parallel computation. The optimization algorithm determined whether or not to perform each individual retrofitting measure. Optimization time was reduced by doing the simulation in two stages. First, the simulation of the building was performed in IDA-ICE and the hourly results archived. In the second stage, the results were utilized in MATLAB for the energy system, emissions and LCC calculations. If during optimization, a previously simulated building configuration was used again, instead of running the same IDA-ICE simulation a second time, the previous solution was retrieved from the archive (Figure 1). This reduced the total time needed for optimization by skipping unnecessary computations.

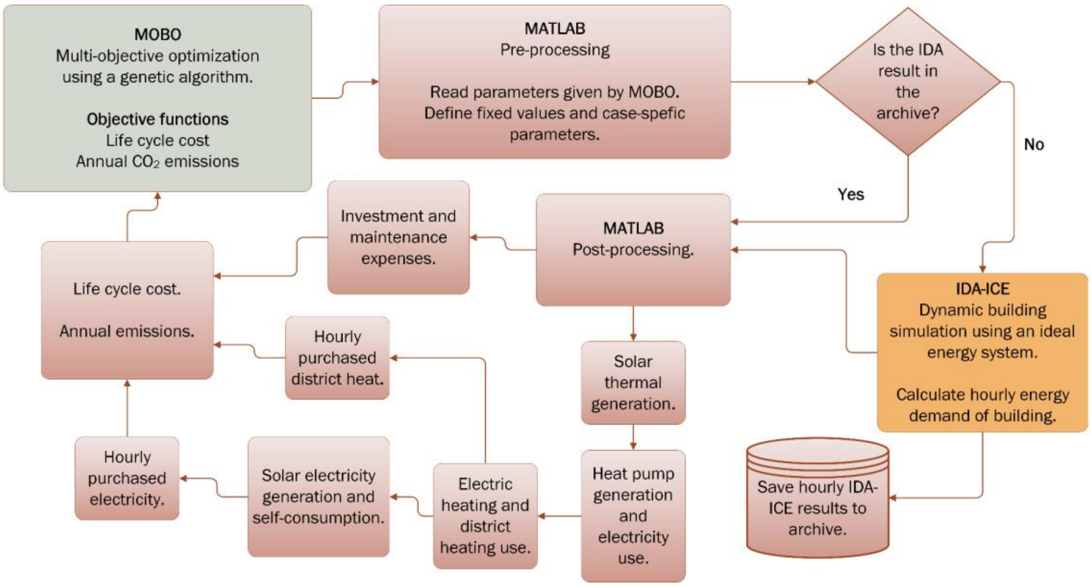

Figure 1: Process flow for the simulation and optimization procedure.

2.2. Building descriptions

The goal of the study was to find the emission and cost reduction potential of retrofits for the Finnish apartment building stock. For that purpose, four different age classes of apartment buildings (AB) were modelled and optimized separately. The utilized building models have been shown to be representative of typical Finnish apartment buildings (Saari, et al., 2012). The age classes were chosen according to changes in the Finnish building regulations (Ministry of the Environment, 2017). Before 1976 there were no building energy regulations. Buildings from before this time were chosen as one age class (AB1). Between 1976 and 2002 the building code was gradually tightened, but the changes were relatively small. Buildings from this period were chosen as the second class (AB2). Both AB1 and AB2 had mechanical exhaust ventilation without heat recovery (Saari, et al., 2012). Between 2003 and 2009, ventilation heat recovery became the norm and U-value requirements for building envelope were tightened, forming the basis for the third age class AB3. The final age class, AB4 consists of buildings built after 2010, equipped with a further improved heat recovery system and thermal insulation level of the envelope, along with a low temperature heat distribution system.

Figure 2 shows the total floor area in buildings of different ages, and groups the age classes according to similar building code. In the age classes with varying demands of the building codes, the building characteristics were averaged, based on the amount of buildings built in different time periods. The details of the chosen age categories, based on carefully selected sources, are shown in Table 1.

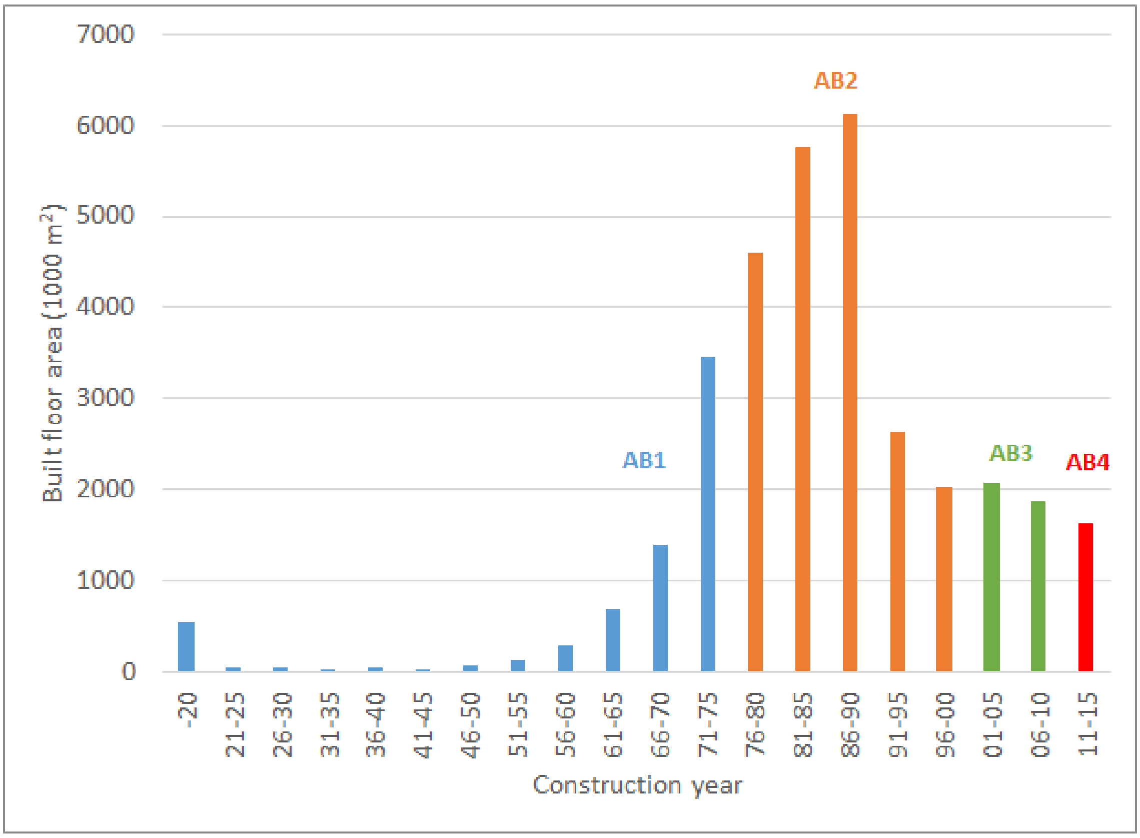

Figure 2: Floor areas of existing Finnish apartment buildings. Periods of different building codes (AB1-AB4) are identified by different colors.

Table 1: Properties of the typical buildings and HVAC systems for four age classes. (Ministry of the Environment, 2017), (Dyhr, 1993)

Type name	**AB1**	**AB2**	**AB3**	**AB4**
Construction years	-1975	1976 - 2002	2003 - 2009	2010 - 2020
U-values of envelope (W/m^2K)				
External wall	0.81	0.34	0.25	0.17
Floor	0.47	0.38	0.27	0.16
Roof	0.47	0.26	0.17	0.09

Doors	2.2	1.4	1.4	1
Windows	1.7	1.7	1.4	1
Glazing properties				
Total solar heat transmittance (g)	0.71	0.71	0.6	0.5
Direct solar transmittance (ST)	0.64	0.64	0.54	0.45
Air tightness				
n_{50}, (1/h)	3.2	1.0	0.9	0.7
q_{50} $m^3/(h\ m^2)$	9.7	2.6	2.0	1.5
Ventilation				
Type	Mech exh	Mech exh	Mech sup-exh	Mech sup-exh
Heat recovery efficiency	0	0	0.60	0.65
Air exchange rate (1/h)	0.5	0.5	0.5	0.5
SFP ($kW/m^3/s$)	1.5	1.5	2.5	2
Supply air temperature (°C)	Ambient	Ambient	18	18
Water radiator design temperatures (°C)	70/40	70/40	70/40	45/35
Heat distribution efficiency	0.8	0.8	0.9	0.9
Room air temperature setpoint (°C)	22	22	21.5	21
Heated net floor area (m^2)	4050	2638	1585	1585
Envelope area (m^2)	3540	2659	1871	1871
Window area (m^2)	464	170	156	156
Total air volume (m^3)	10653	6906	4120	4120

2.3. Building service systems

Three alternative heating systems were used in the buildings. Each heating system was optimized separately so that the main heating system was fixed for each optimization run. The selected heating systems were

(1) District heating only (DH)
(2) Ground-source heat pump with electric backup heating (GSHP)
(3) Exhaust air heat pump with district heating backup (EAHP).

The district heated building was used as the reference case in all optimizations, because it is the most common heating system in Finnish apartment buildings. As the EAHP serves a similar function as ventilation heat recovery, it does not provide any extra energy savings and was not used as an option in buildings AB3 and AB4, which were equipped with ventilation heat recovery by default. The main heating systems were supported by optional solar thermal (ST) (Savo-Solar Oy, 2013) and solar electric systems (PV) (AXITEC Energy GmbH & Co. KG, 2016), which were modelled according to commercial products. The energy system calculations, including calculation of heat pump coefficient of performance (COP) and solar energy effects, were performed by post-processing in MATLAB. This allowed the separation of the building dynamics and the energy balance calculations.

The temperature in the water radiator system was adjusted according to the outdoor temperature. When heat pump systems were utilized, installation of low temperature radiators was one optimization variable. Three linear control curves for inlet water temperature were utilized for the different radiator types: the inlet temperature was 70, 65 or 45 °C when the outdoor temperature was below 26 °C and lowered linearly to 20 °C as the outdoor temperature rose to 20 °C. In the case of domestic hot water (DHW), the distribution temperature was fixed to 60 °C. The coefficient of performance (COP) of the heat pumps (Table 2) was based on values given by the manufacturer (NIBE AB, 2017), which were measured according to the EN 14511 standard (CEN European Committee for Standardization, 2013). The COP at the operation conditions was calculated by taking into account the temperatures of the heat source, radiator network and DHW. The same heat pump model was used for both the ground-source heat pump (GSHP) and the exhaust air heat pump (EAHP), with the heat source temperature being 5 °C for the GSHP and 20 °C for the EAHP.

Table 2: COP of the heat pumps (NIBE AB, 2017) at the standardized test conditions (CEN European Committee for Standardization, 2013).

Temperature (°C/°C) (Source/Output)	COP
0/35	4.32
0/45	3.5
10/35	5.19
10/45	4.22

By default, all buildings used constant air flow rates for their ventilation needs. However, demand-based ventilation (DBV) was used as an option in the renovations of all the studied building types. DBV was operated according to apartment occupancy. With full occupancy the air flow rate was at 100%, while at zero occupancy the flow rate was set to be at 40% to remove material emissions.

2.4. Occupancy and internal loads

Electrical loads of appliances and lighting were based on measured profiles from 1630 Finnish households (Degefa, 2012). The annual average electricity consumption of lighting and electrical appliances was 10.7 kWh/floor-m^2 and 22.15 kWh/floor-m^2, respectively. Domestic hot water (DHW) consumption profiles were based on measured DHW demand in Finnish apartment buildings (Koivuniemi, 2005). Examples for the winter period during typical weekday and weekend are shown in Figure 3. The average daily DHW consumption was chosen according to statistics related to building age (Virta & Pylsy, 2011), so that the DHW consumption was 63.8, 60.2, 57.2 and 56.0 L/person/day for buildings AB1 to AB4 respectively. The occupant density was 1 person/28 m^2, according to the guideline of Finnish building code (Ministry of the Environment, 2012).

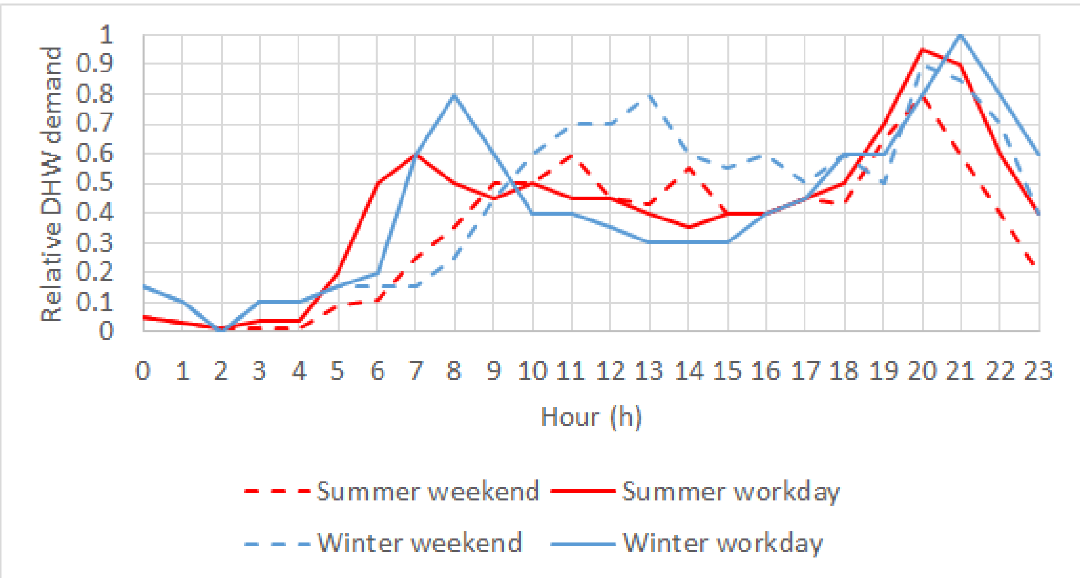

Figure 3: Domestic hot water consumption profiles for a summer (June to August) and winter (September to May). The given values represent relative demand vs. the annual peak demand.

2.5. Optimization setup

The multi-objective optimization was done using the genetic algorithm NSGA-II. Figure 4 describes the optimization scenarios for the different buildings and heating systems. The value ranges for the design variables can be seen in Table 3. Discrete value ranges were used, but only the minimum and maximum values are shown to retain clarity. Addition of thermal insulation or improving the quality of windows is represented by changes in U-values. The highest U-values for the building envelope indicate the choice of keeping the original thermal insulation level. The used variables and their ranges changed slightly depending on the building age class and heating system. The Building column identifies which building age class or heating system the decision variables apply to. Some values are used for all heating systems under the same

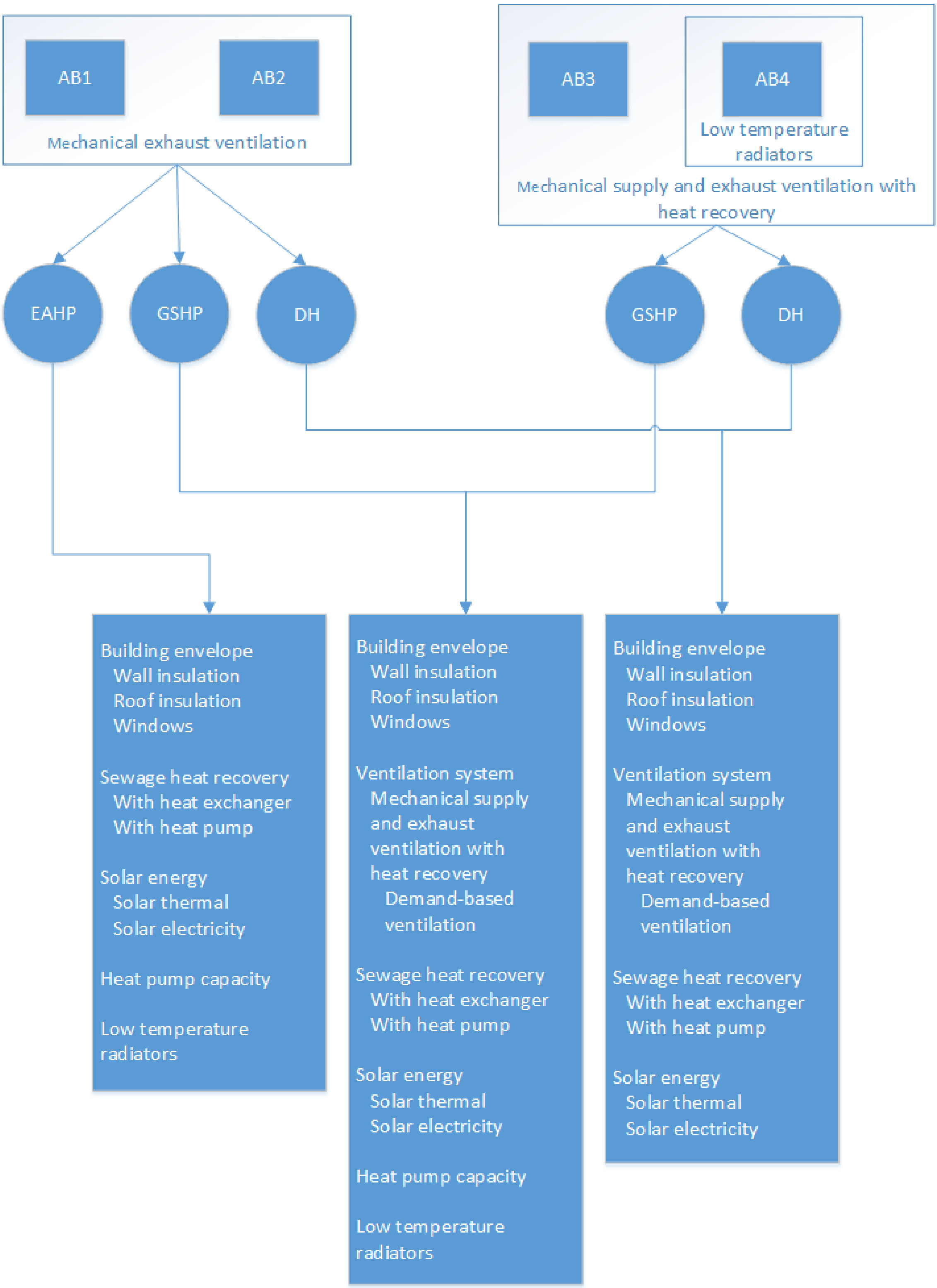

Figure 4: Outline of the optimization scenarios and design variables.

age class, while some settings refer to only to a specific heating system, as highlighted by the identifiers. Some features are not self-explanatory. Sewage HR refers to heat recovery from waste water, which in study includes only DHW. The default option was to have no heat recovery, while during the retrofit it was possible to add passive heat recovery through a heat exchanger (30% efficiency) or active heat recovery using a heat pump (70% efficiency). Radiator design determines the design temperature of the heat distribution system. AB4 uses low temperature radiators by default, while the other buildings start with high temperature radiators. Ventilation system refers to the ventilation method used in the building. Building types AB1 and AB2 use mechanical exhaust ventilation by default, while building types AB3 and AB4 use mechanical supply and exhaust ventilation with heat recovery. The supply-exhaust ventilation can further be upgraded with demand-based ventilation (DBV).

Table 3: Design variables for the optimization of building retrofits.

Building	Variable	Unit	Min	Max	Description
AB1 all	Wall U-value	W/m^2K	0.1	0.81	
	Roof U-value	W/m^2K	0.08	0.47	
	Door U-value	W/m^2K	0.7	2.2	
	Window U-value	W/m^2K	0.6	1.7	
	Sewage HR	-	0	2	0: No HR, 1: HR with HX (30% eff), 2: HR with HP (70% eff)
	ST area	m^2	0	120	
	PV capacity	kW_p	0	40	
AB1 DH	Ventilation system	-	0	2	0: Mech. exh., 1: Mech. sup-exh + HR (72% eff), 2: Mech. sup-exh + HR + DBV
AB1 GSHP	Radiator design	-	0	2	0: 70/40 °C, 1: 65/40 °C, 2: 45/35 °C
	HP capacity	kW_{th}	10	150	
	Ventilation system	-	0	2	
AB1 EAHP	Radiator design	-	0	2	0: 70/40 °C, 1: 65/40 °C, 2: 45/35 °C
	HP capacity	kW_{th}	5	39	
AB2 all	Wall U-value	W/m^2K	0.08	0.34	
	Roof U-value	W/m^2K	0.07	0.26	
	Door U-value	W/m^2K	0.7	1.4	
	Window U-value	W/m^2K	0.6	1.7	
	Sewage HR	-	0	2	0: No HR, 1: HR with HX (30% eff), 2: HR with HP (70% eff)
	ST area	m^2	0	120	
	PV capacity	kW_p	0	50	

AB2 DH	Ventilation system	-	0	2	0: Mech. exh., 1: Mech. sup-exh + HR (72% eff), 2: Mech. sup-exh + HR + DBV
AB2 GSHP	Radiator design	-	0	2	0: 70/40 °C, 1: 65/40 °C, 2: 45/35 °C
	HP capacity	kW_{th}	10	150	
	Ventilation system	-	0	2	0: Mech. exh., 1: Mech. sup-exh + HR (72% eff), 2: Mech. sup-exh + HR + DBV
AB2 EAHP	Radiator design	-	0	2	0: 70/40 °C, 1: 65/40 °C, 2: 45/35 °C
	HP capacity	kW_{th}	5	25	
AB3 all	Wall U-value	W/m^2K	0.07	0.25	
	Roof U-value	W/m^2K	0.06	0.17	
	Door U-value	W/m^2K	0.7	1.4	
	Window U-value	W/m^2K	0.6	1.7	
	Ventilation system	-	1	2	1: Mech. sup-exh + HR (60% eff), 2: Mech. sup-exh + HR + DBV
	Sewage HR	-	0	2	0: No HR, 1: HR with HX (30% eff), 2: HR with HP (70% eff)
	ST area	m^2	0	120	
	PV capacity	kW_p	0	30	
AB3 GSHP	Radiator design	-	0	2	0: 70/40 °C, 1: 65/40 °C, 2: 45/35 °C
	HP capacity	kW_{th}	10	100	
AB4 all	Wall U-value	W/m^2K	0.06	0.17	
	Roof U-value	W/m^2K	0.06	0.09	
	Door U-value	W/m^2K	0.7	1	
	Window U-value	W/m^2K	0.6	1.7	
	Ventilation system	-	1	2	1: Mech. sup-exh + HR (65% eff), 2: Mech. sup-exh + HR + DBV
	Sewage HR	-	0	2	0: No HR, 1: HR with HX (30% eff), 2: HR with HP (70% eff)
	ST area	m^2	0	120	
	PV capacity	kW_p	0	30	
	Radiator design	-	2	2	2: 45/35 °C
AB4 GSHP	HP capacity	kW_{th}	10	100	

2.6. Emissions of energy production

To calculate the annual emissions from the buildings, the emission factors for grid electricity and district heating were determined. District heating in Finland is mostly generated through combustion of fossil fuels and biomass and thus it has a relatively high emission factor of 176 kg-CO_2/MWh (Motiva, 2017) that practically does not vary according to the seasons.

Electricity generation in Finland includes several emission-free energy sources, such as nuclear, hydro and wind power. Thus, the emission factor is noticeably lower than for district heating. There is also strong seasonality, because the average generation mix is affected by the seasonally fluctuating energy demand as well as the availability of weather-dependent energy sources such as wind and hydro power. Using historical emission data from the years 2011 – 2015, average monthly emission factors were determined (Finnish Energy, 2017). The minimum emission factor of 81 kg-CO_2/MWh was in July, while the maximum of 174 kg-CO_2/MWh was in February (Figure 5). The seasonal difference in emission factors reduces the value of solar energy for emission reduction. In this study, self-consumption of solar heat and electricity would reduce emissions by reducing energy imports from the grid, but exporting excess solar energy back to the grid was not counted for any emission mitigation, as defined in the building code (Ministry of the Environment, 2017).

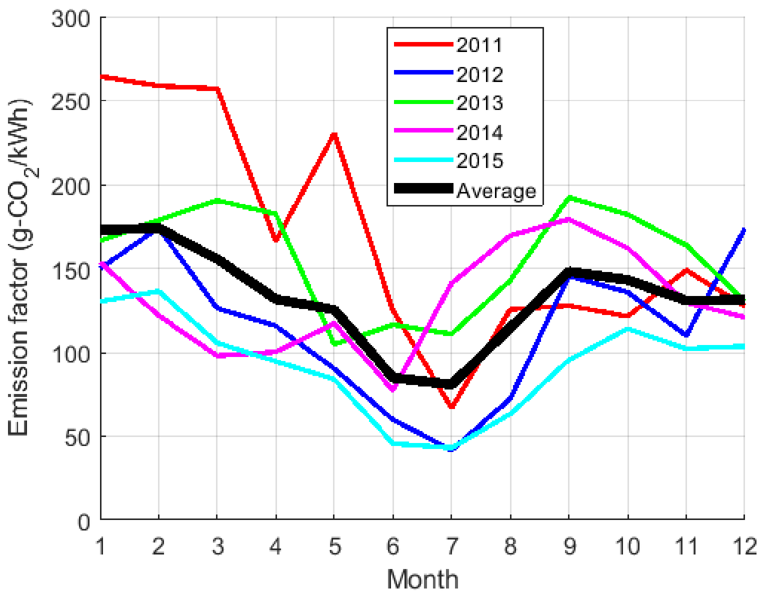

Figure 5: Emission factors of electricity generation in Finland (Finnish Energy, 2017).

2.7. Economic assumptions and cost of retrofitting

The building and energy system simulation was performed for a single year, but the life cycle cost was determined over a period of 25 years. The price of electricity was composed of three parts: the hourly Nord Pool spot price and the constant distribution cost and electricity tax. When purchasing electricity from the grid, the total value of all three factors was used as the price, but when exporting excess electricity back to the grid, only the spot price was used. Since the TRY2012 weather profile did not match any specific year, a synthetic spot price profile was utilized. The profile was generated from the spot price profiles from years 2010-2017 (Nord Pool, 2018) by adjusting the starting days so that each profile started on the same weekday. Then the average price for each hour was used as the final price profile. The average hourly spot price was 39.4 ± 10.2 €/MWh. The distribution cost and electricity tax were fixed at 36.1 and 27.9 €/MWh.

The price of district heating consisted of a monthly changing consumption-based charge (Helen Oy, 2017) and a fixed annual cost (Fortum Oyj, 2017), which was determined by the peak hourly demand during the whole year. The fixed cost with value added tax (VAT, 24%) was calculated with Equation 1

$$C_{DH} = (58 * P_{DH} – 74), \qquad (1)$$

where C_{DH} is the annual cost in € and P_{DH} is the maximum hourly district heating power in kW during the whole year. The consumption-based cost was 60.5 €/MWh in the period of January-February, 53.9 €/MWh during March-April. 33.4 €/MWh between May and September and 54.6 €/MWh from October to December.

In addition to the energy costs, there were annual maintenance costs and predetermined renewal costs for components such as heat pumps and solar collectors. Costs of the renovation measures for the building envelope are shown in Table 4 and costs of the building service systems are shown in Table 5.

The life cycle cost was calculated as the sum of initial investments, annual expenses (energy purchases, maintenance) and periodical system renewal costs, discounted over the lifetime of 25 years. The expenses were discounted using a real interest rate of 3% (EU Commission, 2012). In addition, energy prices were assumed to rise by 2% per year.

Table 4: Costs of envelope retrofits for all building types (Saari, et al., 2012) (Niemelä, et al., 2017) (Niemelä, et al., 2017).

Building	Parameter	Unit	Value								
AB1	Wall U-value	$W/(m^2K)$	0.81	0.49	0.34	0.29	0.23	0.19	0.16	0.13	0.1
	Wall cost	€/wall-m^2	224	255	286	318	353	392	435	483	500
	Roof U-value	$W/(m^2K)$	0.47	0.36	0.25	0.19	0.13	0.1	0.08	0.07	0.06
	Roof cost	€/roof-m^2	0	2	4	8	14	20	26	32	38
	Door U-value	$W/(m^2K)$	2.2	1.4	1	0.7					
	Door cost	€/door-m^2	0	500	577	666					
	Window U-value	$W/(m^2K)$	1.7	1	0.8	0.7	0.6				
	Window cost	€/window-m^2	213	371	395	427	447				
AB2	Wall U-value	$W/(m^2K)$	0.34	0.27	0.23	0.19	0.16	0.13	0.1	0.08	
	Wall cost	€/wall-m^2	0	292	320	325	332	354	369	384	
	Roof U-value	$W/(m^2K)$	0.26	0.21	0.19	0.16	0.13	0.1	0.08	0.07	
	Roof cost	€/roof-m^2	0	97	100	105	113	124	137	146	
	Door U-value	$W/(m^2K)$	1.4	1	0.7						
	Door cost	€/door-m^2	0	577	666						
	Window U-value	$W/(m^2K)$	1.7	1	0.8	0.7	0.6				
	Window cost	€/window-m^2	153	311	335	367	387				
AB3	Wall U-value	$W/(m^2K)$	0.25	0.21	0.17	0.14	0.13	0.11	0.1	0.08	
	Wall cost	€/wall-m^2	0	111	181	192	197	208	215	230	
	Roof U-value	$W/(m^2K)$	0.17	0.14	0.13	0.12	0.11	0.1	0.09	0.08	
	Roof cost	€/roof-m^2	0	4	5.8	7.9	9.7	11.6	14.6	17.9	

	Door U-value	W/(m²K)	1.4	1	0.7						
	Door cost	€/door-m²	0	577	666						
	Window U-value	W/(m²K)	1.4	1	0.8	0.7	0.6				
	Window cost	€/window-m²	0	311	335	367	387				
AB4	Wall U-value	W/(m²K)	0.17	0.15	0.14	0.13	0.12	0.11	0.1	0.09	0.08
	Wall cost	€/wall-m²	0	143	179	185	191	199	208	219	229
	Roof U-value	W/(m²K)	0.09	0.08	0.07	0.06					
	Roof cost	€/roof-m²	0	4.4	9.6	15.3					
	Door U-value	W/(m²K)	1	0.7							
	Door cost	€/door-m²	0	666							
	Window U-value	W/(m²K)	1	0.8	0.7	0.6					
	Window cost	€/window-m²	0	335	367	387					

Table 5: Cost of building service system retrofits for all building types (Saari, et al., 2012) (Niemelä, et al., 2017) (Niemelä, et al., 2017).

Building	Parameter	Unit	Value		
All AB	ST collectors cost	€/panel-m^2	675		
	PV panels cost	€/kW$_p$	1460		
	GSHP fixed cost	€	18600		
	GSHP capacity cost	€/kW$_{th}$	1302		
	EAHP fixed cost	€	90240		
	EAHP capacity cost	€/kW$_{th}$	136		
AB1	Ventilation system	-	No HR	HR with 72% efficiency	HR and DBV
	Ventilation cost	€/floor-m^2	0	110	118
	Low temperature radiators	-	Design temp 70 ºC	Design temp 65 ºC	Design temp 45 ºC
	Radiator cost	€/floor-m^2	0	7	37
AB2	Ventilation system	-	No HR	HR with 72% efficiency	HR and DBV
	Ventilation cost	€/floor-m^2	0	110	115
	Low temperature radiators	-	Design temp 70 ºC	Design temp 65 ºC	Design temp 45 ºC
	Radiator cost	€/floor-m^2	0	7	37
AB3	Ventilation system	-		HR with 60% efficiency	HR and DBV
	Ventilation cost	€/floor-m^2		0	7
	Low temperature radiators	-	Design temp 70 ºC	Design temp 65 ºC	Design temp 45 ºC
	Radiator cost	€/floor-m^2	0	7	37

AB4	Ventilation system	-		HR with 65% efficiency	HR and DBV
	Ventilation cost	€/floor-m^2		0	7
	Low temperature radiators	-			Design temp 45 ºC
	Radiator cost	€/floor-m^2			0
All AB with DH	Sewage HR	-	No HR	HR with heat exchanger	HR with heat pump
	Sewage HR cost	€	0	30000	30000 + 90240 + 136 €/kW
All AB with GSHP	Sewage HR	-	No HR	HR with heat exchanger	HR with heat pump
	Sewage HR cost	€	0	30000	30000 + 1302 €/kW
All AB with EAHP	Sewage HR	-	No HR	HR with heat exchanger	HR with heat pump
	Sewage HR cost	€	0	30000	30000 + 136 €/kW

3. Results

The following sections present the results of the optimization study. First, section 3.1. shows the annual heating demand of the reference buildings before any renovations. Then, sections 3.2. to 3.5. present the details of specific optimally renovated building configurations. In addition, sections 3.2.1. to 3.2.3. show the cost breakdown of all optimal solutions for the oldest building type AB1. Finally, an overview and comparison of all different optimization cases can be found in section 3.6.

3.1. Reference buildings

District heat consumption of the reference buildings without energy renovation measures is shown in Figure 6. In AB1 and AB2, heating demand was dominated by space heating, due to the relatively high heat losses of the envelope and because heating of ventilation was covered by the space heating system. In the newer buildings AB3 and AB4 domestic hot water was the most significant component. Ventilation heating of the buildings was defined as the heat energy consumption of the air handling unit, but its role remained small due to heat recovery systems. When calculating emission reductions and investment costs, the district heated building was used as the reference case for the optimization of all building age classes.

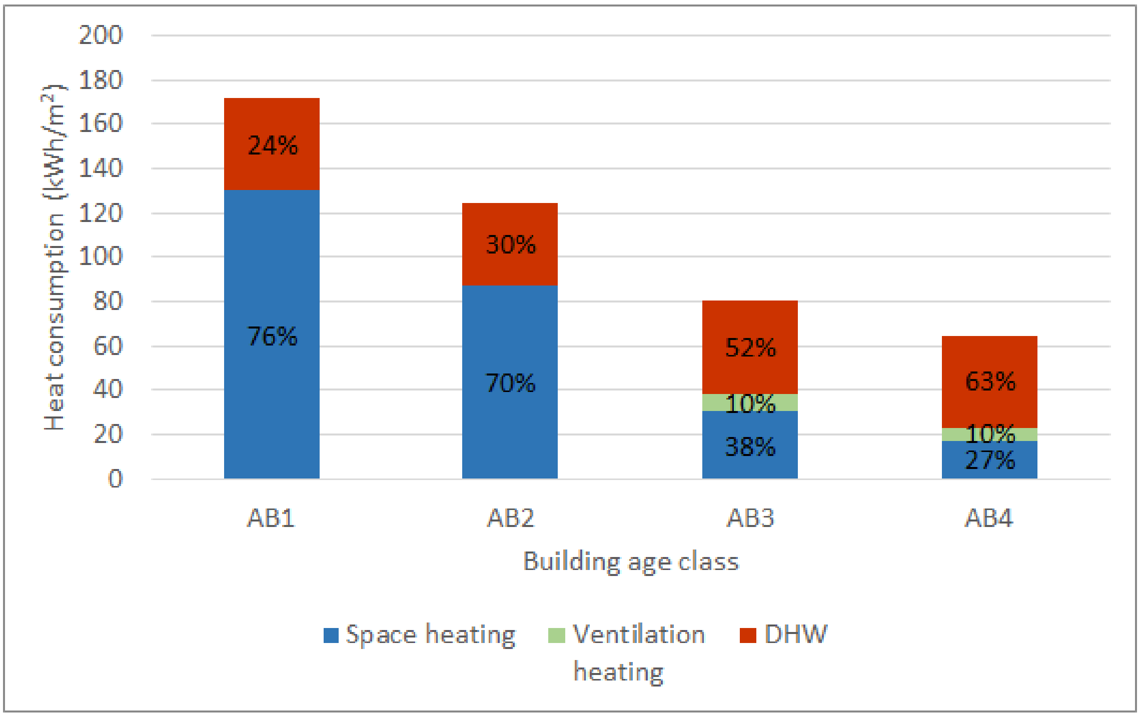

Figure 6: Heat consumption of space heating, ventilation and domestic hot water in the four reference buildings.

3.2. AB1 – Buildings from before 1976

The greatest potential for reducing emissions in a cost effective manner was found in the oldest building class (AB1). The specific details of some solutions, based on their cost levels, are given in Table 6**Error! Not a valid bookmark self-reference.**. Out of many Pareto optimal solutions, four solutions were highlighted in each case: the lowest emission solution (a), the average cost solution (b), the cost-neutral solution (c) and the least cost solution (d).

The widest range of emission reductions were found for the case with district heating: with minimal investment, the emissions could be reduced by 17%, while with the maximum investment a 72% reduction was possible. The other heating systems raised the base level of reductions possible at low cost. By installing an exhaust air heat pump, the emissions could be reduced by 49% with minimum investment and by 75% with maximum investment, relative to the reference DH case. The most effective emission reduction measure was the ground-source heat pump, which made possible a 72% reduction with minimum investment and 86% with maximum investment. For all heating systems, the least cost solution (d) included improved U-values for the roof and windows as well as the installation of PV panels and sewage water heat recovery. The cost-neutral solution (c) included additional thermal insulation of walls for the GSHP and EAHP cases and significant solar thermal capacity for the DH and GSHP cases. At this level, the GSHP case also included low temperature radiators.

Table 6: Details of several optimal solutions for AB1. a) Lowest emission solution, b) Average cost solution, c) Cost-neutral solution, d) Least cost solution

	($kg\text{-}CO_2/m^2/a$)	($kg\text{-}CO_2/m^2/a$)	(%)	(€-LCC/ $kg\text{-}CO_2/a$)	(€/m^2/ 25a)	(€/m^2)	U-values (W/m^2K)				(m^2)	(kW_p)	(kW_{th})		(°C)	
Solution type	Emissions	Emission reduction	Relative reduction	Reduction cost	LCC	Investment cost	Walls	Roof	Doors	Windows	ST	PV	HP	Ventilation	Radiators	Sewage HR
Apartment building (AB1) with district heating (DH)																
a	9.5	24.9	72	6.41	559	498	0.1	0.06	1	0.6	125	25	0	HR+DBV	70/40	Active HR
b	16.0	18.4	54	3.21	459	339	0.36	0.08	2.2	0.8	55	30	0	HR+DBV	70/40	Passive HR
c	24.7	9.7	28	0.07	400	156	0.81	0.08	2.2	0.7	55	30	0	No HR	70/40	Active HR
d	28.6	5.8	17	-3.04	382	122	0.81	0.1	2.2	0.8	5	35	0	No HR	70/40	Passive HR
Apartment building (AB1) with a ground-source heat pump (GSHP) and electric backup heating																
a	4.9	29.5	86	5.46	561	545	0.1	0.06	0.7	0.6	145	20	115	HR+DBV	45/35	Passive HR
b	5.5	28.9	84	2.70	478	443	0.23	0.1	0.7	0.8	0	35	115	HR+DBV	45/35	Passive HR
c	7.0	27.4	80	-0.10	397	296	0.36	0.08	0.7	0.7	60	35	110	No HR	45/35	Active HR
d	9.6	24.8	72	-3.37	316	155	0.81	0.13	2.2	0.8	0	30	135	No HR	70/40	Passive HR
Apartment building (AB1) with an exhaust air heat pump (EAHP) and district heating backup																
a	8.8	25.6	75	4.05	504	399	0.1	0.06	0.7	0.6	90	30	39	No HR	45/35	Active HR
b	9.3	25.1	73	2.06	451	338	0.13	0.06	0.7	0.6	75	30	39	No HR	70/40	Active HR
c	10.9	23.5	68	0.07	401	265	0.23	0.1	1	0.8	0	40	35	No HR	70/40	Active HR
d	17.7	16.8	49	-2.68	355	143	0.81	0.19	2.2	0.8	0	35	35	No HR	70/40	Active HR

3.2.1. *District heating*

Figure 7 presents all the Pareto optimal configurations obtained for the district heated AB1 case. It shows the breakdown of the lifetime costs between different renovation measures, along with the annual emissions. The usage of certain renovation measures can be inferred from the costs. For example, increased cost of solar thermal collectors implies that more collectors were installed.

In the reference case, without any energy conservation measures, most of the cost over the lifetime came from purchased district heating energy. It can be seen that with the energy conservation measures it was possible to considerably reduce the need for importing district heating energy. Thus, the relative cost of DH energy goes down significantly. Due to the initially very poor U-value of the external walls (0.81 $W/m^2,K$)), most of the renovation solutions include additional thermal insulation on the walls. Only in cases 51-63 it was not cost-efficient to improve the U-value of the envelope. Due to the low cost, additional insulation of roof was always included. Improved windows (U-value and g-value) were also included in every renovation configuration. In cases 1-23, the building was retrofitted with mechanical supply and exhaust ventilation and heat recovery. It greatly improved the energy efficiency, but the life cycle cost increase was also significant. The mechanical ventilation could be upgraded to a demand-based ventilation, where the flow rate was controlled based on the occupancy. The additional cost of DBV was so small that all cases with mechanical ventilation were also equipped with the demand-based ventilation feature.

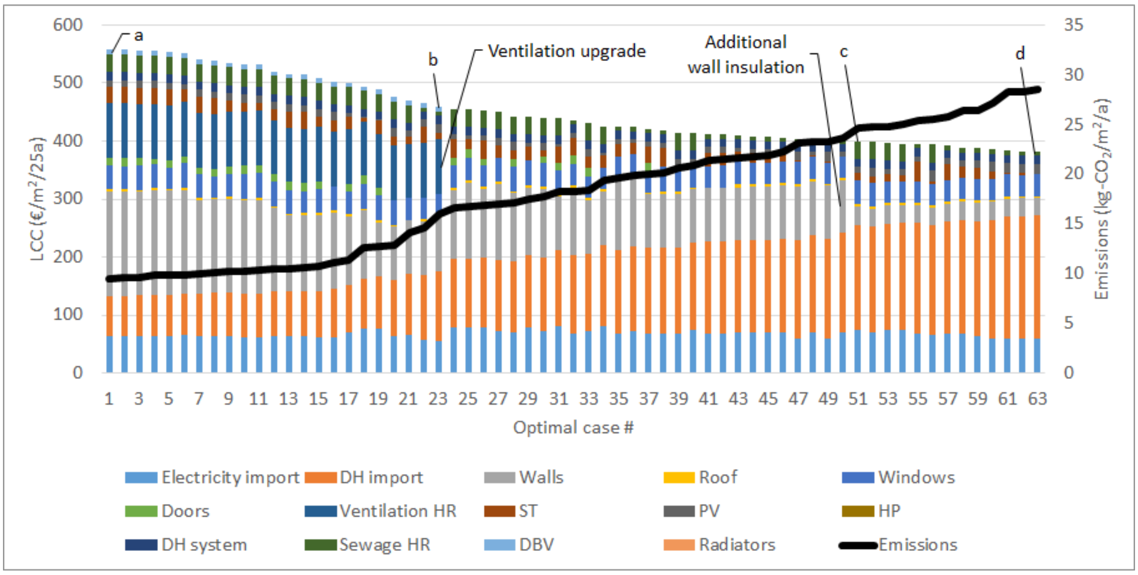

Figure 7: LCC distribution in the Pareto optimal renovation solutions of the building type AB1 with district heating. The letters refer to the chosen cases in Table 6.

3.2.2. Ground-source heat pump

Figure 8 shows the cost breakdown of the optimal solutions for AB1 when GSHP was used to replace the default district heating system. With the GSHP, the most costly investments for AB1 renovations were in the additional wall insulation and upgrading the ventilation to full mechanical supply and exhaust ventilation with heat recovery. Second highest cost components were the window upgrades and the cost of the heat pump system. Other important cost components were replacing the old radiators with low temperature radiators and solar collectors if a very high capacity was used. The electrified heating roughly tripled the electricity consumption, but the total cost of electricity was reduced by up to half due to energy saving measures. However, the cost of the investments exceeded the savings for cases with very low emission levels.

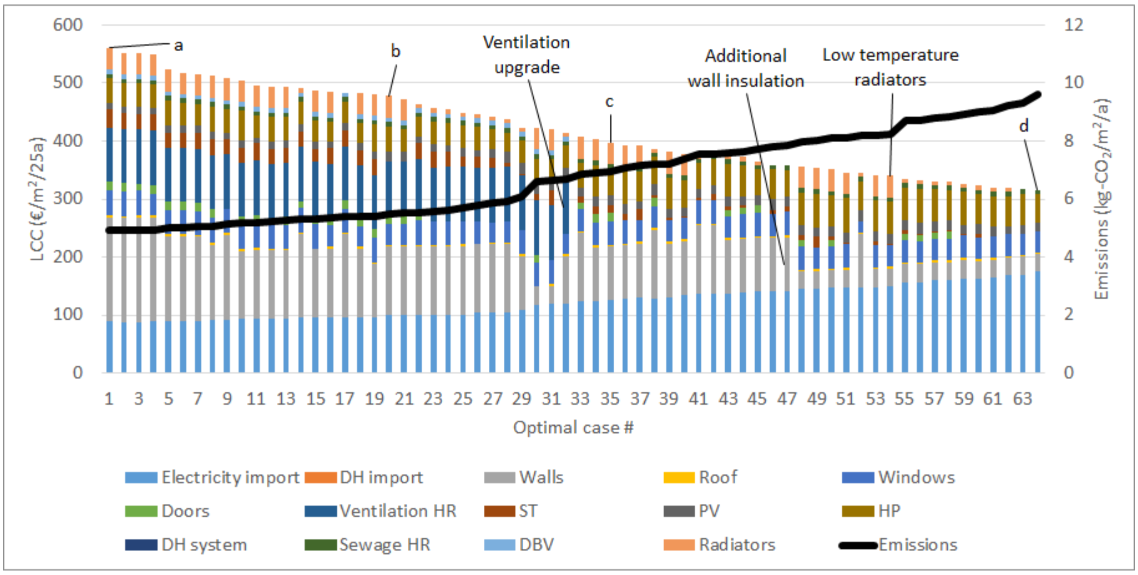

Figure 8: LCC distribution in the Pareto optimal renovation solutions of the building type AB1 with a ground-source heat pump. The letters refer to the chosen cases in Table 6.

3.2.3. *Exhaust air heat pump*

Figure 9 shows the cost breakdown of the optimal solutions for AB1 when EAHP was used. The exhaust air heat pump (EAHP) was installed alongside the existing DH system, but did not completely replace district heating. The building with the EAHP did not include the possibility to add mechanical supply and exhaust ventilation and heat recovery. The most significant performance improvements came from the exhaust air heat pump itself as well as additional wall insulation. PV. The additional wall insulation was also the most expensive energy saving measure in most of the cases. With the EAHP system, original district heating system was still cost-efficiently used as a backup heating system. The energy cost of district heating was about 30% of the total cost in the low performance cases (high emissions), but it was reduced to around 10% in the most expensive cases. Electricity cost surpassed the district heating cost as emissions lowered. The electricity cost remained roughly constant in all the cases, because the EAHP capacity was always at (or near) the maximum value of 39 kW. Any energy demand not covered by the EAHP was met using district heat. Compared to the cost of wall insulation, most of the other energy saving measure expenses were small. Still, the costs of window upgrades and retrofitting of low temperature radiators (which improved the COP of the EAHP) were relatively expensive.

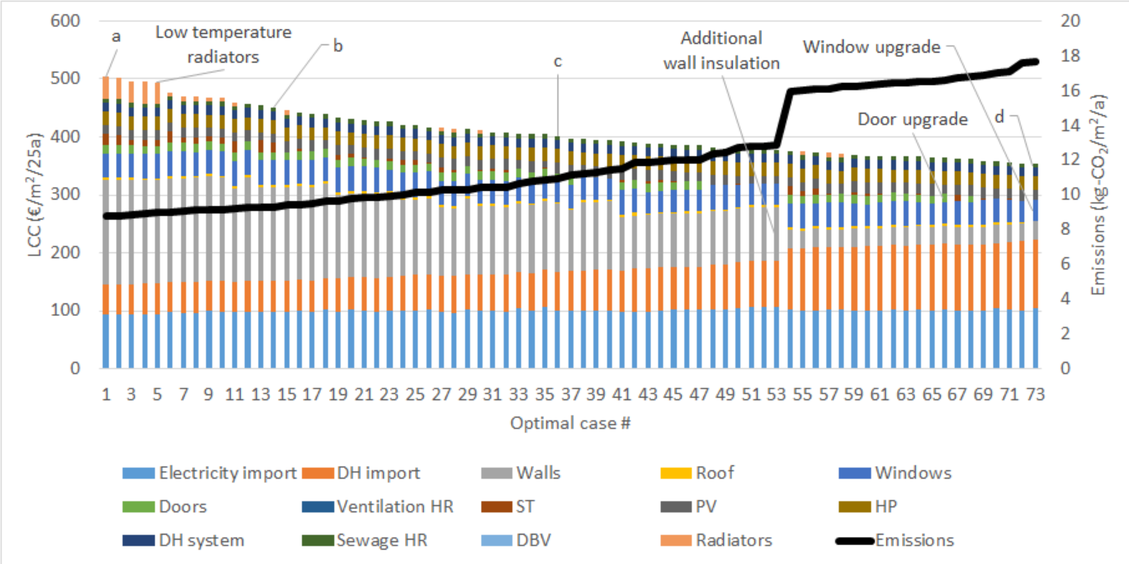

Figure 9: LCC distribution in the Pareto optimal renovation solutions of the building type AB1 with exhaust air heat pump. The letters refer to the chosen cases in Table 6.

3.3. AB2 – Buildings from 1976 to 2002

Table 7 shows a selection of optimal solutions with different emission levels for the building AB2. Using a GSHP, the least cost solution d could obtain similar emission levels as the more expensive solutions b and a for DH and EAHP, respectively. The least cost renovation options for all cases included the installation of solar PV panels and sewage heat recovery. To reduce emissions further, it was useful to upgrade the windows and install solar thermal collectors. Additional thermal insulation to roof and walls were only used in the expensive scenarios (a and b).

In the expensive scenarios, AB2 with a district heating system was able to reach higher emission reductions than the same building with an EAHP system. This was due to ventilation heat recovery and demand-based ventilation, which were not available for the EAHP system. In the AB2 DH case, the biggest reduction in emissions was caused by upgrading the HVAC system from exhaust ventilation to mechanical supply and exhaust ventilation with heat recovery. This increased LCC only slightly. However, to obtain the highest performance, an expensive wall renovation was needed.

Just the installation of a ground-source heat pump reduced emissions in AB2 from over 25 kg-CO_2/m^2/a down to 7 kg-CO_2/m^2/a. The greatest performance improvement beyond that came from the addition of mechanical supply and exhaust ventilation with heat recovery. The ventilation retrofit was the greatest individual cost component until the inclusion of the additional wall thermal insulation, which had only a marginal effect on the emissions. With the EAHP, the emissions of the lowest performing system were 50% lower than in the reference DH case. The EAHP significantly reduced the cost and emissions of imported district heating.

Table 7: Details of several optimal solutions for AB2. a) Lowest emission solution, b) Average cost solution, c) Cost-neutral solution, d) Least cost solution

Solution type	Emissions ($kg\text{-}CO_2/m^2/a$)	Emission reduction ($kg\text{-}CO_2/m^2/a$)	Relative reduction (%)	Reduction cost (€-LCC/ $kg\text{-}CO_2$/a)	LCC (€/m^2/ 25a)	Investment cost (€/m^2)	Walls (U-values W/m^2K)	Roof	Doors	Windows	ST (m^2)	PV (kW_p)	HP (kW_{th})	Ventilation	Radiators (°C)	Sewage HR
Apartment building (AB2) with district heating (DH)																
a	5.4	20.0	79	9.96	482	450	0.1	0.1	0.7	0.8	110	25	0	HR+DBV	70/40	Active HR
b	7.3	18.1	71	4.99	373	298	0.34	0.1	0.7	0.7	100	25	0	HR+DBV	70/40	Active HR
c	16.2	9.2	36	-0.01	283	97	0.34	0.26	0.7	1	100	25	0	No HR	70/40	Passive HR
d	19.4	6.0	24	-2.68	267	72	0.34	0.26	0.7	1	0	25	0	No HR	70/40	Passive HR
Apartment building (AB2) with ground-source heat pump (GSHP) and electric backup heating																
a	3.6	21.8	86	8.83	475	476	0.1	0.1	0.7	0.6	90	35	45	HR+DBV	45/35	Passive HR
b	4.0	21.4	84	3.81	364	331	0.34	0.1	0.7	0.7	90	35	60	HR+DBV	45/35	Passive HR
c	4.7	20.7	82	-0.04	282	235	0.34	0.26	1.4	0.7	25	35	35	HR+DBV	65/40	Active HR
d	7.2	18.2	72	-2.99	228	101	0.34	0.26	1.4	1	0	35	75	No HR	70/40	Passive HR
Apartment building (AB2) with exhaust air heat pump (EAHP) and district heating backup																
a	7.3	18.1	71	10.05	465	366	0.1	0.1	0.7	0.6	125	30	25	No HR	45/35	Active HR
b	9.1	16.3	64	4.54	357	215	0.34	0.1	0.7	0.6	125	30	25	No HR	45/35	Active HR
c	10.4	15.0	59	-0.04	282	133	0.34	0.26	0.7	0.6	35	45	25	No HR	70/40	Active HR
d	12.0	13.4	53	-0.96	270	103	0.34	0.26	0.7	1.7	0	35	20	No HR	70/40	Active HR

3.4.AB3 – Buildings from 2003 to 2009

Table 8 shows a collection of optimal retrofit solutions for AB3, based on cost levels. Solar electric systems and demand-based ventilation were the cheapest renovation options. Further economical emission reductions could be done with improved roof insulation and through the installation of solar thermal collectors and sewage heat recovery. Sewage heat recovery was used in most cases with both DH and GSHP because most of the heating demand came from domestic hot water. The preferred PV capacity was larger for the more electrically intensive GSHP case than for the DH case, but within each optimization the capacity remained almost constant. Upgrading the walls and windows was not cost-effective for either heating system.

Table 8: Details of several optimal solutions for AB3. a) Lowest emission solution, b) Average cost solution, c) Cost-neutral solution, d) Least cost solution

Solution type	Emissions ($kg\text{-}CO_2/m^2/a$)	Emission reduction ($kg\text{-}CO_2/m^2/a$)	Relative reduction (%)	Reduction cost (€-LCC/ $kg\text{-}CO_2$/ a)	LCC (€/m^2/ 25a)	Investment cost (€/m^2)	Walls (U-values (W/m^2K))	Roof	Doors	Windows	ST (m^2)
Apartment building (AB3) with district heating (DH)											
a	7.9	11.1	59	17.59	423	309	0.08	0.06	0.7	1	95
b	9.1	10.0	52	8.20	308	156	0.25	0.06	0.7	1.4	95
c	11.3	7.7	41	-0.25	225	66	0.25	0.07	1.4	1.4	50
d	16.6	2.4	13	-7.36	209	19	0.25	0.1	1.4	1.4	0
Apartment building (AB3) with ground-source heat pump (GSHP) and electric backup heating											
a	5.2	13.9	73	10.97	379	300	0.08	0.06	0.7	1.4	65
b	5.4	13.6	72	5.53	302	198	0.25	0.06	0.7	1.4	65
c	5.8	13.2	69	0.01	227	115	0.25	0.1	1.4	1.4	60
d	7.1	11.9	62	-2.49	197	63	0.25	0.17	1.4	1.4	0

3.5. AB4 – Buildings from 2010 to 2020

Table 9 shows the optimal renovation configurations for AB4 under different cost levels. Similar to AB3, the most cost-effective solutions were the inclusion of demand-based ventilation and solar electric panels. They were both used in all optimal configurations. These were followed by sewage heat recovery and solar thermal collectors for increased emission reductions. Changes to the envelope were not cost-effective. When maximum emission reductions were obtained, the greatest costs came from the HP-based sewage HR, solar thermal investments and the upgrading of walls and windows.

Table 9: Details of several optimal solutions for AB4. a) Lowest emission solution, b) Average cost solution, c) Cost-neutral solution, d) Least cost solution

Solution type	Emissions	Emission reduction	Relative reduction	Reduction cost	LCC	Investment cost	Walls	Roof	Doors	Windows	ST	PV	HP	Ventilation	Radiators	Sewage HR
	(kg-CO_2/ m^2/a)	(kg-CO_2/ m^2/a)	(%)	(€-LCC/ kg-CO_2/ a)	(€/m^2/ 25a)	(€/m^2)	U-values (W/m^2K)				(m^2)	(kW_p)	(kW_{th})		(°C)	
Apartment building (AB4) with district heating (DH)																
a	6.5	9.7	60	20.46	398	300	0.08	0.07	1	0.6	95	15	0	HR+DBV	45/35	Active HR
b	7.3	8.9	55	9.88	287	153	0.17	0.06	0.7	1	95	15	0	HR+DBV	45/35	Active HR
c	9.4	6.8	42	-0.05	199	59	0.17	0.09	1	1	45	15	0	HR+DBV	45/35	Passive HR
d	14.5	1.7	11	-7.38	186	16	0.17	0.09	1	1	0	10	0	HR+DBV	45/35	No HR
Apartment building (AB4) with ground-source heat pump (GSHP) and electric backup heating																
a	4.8	11.4	71	14.42	364	293	0.08	0.07	1	0.6	95	15	35	HR+DBV	45/35	Passive HR
b	4.9	11.3	70	7.05	279	184	0.17	0.06	0.7	0.6	95	15	35	HR+DBV	45/35	Passive HR
c	5.1	11.1	68	-0.10	198	104	0.17	0.09	1	1	30	25	25	HR+DBV	45/35	Passive HR
d	6.3	9.9	61	-2.20	177	59	0.17	0.09	1	1	0	15	20	HR+DBV	45/35	No HR

3.6. Optimization overview

An overview of all the optimization results is shown in Figure 10, which shows the CO_2 emissions and life cycle costs for all Pareto optimal renovation strategies. Each building type is represented by one color and different heating systems are identified by different symbols. Each point in the figure represents one optimal retrofitted building configuration, while the diamond shapes represent the reference cases. The horizontal axis describes the annual emissions while the vertical axis represents the life cycle costs over a 25 year period, including initial investments, energy purchases, maintenance and renewals. Emission reductions were obtained for all buildings and heating systems, but after a certain emission level, the costs started to increase very quickly compared to the emissions reductions. In all building age classes, changing from district heating to ground source heat pump resulted in the lowest emissions with the lowest life cycle cost. This is clear when comparing the GSHP results to DH results of the same color.

Figure 11 shows the reduction of emissions and the life cycle cost of the energy renovation compared to the reference case before renovation. Any configuration with a cost below zero reduces emissions with lower life cycle costs compared to the unrenovated building. In the new buildings, AB3 and AB4, use of the GSHP provided great emission reductions and cost-savings, but additional measures did little else than increase costs.

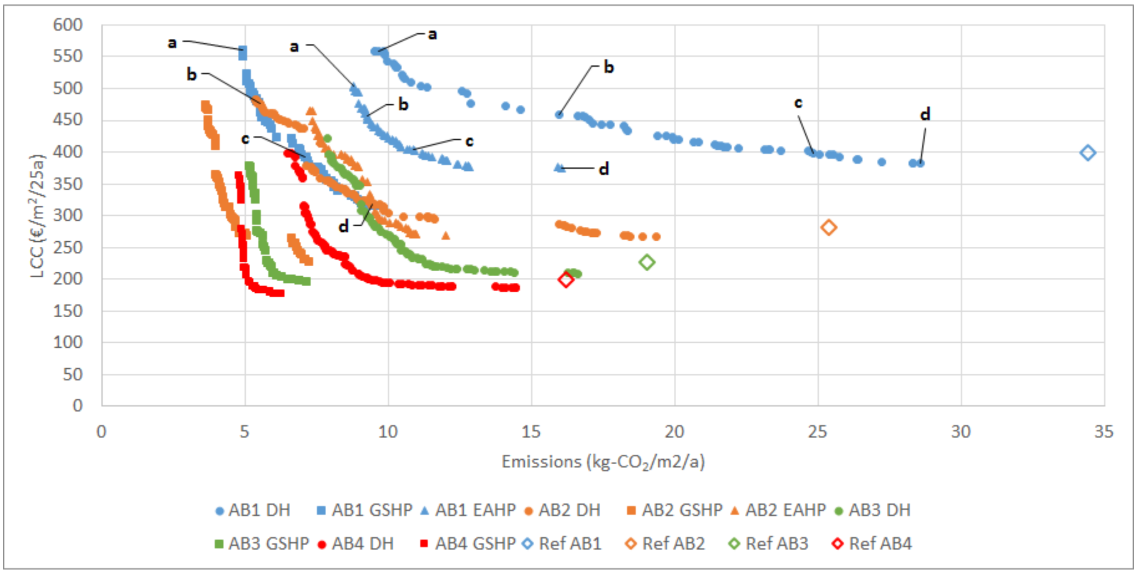

Figure 10: The annual emissions and life cycle cost for the optimally renovated cases of all buildings and systems. Reference cases are presented as diamond shapes. The letters signify the specific configurations of AB1 that were presented in Table 6.

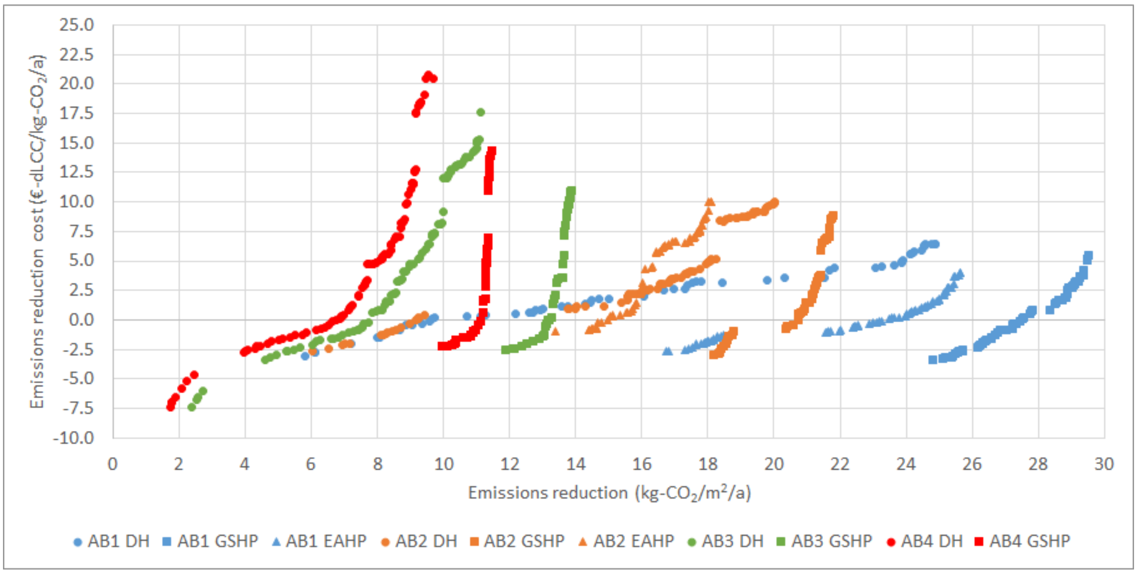

Figure 11: The cost of reducing emissions vs. achieved reduction compared to the reference case. Negative cost implies cost savings.

With a GSHP, the retrofitted AB2 obtained the lowest total emissions out of all the buildings, even lower than the newer buildings AB3 and AB4 (see Figure 10). This was because of two reasons. Firstly, the ventilation heat recovery (HR) efficiency for the retrofitted AB2 was higher (72%) than the HR used for the standard solution of AB3

(60%) and AB4 (65%), which were not upgraded as part of the optimization scheme. Secondly, the floor plan of the AB2 contained a larger cellar floor area than AB3 and AB4. The specific energy consumption of the cellar area was lower than in the living areas. This reduced the relative energy consumption and emissions of AB2 compared to AB3 and AB4.

The results show, that while there are many ways to reduce energy consumption and emissions in existing apartment buildings, a large fraction of the solutions are not economically viable in life cycle costs. For example, envelope improvements such as additional thermal insulation of walls are often not economically justified. Especially in relatively new buildings that are already well insulated, adding more thermal insulation to the walls has very little actual energy saving benefit. However, low cost roof insulation was usually cost-effective. Window retrofits were typically not useful for the newer buildings, but were beneficial in the older buildings. Heat recovery from ventilation offers a significant improvement to a building's energy performance, but a large overhaul from exhaust ventilation to supply-exhaust ventilation is usually not cost-effective. For new buildings, upgrading to demand-based ventilation was the most cost-effective renovation solution, followed by installations of solar electric and, to a lesser extent, solar thermal systems. Solar electricity was useful in all cases, but to avoid selling excess power at low cost to the grid, its capacity was limited. Higher amounts of solar thermal collectors could be utilized, due to short-term energy storage in water tanks.

Using district heating, emissions in all the buildings could cost-effectively be reduced by 24 – 41%. The initial investment was 30 – 46% out of the total LCC. With a ground-source heat pump, the emissions could be cost-effectively reduced by over 80% in AB1 and AB2 and by almost 70% in AB3 and AB4. This would require more initial investments, however. For AB1 and AB2 the investment to LCC ratio was about 80%, while with AB3 and AB4 it was 50%.

4. Discussion

Energy efficiency improvements and solar energy had great potential in reducing emissions in apartment buildings. However, the most cost-effective measure to reduce emissions, relative to the reference district heated building, was to utilize heat pumps. This is due to the low electricity prices in Finland as well as the much lower emission factors of electricity compared to district heating. Under the assumptions of this study, winter heat generation by heat pump can be less than half the cost of district heating. It was also assumed that all electricity would be supplied using the average monthly emission factors. However, the uptake of electrified heating increases power demand in the national grid, making it more likely that electricity is generated using CO_2-intensive energy sources that are more expensive to operate. This could reduce or even negate the environmental benefit of heat pumps as well increase the cost of electricity.

Because significant reductions in energy use and emissions were possible, energy retrofits of old buildings should be a priority for Finland to reach its emission targets (-80% compared to 1990 levels by the year 2050). However, the highest emission reductions could not be reached cost-effectively, which is an obstacle as most people prioritize cost On the other hand, the upfront investment cost of many renovation solutions can be quite low compared to some non-energy related renovation tasks. For example, the water pipeline renovation typically needed in 40-60-year-old buildings can cost 500-900 €/m^2 (Orava & Turunen, 2016), while most of the effective energy renovation solutions found in this study had investment costs lower than 300 €/m^2. Some energy retrofit measures could even be combined with other mandatory renovation tasks, which can lower the cost of efficiency improvements. The renovation rate of buildings could also be increased through economic incentives such as tax cuts or government grants for performing the retrofits. For example, in Estonia government grants for energy retrofits were available, with more money given for meeting more ambitious efficiency targets (Kuusk & Kalamees, 2016).

The limitations of this study are related to the estimation of current and future prices and the state of the national energy system. To make optimization feasible, four buildings were chosen to represent all the apartment buildings in Finland. Average building properties were chosen according to the building regulations and guidelines of their construction periods. To limit the number of different cases, the buildings were only modeled for the climate of Southern Finland. As such, the buildings do not represent the whole of Finnish building stock and some adjustments would have to be made when extrapolating from this study to other parts of Finland. However, it has been shown that the test reference year used in this study represents the current climatic conditions of the Finnish climate zones I and II, in which 75% of the Finnish building stock is located. The need for mechanical cooling was ignored, since it is not typically used in Finnish apartment buildings, but in a warming climate that might require extra consideration (Jylhä, et al., 2015).

Costs of different energy retrofit options were estimated according to previous studies and private communications with experts, but truly universal prices don't exist, as costs change according to local operators, building envelope design, size of buildings and other specific features. The results could change depending on the future of the Nordic energy system and changes in prices and tariffs. New electricity transmission lines opening up between the Nordic region and the United Kingdom or Germany could create upward pressure for Finnish electricity prices, as less power would be available for importing to Finland. The study was done for a 25 year time period, assuming that energy prices steadily increase, but that emission levels of energy generation stay the same. If the energy transformation continues, it could be assumed that emissions levels on the generation side are also reduced. Reduction of emission factors on the district heating side, for example through heat generation with nuclear energy using small modular reactors (SMR) (Partanen, 2017), would have significant effect on both the reference cases and the optimized cases. Use of utility scale solar heat and seasonal thermal energy storage could also reduce the carbon intensity of district heating. On the other hand, very large scale penetration of heat pumps would significantly increase the national electricity consumption while lowering the need for district heating. This would reduce the benefits of cogeneration plants, while possibly increasing the use of high emission peaking plants. To keep the scope of the study reasonable, these issues were disregarded. Separate studies need to be done to compare the cost-effectiveness of emission reductions on the generation side (power plants and energy grid) and the consumption side (buildings) as well as the effect of scaling up the retrofits from individual buildings to cities and communities.

5. Conclusions

The goal of the European Union is to reduce total emissions by 80% from the levels of 1990 by the year 2050. This study examined the emission reduction potential of optimal energy renovation solutions for Finnish apartment buildings of different ages and technical building systems. For the oldest building type AB1 (built before 1976) emissions could be cost-effectively reduced by 28 to 80%, depending on whether district heating or heat pumps were utilized. This translates to final emissions levels of 25 to 7 kg-CO_2/m^2/a. For age class AB2 (built in 1976 – 2002), cost-effective emission reductions of 36 to 82% could be obtained. This resulted in specific emissions of 5 to 16 kg-CO_2/m^2/a. For the newer building type AB3 (built in 2003-2009) cost-effective solutions resulted in CO_2 reductions of 41 to 69%, translating to final emission levels of 11 to 6 kg-CO_2/m^2/a. For the newest building type AB4 (built after 2010), the emission reductions were similarly 42 – 68%, with specific emissions of 9 – 5 kg-CO_2/m^2/a.

The largest and most cost-effective emission reductions were obtained with the use of ground-source heat pumps. However, with district heating and exhaust air heat pumps, it was also possible to significantly reduce emissions without incurring net costs over a period of 25 years. The most substantial emission reductions, however, were not cost-effective.

In buildings of all age groups, heat recovery from waste water proved to be a cost-effective solution, which was utilized in almost all optimized configurations. In systems with mechanical ventilation, demand-based ventilation was also cost-effective to introduce in every case. In the oldest buildings (AB1), better insulation of the roof and installation of energy efficient windows were always economical. For new buildings (AB3 and AB4) with a low heating demand even before renovation, solar electricity was the first cost-efficient retrofitting measure. For higher levels of emission reductions, inclusion of solar thermal generation was effective, as was retrofitting of mechanical exhaust ventilation system to mechanical supply and exhaust ventilation system with heat recovery in old buildings (AB1 and AB2).

This study shows that with the help of building energy retrofits it is possible to reduce emissions of old Finnish apartment buildings by 80%, which matches the emission reduction targets of the EU. The reductions are made possible by improved building envelope, heat recovery, on-site energy generation and electrification of heating. Not all of the emission reduction measures are currently economically feasible, so Finland and other EU member states need to create policies to motivate building owners to perform the upgrades. The availability of low emission electricity must also be ensured.

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References

AXITEC Energy GmbH & Co. KG, 2016. *ENF photovoltaic panel database, AC-250-260P/156-60S datasheet.* [Online]
Available at: https://www.enfsolar.com/pv/panel?page=1
[Accessed 2016].

Barkhudaryan, N. R., Roshan, G. & Orosa, J. A., 2016. A new way to define better improvement options of existing buildings for energy saving. *International Journal of Sustainable Energy*, 35(9), pp. 903-913.

CEN European Committee for Standardization, 2013. *Standard EN 14511-3:2013. Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling. Part 3: Test methods*, s.l.: s.n.

Chadiarakou, S. & Santamouris, M., 2014. Field survey on multi-family buildings in order to depict their energy characteristics. *International Journal of Sustainable Energy*, 34(3-4), pp. 271-281.

Charalambides, A. G. et al., 2018. The impact of Energy Performance Certificates on building deep energy renovation targets. *International Journal of Sustainable Energy.*

Dyhr, R., 1993. *Asuinrakennusten ilmanvaihtoselvitys (Report on residential building ventilation systems) [In Finnish]*. Helsinki: City of Helsinki.

EQUA Simulation AB, 2010. *Validation of IDA Indoor Climate and Energy 4.0 with respect to CEN Standards EN 15255-2007 and EN 15265-2007*, Solna: EQUA Simulation AB.

EQUA Simulation AB, 2018. *IDA Indoor Climate and Energy.* [Online]
Available at: https://www.equa.se/en/ida-ice
[Accessed 8 June 2018].

EU Commission, 2012. *Commission delegated regulation on calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements.* [Online]
Available at: http://ec.europa.eu/transparency/regdoc/rep/3/2011/EN/3-2011-10050-EN-F1-1.Pdf
[Accessed 2018].
European Commission, 2018. *2030 climate & energy framework.* [Online]
Available at: https://ec.europa.eu/clima/policies/strategies/2030_en
[Accessed June 2018].
European Commission, 2018. *2050 low-carbon economy.* [Online]
Available at: https://ec.europa.eu/clima/policies/strategies/2050_en
[Accessed June 2018].
Ferreira, M., Almeida, M., Rodrigues, A. & Silva, S. M., 2016. Comparing cost-optimal and net-zero energy targets in building retrofit. *Building Research & Information,* 44(2), pp. 188-201.
Finnish Energy, 2017. *Email communication.* [Online]
Available at: https://energia.fi/en
[Accessed 2017].
Fortum Oyj, 2017. *District heat pricing [In Finnish]*. [Online]
Available at: https://www.fortum.fi/yrityksille-ja-yhteisoille/lammitys/kaukolampo-0/kaukolammon-hinnat-taloyhtioille-ja-yrityksille
[Accessed October 2017].
Gagliano, A. et al., 2016. Synergic effect of thermal mass and natural ventilation on the thermal behaviour of traditional massive buildings. *International Journal of Sustainable Energy,* 35(5), pp. 411-428.
Gustafsson, M. et al., 2017. Economic and environmental analysis of energy renovation packages for European office buildings. *Energy and Buildings,* Volume 148, pp. 155-165.
Helen Oy, 2017. *District heating prices.* [Online]
Available at: https://www.helen.fi/en/heating/homes/district-heat-prices/
[Accessed October 2017].
Henning, H.-M. & Palzer, A., 2014. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable

energy technologies - Part I: Methodology. *Renewable and Sustainable Energy Reviews,* Volume 30, pp. 1003-1018.

Holopainen, R., Milandru, A., Ahvenniemi, H. & Häkkinen, T., 2016. Feasibility studies of energy retrofits - Case studies of nearly zero-energy building renovation. *Energy Procedia,* Volume 96, pp. 146-157.

Jradi, M., Veje, C. T. & Jørgensen, B., 2018. A dynamic energy performance-driven approach for assessment of buildings energy renovation - Danish case studies. *Energy and Buildings,* Volume 158, pp. 62-76.

Jylhä, K. et al., 2015. Energy demand for the heating and cooling of residential houses in Finland in a changing climate. *Energy and Buildings,* Volume 99, pp. 104-116.

Kalamees, T. et al., 2012. Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard. *Energy and Buildings,* Volume 47, pp. 53-60.

Koivuniemi, J., 2005. *Lämpimän käyttöveden mitoitusvirtaama ja lämpötilakriteerit veden mikrobiologisen laadun kannalta kaukolämmitetyissä taloissa (Water for and temperature considering microbiological conditions, M.Sc. thesis) [In Finnish],* Espoo: s.n.

Kuusk, K. & Kalamees, T., 2016. Estonian grant scheme for renovating apartment buildings. *Energy Procedia,* Volume 96, pp. 628-637.

Kuusk, K., Kalamees, T. & Maivel, M., 2014. Cost effectiveness of energy performance improvements in Estonian brick apartment buildings. *Energy and Buildings,* Volume 77, pp. 313-322.

Ministry of the Environment, 1987. *D2, Indoor climate and ventilation of buildings. Regulations and guidelines [In Finnish]*. [Online]
Available at: http://www.ym.fi/download/noname/%7B3C555C28-04E8-4DDC-B6F5-EBA879CB50A3%7D/100782
[Accessed 8 June 2018].

Ministry of the Environment, 2003. *D2, Indoor climate and ventilation of buildings. Regulations and guidelines [In Finnish]*. [Online]
Available at: http://www.ym.fi/download/noname/%7BCE4601D6-732C-4C9A-BC82-AA16C7EF4D29%7D/101112
[Accessed 8 June 2018].

Ministry of the Environment, 2010. *D2, Indoor climate and ventilation of buildings. Regulations and guidelines [In Finnish]*. [Online]

Available at: http://www.ym.fi/download/noname/%7BD7685B7F-AE4B-4DD3-B689-BC8418933265%7D/102967
[Accessed 8 June 2018].

Ministry of the Environment, 2012. *D3, Energy efficiency of buildings. Regulations and guidelines.*, s.l.: s.n.

Ministry of the Environment, 2017. *Directive on building energy certificates, Attachment 1 [In Finnish]*. [Online]
Available at: https://www.finlex.fi/data/sdliite/liite/6822.pdf
[Accessed 8 June 2018].

Ministry of the Environment, 2018. *Energy efficiency. Calculation of a building's energy consumption and heating power [In Finnish]*. [Online]
Available at: http://www.ym.fi/download/noname/%7B4332AA81-75E1-4CA0-B208-B0ACB60A267F%7D/133692
[Accessed 8 June 2018].

Mora, T. D. et al., 2018. Tools and procedures to support decision making for cost-effective energy and carbon emissions optimization in building renovation. *Energy and Buildings,* Volume 167, pp. 200-2015.

Motiva, 2017. *CO2 emissions factors for district heating.* [Online]
Available at: https://www.motiva.fi/ratkaisut/energiankaytto_suomessa/co2-laskentaohje_energiankulutuksen_hiilidioksidipaastojen_laskentaan/co2-paastokertoimet
[Accessed December 2017].

Nageler, P. et al., 2018. Validation of dynamic building energy simulation tools based on a real test-box with thermally activated building systems (TABS). *Energy and Buildings,* Volume 168, pp. 42-55.

Nguyen, A.-T., Reiter, S. & Rigo, P., 2014. A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy,* Volume 113, pp. 1043-1058.

NIBE AB, 2017. *NIBE F1345 heat pump technical manual.* [Online]
Available at: https://www.nibe.eu/nibedocuments/20834/331036-5.pdf

Niemelä, T., Jokisalo, J. & Kosonen, R., 2017. Energy performance and environmental impact analysis of cost-optimal renovation solutions of large panel apartment buildings in Finland. *Sustainable Cities and Society,* Volume 32, pp. 9-30.

Niemelä, T., Kosonen, R. & Jokisalo, J., 2016. Cost-optimal energy performance renovation measures of educational buildings in cold climate. *Applied Energy,* Volume 183, pp. 1005-1020.

Niemelä, T., Kosonen, R. & Jokisalo, J., 2017. Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings. *Energy and Buildings,* Volume 137, pp. 60-75.

Nord Pool, 2018. *Historical market data, hourly electricity prices.* [Online] Available at: https://www.nordpoolgroup.com/historical-market-data/ [Accessed January 2018].

Orava, J. & Turunen, O., 2016. *Osta, vuokraa, vaurastu (Buy, rent, get wealthy) [In Finnish]*. Helsinki: Alma Talent.

Paiho, S. et al., 2013. Energy saving potentials of Moscow apartment buildings in residential districts. *Energy and Buildings,* Volume 66, pp. 706-713.

Partanen, R., 2017. *Decarbonizing cities: Helsinki metropolitan area - Providing district heating, power and transportation fuels with advanced nuclear reactors.* Helsinki: Ecomodernist Society of Finland.

Ruotsalainen, R. et al., 1992. Indoor climate and the performance of ventilation in Finnish Residences. *Indoor Air,* 2(3), pp. 137-145.

Saari, A. et al., 2012. *Energiatehokkuutta koskevien vähimmäisvaatimusten kustannusoptimaalisten tasojen laskenta (Calculation of cost-optimal energy efficiency levels) [In Finnish],* Helsinki: Ministry of the Environment.

Savo-Solar Oy, 2013. *Solar Keymark Database, SF100-01A-RUUKKI solar thermal collector datasheet.* [Online] Available at: http://www.estif.org/solarkeymark/Links/Internal_links/certif/PSK-042-2013.pdf [Accessed June 2018].

Statistics Finland, 2017. *Number of buildings by intended use and year of construction.* [Online] Available at: http://pxnet2.stat.fi/PXWeb/pxweb/en/StatFin/StatFin__asu__rakke/statfin_rakke_pxt_001.px/?rxid=6bbd9974-1910-43d9-b7c3-1501f0796118 [Accessed June 2018].

Säteri, J., Kovanen, K. & Pallari, M.-L., 1999. *Kerrostalojen sisäilmaston ja energiatalouden parantaminen (Improving the indoor air and energy economics in apartment buildings) [In Finnish],* Espoo: VTT Technical Research Centre of Finland.

The European Parliament and the Council of the European Union, 2010. *DIRECTIVE 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings,* s.l.: s.n.

Tuominen, P. et al., 2014. Calculation method and tool for assessing energy consumption in the building stock. *Building and Environment,* Volume 75, pp. 153-160.

Vinha, J. et al., 2005. *Puurunkoisten pientalojen kosteus- ja lämpötilaolosuhteet, ilmanvaihto ja ilmatiiviys [In Finnish],* Tampere: Tampere University of Technology, Department of Civil Engineering.

Virta, J. & Pylsy, P., 2011. *Taloyhtiön energiakirja (Energy manual for housing cooperatives) [In Finnish].* s.l.:s.n.

Z., D. M., 2012. *Electrical load disaggregation - A project report of SGEM,* Espoo: s.n.

Zannis, G. et al., 2006. Energy efficiency in retrofitted and new museum buildings in Europe. *International Journal of Sustainable Energy,* 25(3-4), pp. 199-213.