Sustainable renovation solutions for Finnish apartment buildings

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Abstract: To achieve carbon neutrality in Finland, it is necessary to improve energy efficiency of residential stock through renovation. The study evaluates the performance of several renovation technologies in a Finnish apartment building by simulation. The renovation technologies include roof and balcony walls' thermal insulation, vapour barrier, heat distribution pipes' thermal insulation, daylighting louvers, mechanical balanced ventilation systems with heat recovery, bi-facial photovoltaic panels and ground-source heat pump. IDA ICE was utilized to simulate the demo building model, serving as the reference for renovation technologies' simulations. The renovation technologies were divided into the passive, ventilation and generation packages, and then integrated into the reference model to examine their effect on primary energy, CO_2 emissions and indoor climate. The biggest impact on CO_2 emissions (31% reduction) was gained by installing ground-source heat pump, which converts significant coal-based district heating into low emission electricity. Converting the mechanical exhaust ventilation into mechanical balanced ventilation with heat recovery was another significant measure, reducing CO_2 emissions by 21%. In contrast, the thermal insulation technologies possess lower emission reduction potential. However, the thermal insulation technologies and mechanical balanced ventilation systems slightly worsen overheating problem in summertime. Installing daylighting louvers significantly reduces summer indoor temperature.

Keywords: Finnish residential buildings, Energy renovation, Primary energy, CO_2 emissions, Indoor climate

1. Introduction

As the largest single contributor to energy consumption and carbon emissions, the building sector shares 40% of total energy consumption and 36% of GHG emissions in the EU (CITY MINDED, 2021). Thus, it is important to cut down energy consumption and carbon emissions from the building sector. In addition to building up energy-efficient new buildings, it is more important to implement energy renovations in the existing buildings since 70-90% of the existing buildings will still be used by 2050 due to the low demolish rate (Eurima, 2020).

However, the current EU energy renovation rate is only around 1.2%-1.4% per year (Eurima, 2020). In response to the situation, the EU commission published its Renovation Wave Strategy to accelerate the renovation step (*Renovation Wave*, 2020).

Against the backdrop of EU renovation wave, the EU commission initiated SUREFIT project, which aims at finding sustainable solutions for affordable retrofit of EU residential buildings. The target of this project is to reduce heat loss though building envelopes and energy consumption of heating, cooling, ventilation and lighting, while increasing share of renewable energy in the building to achieve near zero energy consumption. To explain the sustainable retrofit solutions intuitively, some representative residential buildings in different countries were chosen as the demo buildings to implement different energy-saving measures.

The study focuses on analysing the impact of different renovation technologies on energy consumption and CO_2 emissions of the Finnish demo building through building level simulations. The energy renovation measures not only affect building energy consumption and CO_2 emissions but indoor climate. Thus, the study also reveals the indoor climate change after renovation. The study's novelty is to consider and compare the impact of renovation technologies aiming at different aspects from multiple perspectives in cold climates. It can act as a reference for choosing appropriate renovation technologies for the same type of residential buildings in cold climates.

2. Methods

2.1 Simulation tool and setup

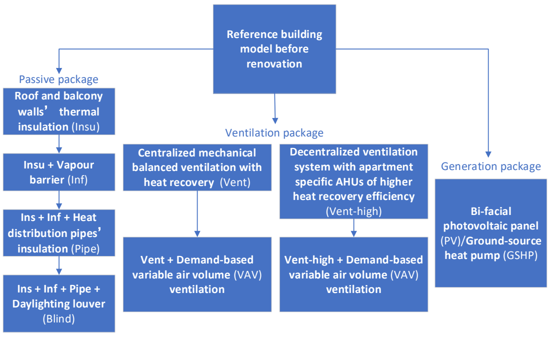
The simulation tool IDA ICE was utilized to model and simulate the demo building in the study. IDA-ICE has been validated for providing reliable results of building energy use and indoor climate in several studies (Björsell et al., 1999; Dimitruk et al., 2007). According to input data from building owners or expert evaluation, the building model was built up and simulated on an hourly timescale to acquire hourly indoor climate conditions before renovation. Then, the demo building model was used as the benchmark for the building level simulations of retrofit technologies.

The retrofit technologies were chosen according to the plans of the owner, the city of Helsinki. They were divided into three retrofit packages: the passive package, comprising roof and balcony walls' thermal insulation, vapour barrier, heat distribution pipes' thermal insulation and daylighting louvers; the ventilation package, including centralized mechanical balanced ventilation with heat recovery and decentralized ventilation system with apartment specific air handling units; and the generation package, consisting of bi-facial PV panels and ground-source heat pump.

As shown in **Figure 1**, they were integrated into the building models and simulated separately by following the order from a single technology to all technologies in each package. In the ventilation package, in addition to the basic cases retrofitted with centralized or decentralized ventilation system with heat recovery, two extra cases were also simulated, in which the ventilation system was modified by using demand-based variable air volume ventilation.

Figure 1

Simulation of retrofit packages in IDA ICE.



2.2 Building description

The Finnish demo building is a rental apartment building in Helsinki (see **Figure 2**). There are four residential floors and a basement area, consisting of garages, storage rooms and a shared sauna area. Each apartment contains a bathroom, a kitchen and other living spaces.

Figure 2

The demo apartment building in Helsinki, Finland.

The demo building has been renovated for several times over the years. The thermal insulation of external walls was improved, and all the windows were replaced by new windows with lower U-value. **Table 1** shows more building properties of the Finnish apartment building before renovation.

Table 1

Building properties of Finnish apartment building before renovation.

Demo building	Finnish apartment building
U-values of envelope [W/m²K]	
External wall	0.48
Roof	0.47
External floor	0.47
External door	1.00
Windows	1.00
Airtightness	
Air leakage rate, n_{50} [ACH]	3.0

In terms of the HVAC systems, it is heated by the municipal district heating grid and equipped with mechanical exhaust ventilation without heat recovery. Due to cold climate conditions, the apartments in the demo building are continuously heated. More detailed properties of the HVAC systems are presented in **Table 2**.

Table 2

Properties of HVAC system in the Finnish apartment building before renovation.

Demo building	Finnish apartment building
Ventilation system	Mechanical exhaust
Air change rate, n_{50} [1/h]	0.5 + 30% boost
Space heating system	District heating, water radiators
Efficiency [%]	97
Setpoint, living spaces [°C]	21
Setpoint, other rooms[°C]	17
Design temperature of water radiators [°C/°C]	70/40
Heating temperature [°C]	-26
DHW	District heating
Cold city water temperature [°C]	5
DHW outlet temperature [°C]	55
DHW use [L/day/person]	85
DHW recirculation loss [W/m^2]	2

2.3 Primary energy and CO_2 emissions factor

The primary energy and emission factors are shown in **Table 3**, along with the main heat source. The heating emission factor for Finland is the district heating emission factor in Helsinki. The CO_2 emissions factor for Finland is relatively low since the most electricity is produced by low-emission sources, such as nuclear, hydro and bio energy.

Table 3

The primary energy and CO_2 emission factors for Finland.

	District heat	Electricity
Primary energy factor [kWh/kWh]	0.5	1.2
CO_2 emissions [kg-CO_2/MWh]	220	96

2.4 Retrofit packages

2.4.1 Passive package

The thermal insulation improvement measures for building envelopes include roof thermal insulation consisting of EPS insulation (10 cm) and light gravel (9 cm) and balcony walls' thermal insulation by mineral wool (15 cm). To improve the building airtightness, vapour barrier was used to cover one balcony wall of each apartment. The heat distribution pipes were covered by thermal insulation material (2 cm) to reduce heat loss.

Daylighting louvers are advanced window blinds with special shapes that reduce excess sunlight during the day and increase diffuse natural light during the night, while avoiding glare caused by direct radiation (Eltaweel et al., 2021). This technology can reduce overheating and improve thermal and lighting comfort. In the simulation, they were installed for three windows and balcony in each apartment.

2.4.2 Ventilation package

Centralized mechanical balanced ventilation with heat recovery blows fresh air through ventilation ducts from a centralized air handling unit (Gibbons & Javed, 2022). It also manages exhaust air via parallel ducts and waste heat via an air-to-air heat exchanger. The waste heat is used to pre-heat the incoming fresh air, which increases energy efficiency. The basic heat recovery efficiency is 73%.

Decentralized ventilation provides a short air distribution path since separate compact air handling units, consisting of air filters, heat exchangers, and fans, control the air conditions in each apartment (Kim & Baldini, 2016). Compared with centralized systems, decentralized systems have lower pressure losses. The fan speed and air flow rate can be modified simply and effectively according to indoor climate. In the study, the analysed decentralized ventilation system with apartment specific air handling units has a higher heat recovery efficiency (85%) than centralized mechanical balanced ventilation.

Demand-based variable air volume (VAV) ventilation is a ventilation solution which regulates supply airflow volume over an operating time to be adapted to temperature or air quality. VAV is typically associated with lower investment costs but provides significant energy savings when compared to constant air volume (CAV) system (Okochi & Yao, 2016).

2.4.3 Generation package

Bi-facial photovoltaic panels are high-efficiency solar electric panels (Tina et al., 2021). They can generate electricity from both sides of the panel, resulting in a 21% efficiency. When connected to a PV array, micro-inverters that are directly installed on the panel will reduce installation time and improve reliability. In the study, these PV panels (140 m^2) were installed on the roof of south façade.

Ground-source heat pump is a heat pump system in which the ground act as its heat source (Bayer et al., 2012). Brine flows through underground boreholes (typically 100-300 m in length), collecting heat stored into the ground. The heating capacity and COP of ground-source heat pump for the Finnish apartment building is 35 kW and 4.8 at the standardised test condition (0/35 °C).

3. Results

3.1 Energy consumption and CO_2 emissions

Table 4 shows the district heating, electricity and primary energy use as well as CO_2 emissions before and after retrofitting with the passive package. If the roof and balcony walls were renovated for a better thermal insulation performance, the district heating consumption dropped by 13.3 kWh/m^2 due to the decreased heat transfer through the building envelopes during wintertime. In comparison, although vapour barriers improved the building airtightness, reducing heat loss through infiltration, it has a quite minor impact (1.0 kWh/m^2) on district heating consumption.

Table 4

The simulated energy consumption [kWh/m^2] and emissions [kg/m^2] before and after renovation with the passive package.

	DH	Elec	Primary	Emissions
Ref	133.6	30.0	102.8	32.3
Insu	120.3	29.9	96.0	29.3
Insu + Inf	119.3	29.8	95.5	29.1
Insu + Inf + Pipe	107.4	29.8	89.4	26.5
Insu + Inf + Pipe + Blind	107.6	29.8	89.5	26.5

***DH**: District heat consumption; **Elec**: Electricity consumption; **Primary**: Primary energy consumption; **Emissions**: CO_2 emissions; **Ref**: Reference case before renovation; **Insu**: Thermal insulation improvement for roof and all the balcony walls; **Inf**: Airtightness improvement by vapour barrier; **Pipe**: Thermal insulation for heat distribution piping; **Blind**: Daylighting louvers.

Then, insulating heat distribution pipes reduced the heat loss during the distribution process significantly. Thus, the district heat consumption lower down 11.9 kWh/m^2. Finally, when daylighting louvers were installed for windows, the indoor solar heat gain reduced during wintertime, leading to a higher space heating demand. Correspondingly, daylighting louvers have a slight negative impact on district heat consumption, increased by 0.2 kWh/m^2.

As all the technologies in the passive package focus on changing space heating demand, they basically have no effect on building electricity consumption.

The primary energy reduction level varies from 7% when only the thermal insulation of roof and balcony walls was improved to 13% when all the technologies in the passive package were applied in the simulation. The corresponding CO_2 emissions were reduced from 9% to 18%.

As shown in **Table 5**, when the mechanical exhaust ventilation was replaced with centralized mechanical balanced ventilation with heat recovery, the district heat and electricity consumption were reduced by 31.2 kWh/m^2 and 0.4 kWh/m^2. Further adjustments by using decentralized ventilation system with apartment specific AHUs of higher heat recovery efficiency or demand-based variable air volume ventilation only slightly reduced the total energy consumption.

Table 5

The simulated energy consumption [kWh/m^2] and emissions [kg/m^2] before and after renovation with the ventilation package.

	DH	Elec	Primary	Emissions
Ref	133.6	30.0	102.8	32.3
Vent	102.4	29.6	86.7	25.4
Vent + VAV	101.5	29.2	85.8	25.1
Vent-high	101.8	29.6	86.4	25.2
Vent-high + VAV	100.8	29.2	85.5	25.0

***Vent**: Centralized mechanical balanced ventilation system; **VAV**: Demand-based variable air volume ventilation; **Vent-high**: Decentralized ventilation system with apartment specific AHUs of higher heat recovery efficiency.

In compared with the reference case before renovation, the primary energy and CO_2 emissions decreased by 16% and 21%, respectively, after renovation with centralized mechanical balanced ventilation with heat recovery. As usage of the decentralized ventilation system with higher heat recovery efficiency or demand-based variable air volume ventilation does not reduce much further energy consumption, CO_2 emissions only lowered by around 1% more.

Table 6 presents the energy consumption and CO_2 emissions change before and after retrofitting with generation measures. Utilizing electricity generated by bi-facial photovoltaic panels reduced building electricity consumption by 5.7 kWh/m^2. Nevertheless, as the electricity consumption only accounts for around 20% of total energy consumption, the installation of bi-facial photovoltaic panels hardly affects the total building energy consumption.

Table 6

The simulated energy consumption [kWh/m²] and emissions [kg/m²] before and after renovation with the generation package.

	DH	Elec	Primary	Emissions
Ref	133.6	30.0	102.8	32.3
PV	133.6	24.3	95.9	31.7
GSHP	84.1	40.0	90.1	22.3

***PV**: Bi-facial photovoltaic panels; **GSHP**: Ground-source heat pump.

After installing ground-source heat pump, the district heat consumption dropped down significantly by 49.5 kWh/m^2, while the electricity consumption increased by 10.0 kWh/m^2 due to energy demand for ground-source heat pump.

Thus, the installation of ground-source heat pump led to 12% reduction in primary energy and 31% reduction in CO_2 emissions, while the primary energy and CO_2 emissions were reduced by 7% and 2% when bi-facial photovoltaic panels were installed.

3.2 Indoor climate

In the study, the simulated indoor temperature and indoor CO_2 concentration level were chosen as the index for evaluating indoor climate.

The simulated indoor climate conditions before and after retrofitting with the passive package are shown in **Table 7**. As the Finnish apartment building is continuously heated, all the time indoor temperature was higher than 21 °C before renovation. Around 11.9% of time indoor temperature is higher than 25 °C before renovation since there is no mechanical cooling system. In terms of the indoor air quality, the indoor CO_2 concentration level was always below 1200 ppm.

Improving the thermal insulation level of roof and balcony walls led to an increased proportion of time indoor temperature level above 25 °C. It means a slightly worse overheating issue during summertime after renovation. Vapour barrier and insulating heat distribution pipes basically has no impact on indoor temperature level. Finally, to solve worse summer overheating problem, the installation of daylighting louvers reduced the share of time indoor temperature higher than 25 °C to only 5.1%.

Table 7

The simulated indoor temperature and CO_2 concentration level before and after renovation with the passive package.

	T<21 [%]	T>25 [%]	CO_2 <1200 [%]	CO_2 <1800 [%]
Ref	0.0	11.9	100	100
Insu	0.0	13.5	100	100
Insu + Inf	0.0	13.5	100	100
Insu + Inf + Pipe	0.0	13.5	100	100
Insu + Inf + Pipe + Blind	0.0	5.1	100	100

***T<21/T>25:** Proportion of time indoor temperature lower than 21 °C or higher than 25 °C; **CO_2<1200/1800:** Proportion of time indoor CO_2 concentration level lower than 1200/1800 ppm.

As shown in **Table 8**, when centralized mechanical balanced ventilation with heat recovery replaced the mechanical exhaust ventilation, the proportion of time indoor temperature above 25 °C was improved by 3.2%. During certain times of the summer, the supply air temperature of mechanical balanced ventilation system is higher than outdoor temperature at the same time, which exacerbates the overheating problem. Further modifications for the ventilation system did not affect the indoor temperature level.

Table 8

The simulated indoor temperature and CO_2 concentration level before and after renovation with the ventilation package.

	T<21 [%]	T>25 [%]	CO_2 <1200 [%]	CO_2 <1800 [%]
Ref	0.0	11.9	100	100
Vent	0.0	15.1	100	100
Vent + VAV	0.0	15.1	100	100
Vent-high	0.0	15.1	100	100
Vent-high + VAV	0.0	15.1	100	100

Since the generation technologies only changed the energy sources for the Finnish demo building, they have no effect on indoor temperature.

As for the indoor air quality after renovation, regardless of renovation technologies used in the Finnish demo building, the indoor CO_2 concentration was always less than 1200 ppm (see **Table 7** and **Table 8**).

4. Discussion

Some of the renovation technologies have a significant impact on energy consumption and CO_2 emissions, while they bring negative effect on indoor climate, such as thermal insulating measures for building envelopes. Thus, if they are chosen for energy renovation scenarios, the corresponding technologies aiming at improving indoor climate should be taken into account. For instance, it is recommended to include thermal insulating measures for building envelopes and daylight louvers in the scenarios at the same time for both lower emissions and better thermal comfort.

In addition to the simulated impact of renovation technologies on energy consumption and CO_2 emissions, whether a renovation technology is feasible for the actual plan also depends on the economical analyzation of the technologies. However, the investment analysis and life cycle cost calculation of renovation technologies are not included in the study.

The renovation technologies chosen according to the simulation results and economical analyzation will be implemented in the real retrofit of the demo building later. Real-time monitoring will be utilized to evaluate simulation accuracy and improve operational performance by using advanced control algorithms. The measurements will be used for model validation and development in the future.

5. Conclusion

The study examines several renovation technologies' impact on energy consumption, CO_2 emissions and indoor climate in a Finnish apartment building by simulation. Among all the technologies belonging to the passive package, thermal insulation improvement for roof and external wall and heat distribution piping insulation conserves the largest emission reduction potential, leading to 7% and 6% CO_2 emissions reduction. In contrast, vapour barrier only has a negligible positive effect on CO_2 emissions.

As for the ventilation package, renovating with centralized mechanical balanced ventilation with heat recovery affects building emissions significantly, reducing CO_2 emissions by 16%. Then, the modification for the ventilation system, using a higher efficiency decentralized ventilation or demand-based variable air volume ventilation, further improves CO_2 emissions reduction potential slightly.

In terms of the generation package, ground source heat pump, conserves a much higher CO_2 emissions reduction potential (31% reduction) than bi-facial photovoltaic panels (2% reduction). It is also the most effective renovation technologies in the study.

In addition, some of the renovation technologies affect the indoor climate conditions. The thermal insulation technologies and centralized mechanical balanced ventilation with heat recovery result in a slightly increased indoor temperature. The installation of daylighting louvers can remarkably relieve the overheating issue.

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