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Socio-economic impacts of large-scale deep energy retrofits in Finnish apartment buildings

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ABSTRACT

Energy use in buildings is a major source of carbon dioxide (CO_2) emissions in Europe. Energy use is a major expense for building owners, but also a source of tax revenue for the government. Deep energy retrofitting of buildings can significantly reduce the energy consumption and CO_2 emissions of buildings. However, the environmental benefits are linked to the CO_2 emissions of the national energy grid. Deep retrofits have a significant cost and are not always cost-effective for building owners. On the other hand, they require a lot of investments and labor, which provides employment for citizens and tax revenue for governments. This study examines the environmental and economic impacts of large-scale deep energy retrofitting in the Finnish apartment building stock continuing until 2050. Low and high impact retrofit configurations were obtained from a previous study, which utilized simulation-based multi-objective optimization to find cost-effective solutions. Four archetypes of apartment buildings from time periods of different building codes were used to form the building stock. A building stock model based on Finnish statistics was used to estimate the future changes in the building stock. The study combines optimized energy retrofitting configurations and the building stock model to estimate the energy consumption development in the building stock undergoing large-scale retrofitting. Three retrofitting timelines were tested to show the effect of immediate and delayed retrofitting action. Then, a new socio-economic model was used to calculate the impact of energy retrofitting on the CO_2 emissions, life cycle cost, tax revenue, employment and foreign fossil fuel imports. The effect of energy grid decarbonization and long-term scheduling of the retrofits were also examined. The results show that by 2050, the CO_2 emissions of the building stock were reduced by 12–30% compared to the reference scenario with energy grid decarbonization, but no building energy retrofitting. A million euros invested into retrofitting created 15–17 jobs. Economic viability for the building owners was inversely correlated with the changes in tax revenues for the government. Cost-effective retrofitting reduced energy-based tax revenues more than it created new tax revenues through direct employment, thus providing a funding challenge for governments desiring to advance building retrofitting. However, more money would be left in the local economy due to reduced fossil fuel imports, but induced economic effects were not analyzed in this study.

1. Introduction

Energy use in buildings causes 36% of CO_2 emissions in Europe, which is why the European Union has implemented the Energy Performance of Buildings Directive (EPBD) (European Parliament, 2018). With the Paris Climate Agreement, the European Union is committed to carbon neutrality by 2050. Finland's goal is to be carbon neutral already by 2035. Achieving carbon neutrality requires significant measures to reduce greenhouse gas emissions in various sectors. To reduce the climate impact of buildings, requires not only increased efficiency requirements in new buildings and attention to the growing share of embodied emissions, but large-scale energy retrofitting of the currently existing building stock as well (European Parliament, 2018). The emission benefits of such retrofits are obvious and the EU Renovation Wave strategy has been devised to increase renovation activities and to speed up the transformation (European Commission, 2020). In addition,

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the European Commission has proposed further changes to the EPBD, declaring that all existing buildings in EU member states should be carbon neutral by 2050 (European Commission, 2021a). Every member state should devise a plan which ensures that the goal is reached. Targets for CO_2 emissions, the amount of retrofitting and retrofitting-related employment in 2030, 2040 and 2050 need to be set.

For example in Finland under the current energy mix, retrofitting the building stock might result in CO_2 emission reduction of 50–70%, depending on how deep the retrofits would be (Hirvonen et al., 2021). In Canada, just installing solar energy systems in eligible houses in the building stock could reduce greenhouse gas (GHG) emissions by 17% (Asaee et al., 2017). In Spain, cost-effective deep retrofitting could reduce the GHG emissions of detached houses by 60%, even though carbon neutrality could not be reached economically (Garriga et al., 2020). In the Northern United States, deep retrofitting of the residential building stock could reduce energy consumption by 50% with a simple payback of 25 years (Leinartas and Stephens, 2015). While the payback period was long, the modified internal rate of return was still higher than the return on US savings bonds, making building retrofitting a sensible investment for a conservative investor. A study on retrofitting the residential building stock of the United Arab Emirates (UAE) considered three levels of retrofitting, based on impacts obtained from literature (Krarti and Dubey, 2018). The estimation of socio-economic impacts included the implementation cost and simple payback period as well as job creation potential from both direct (installation and design) and indirect (equipment manufacturing) sources. Deep retrofitting of the entire UAE building stock was estimated to reduce CO_2 emissions by 28 Mt per year, with a short 2.3 year payback period. The large differences in cost between different countries highlights the need for national studies and retrofitting strategies.

Digitalization and increased connectivity between parts of the energy grid also means that energy efficiency measures done in individual buildings will start to have an impact on the whole society. On-site energy storage and demand response will affect both environmental and economic aspects of a smart grid, where each building is connected and energy use decisions can be made on the level of blocks or districts. In individual buildings, when a gas boiler is replaced with a heat pump, demand response could reduce CO_2 emissions by 5–20% (Patteeuw et al., 2015). Heat pumps can be used for heating (Esen et al., 2006) and cooling (Esen et al., 2007) and in residential and non-residential buildings (Esen and Yuksel, 2013). Demand response done on the district heating grid level can shave peak demand by 30% and reduce emissions and costs by up to 10% (Guelpa and Verda, 2021). Emissions of the building stock are also influenced by the underlying energy generation mix. Deep energy retrofitting of Finnish residential buildings combined with integration of wind power to the energy grid could reduce CO_2 emissions by 47–60% (Jokinen et al., 2020). In other decarbonization scenarios of the Finnish energy system, converting building heating to heat pumps was found to have a lower CO_2 abatement cost when forestry and land use changes were accounted for, because district heating utilizes a lot of forest biomass (Olkkonen et al., 2021). Sector coupling between the building stock and road transport is also of importance. Smart charging for electric cars and buses can increase the utility of rooftop solar electric systems and double the solar electric share of electric vehicle charging electricity mix (Heinisch et al., 2021). Buildings produce emissions not only during use, but also during construction and demolition. Circular economy could be utilized to reduce the environmental and economic impact of materials in the construction sector. A review on the topic (Joensuu et al., 2020) revealed a need for further research on product-service systems and extended service life and suggested an urban-rural symbiosis as an approach for resource recovery in integrated urban waste, water and energy systems. Cities should establish and maintain cross-institutional databases on best practices related to circular economy.

A dynamic building stock model based on population statistics and probability functions of demolition and renovation was used to estimate the potential of future development of energy-related renovations in 11 European countries (Sandberg et al., 2016). The simulations showed a future renovation rate of 0.6–1.6% towards 2050, which falls far short of the 2.5–3% that is assumed in retrofitting roadmaps. Even though many studies show building retrofitting to be financially viable, deep retrofitting has not been adopted as widely as might be expected. Most significant barriers to retrofitting have been shown to be the lack of access to funding as well as information and market failures resulting in perceived long payback periods (Lai et al., 2022). The majority of apartment buildings in Finland are owned by housing cooperatives with dozens or hundreds of shareholders, which can result in slow and conservative decision-making. A growing population of low-income pensioners lacks interest in very long-term investments, especially when combined with a perceived high cost of retrofitting.

While deep retrofitting of the building stock is often presented as economically viable, what is more complicated is the total economic impact of retrofitting. The most commonly studied economic impact is the profitability of building energy retrofitting for the building owner, measured through metrics such as the life cycle cost (LCC) or the payback period. However, there are also impacts on other stakeholders, such as the labor force and the government. New investments can influence the employment rate and tax revenues while also adjusting the trade balance of energy resources.

1.1. Economic impacts

Very typically, the only economic impact of deep retrofitting of buildings is the direct economic impact of the building owners, such as in these studies set in Kuwait (Krarti, 2015), Germany (Mayer et al., 2022) and Portugal (Palma et al., 2022), even if government subsidies are included in the calculations. In Croatia, building energy retrofits were found not to be economical for investors, but were beneficial for the society as a whole (Mikulić et al., 2016). In Finland, national level building retrofits were expected to have short-term negative effects on GDP and employment, but positive effects in the long-term (Tuominen et al., 2013). However, from the building owner's point of view, building energy retrofits can be a profitable investment as well (Hirvonen et al., 2018). Energy efficiency measures such as installing heat pumps can also increase house value, even above the calculated social benefit of the measures (Shen et al., 2021). 4–7% price premiums were observed the United States. Real estate transfer taxes for energy efficiency were examined in North Carolina (Lester, 2013). Energy Efficiency Transfer Tax (EETT) would charge an increased property tax for all purchases of old, non-certified properties, which would be rebated with proof of performed energy renovation. The study accounted for employment changes, energy saving cost savings (to spend on other things), increased real estate cost (which reduces other purchases) and reduced sales of fossil fuels (negative for the local energy production sector). Overall, EETT was estimated to have a positive impact for the economy, but the impact on tax revenues was not presented.

22 social, environmental and economic benefits of energy efficiency were identified in a systematic review of retrofitting studies (Kamal et al., 2019). However, only 2 to 12 of these benefits were included in the reviewed studies and a typical study only examines, on average, 6 of these benefits, neglecting the social and environmental aspects of energy efficiency. Benefits of building energy retrofits are found in all of building owner, industrial sectoral, national and international levels (Ryan and Campbell, 2012). Building owner and occupant level: health, comfort, convenience and well-being, increased asset value of building, energy access and affordability, increased disposable income. Industrial sectoral level: Industrial turnover through on-site work and increased manufacturing, energy provider and infrastructure benefits due to reduced capacity needs, increased asset values and green funding availability. National level: job creation, increased research activity and creation of new innovative products, reduced energy-related public expenditures, reduced particle emissions from energy generation,

energy security, macroeconomic effects (GDP, trade balance). International level: Reduced CO_2 emissions, moderating energy prices, natural resource management, development goals (energy access, poverty reduction, environmental sustainability).

Copenhagen Economics estimated in 2012 that depending on investments into building energy retrofits, the EU economy might receive a permanent annual societal benefit of 104–175 billion euros by 2020 (Næss-Schmidt et al., 2012). This includes lower energy bills, reduced subsidies and air pollution as well as the health benefits and productivity increases of improved indoor climate. Direct retrofitting-related employment benefits could affect 760 000 to 1 480 000 people and raise the EU GDP by 1.2–2.3%. Reduced unemployment could stimulate further indirect economic benefits. In the United States, intensive building energy retrofitting could reduce national CO_2 emissions by 4–11%, while also reducing SO_2 and $PM_{2.5}$ emissions, helping to avoid 3700 to 7800 premature deaths per year by 2050 (Gillingham et al., 2021).

Government subsidies for energy retrofitting can be cost-neutral due to increased employment and new tax revenues. In Estonia, it was estimated that 17 jobs would be created by a million euro investment into building retrofits (Pikas et al., 2015). Tax returns on renovation projects were estimated at 33%, which could be used as a basis for subsidies. Economic benefits were found in both individual and government level. However, this study did not account for the reduction in consumption-based tax revenue. Carbon mitigation unit costs of retrofits in large buildings were estimated in the UK under 12 different fuel carbon intensity and 14 economic scenarios (Royapoor et al., 2019). Economic impact was measured by end-user profitability and by the required carbon tax to make retrofitting profitable.

Few studies consider the potential negative impacts of retrofitting. A study on the retrofitting of Gothenburg building stock revealed cost estimates based on realized projects (Mangold et al., 2016). The costs of retrofitting rental properties were typically to be paid by rent increases, which could mean a 240 €/month increase in living expenses, a hefty raise for those with below median incomes. This finding reveals the need for socially sustainable funding of retrofitting. Fair rent increases following building retrofits were studied in Germany (Ahlrichs and Rockstuhl, 2022). Currently building owners can charge a fixed percentage (8%) of retrofitting costs as rent increases. However, when accounting for the actual energy efficiency benefits of the retrofits, lower fair percentage levels were found for expensive retrofits due to diminishing returns when more measures are utilized. In old houses fair percentages were larger than the current limit, while in new houses they were lower. Investment subsidies and emission prices would not benefit the landlord (investor) in the current percentage-retrofitting-fee model, highlighting the need for fair retrofit cost-sharing in non-owner-occupied buildings.

1.2. *Fossil fuel trade and energy supply security*

Energy efficiency has an impact on energy supply security. For example, EU imports 100% of its natural gas supplies (Ruble, 2017), even though it is an essential heating fuel for millions of people with a 32% of household final energy consumption (Eurostat, 2021a). During the 2017–2020 period, the average natural gas imports into EU were valued at over 50 billion euros per year (Eurostat, 2021b). 44% of solid fossil fuels, such as coal, are also imported (Eurostat, 2022). Any improvement in building energy efficiency will reduce reliance on imported energy and improve the trade balance by corresponding amounts. This will also mitigate the impact of trade shocks due to increased energy prices (Bildirici and Kayıkçı, 2021). The EU is operating the Emission Trading System (ETS), which causes electricity and district heating prices to rise according to the CO_2 emissions of energy generation and the development of emission allowance prices (European Commission, 2022). Revenues collected through the ETS are paid to EU member states, which could be considered a form of taxation. When utilities reduce their emissions, this should in principle result in lower energy prices, which would benefit both individuals and companies. On the other hand, the loss of ETS revenues puts a pressure on the government to raise taxes. The EU climate targets also function like energy security targets, as an energy mix consisting more of renewable energy will reduce the political pressure that fuel providers can bring to bear on the EU and its member states (Strambo et al., 2015).

1.3. *Decision-making*

Uncertainty in retrofitting outcomes may result in people canceling their planned retrofitting projects (Pornianowski et al., 2019). Retrofit plans need to be communicated in non-technical language and presented as transparent package solutions that can be trusted to provide the promised improvements at the expected cost. The most economical retrofit packages are not necessarily selected, as people also care about comfort, real estate value and architectural aesthetics. Desirable packages should be developed jointly with various stakeholders, so that people find it easy to plan and make investment decisions. An Irish study examined households' willingness to pay for building energy retrofitting, by comparing the differences in the amount of retrofitting performed with or without government grants (Collins and Curtis, 2018). It was estimated that only 7% of retrofits would have been performed even if no grants were available. This shows the importance of monetary incentives. The issue of funding availability could be helped by the EU Taxonomy and Sustainable Finance plans, as more money will be directed for emission mitigating actions (European Commission, 1804). The effect of budget constraints on retrofit investments were studied in (He et al., 2019).

There are many studies on the impact of retrofitting on the building stock (Garriga et al., 2020), (Leinartas and Stephens, 2015). A common approach is to utilize a set of building archetypes, which represent large sections of the building stock. Hourly simulation of building archetypes is often coupled with optimization methods, to find the most cost-effective retrofitting solutions. Most commonly the focus is on direct economic impact on the building owner and the reduction in CO_2 emissions. Some studies have also considered the impact on taxation, employment or human well-being (Næss-Schmidt et al., 2012), (Pikas et al., 2015). However, only some of the factors were considered in each paper and a comprehensive study that includes both positive and negative tax impacts, along with effects on trade balance was not found. Differences in climate, the national energy mix and the current condition of the building stock create the need for national studies that account for the specific challenges of building stock retrofitting in each country.

In this study, we examine the economic impacts of deep retrofitting of Finnish apartment buildings. The socio-economic model utilizes energy consumption results from a detailed building energy retrofit optimization study, combined with the latest building stock model, designed for Finnish conditions. We take into account the current plans for emission reduction in the energy sector and estimate the long-term economic impacts on building owners and society. This includes changes in employment and the trade balance, as well as CO_2 emission reduction. We separate the impact of building retrofitting from the changes in the energy mix and calculate the influence of different long-term retrofitting schedules. The novelty can be found both in the extensive economic impact calculation and the joint estimation of changes in the building stock and energy system. No such study has been performed in the Finnish context before. This study presents how energy efficiency reduces consumption-based tax revenues, which was not found in any prior research paper. In contrast to the typical method, we also report the GHG impacts in terms of cumulative CO_2 emissions over the long term, instead of just as the final annual emission value. Accounting for different retrofitting timelines is another novel feature of the study. Finally, this paper presents the large-scale renovation impact on imported fossil fuels in a changing energy grid, which was not done in any of analyzed prior studies. The research questions are the following:

RQ1. How does the time distribution of energy retrofits affect the cumulative CO_2 emissions of the building stock over a long time?
RQ2. How do building energy retrofits reduce the cost of imported fossil fuels?
RQ3. How many jobs are generated due to building retrofitting?
RQ4. How do large-scale investments into building energy retrofits influence tax revenues?

2. Methods

This study examines the large-scale deep energy retrofitting of the Finnish apartment building stock. The building stock of 2020 is established as the baseline for the transformation happening until 2050. Two retrofitting strategies are defined, with three different timelines for retrofitting. The lifetime of the retrofit investments is 30 years, so part of the gradual retrofit actions can extend influence up to 2080.

The study is based on computational methods. The input data comes from previous scientific studies, official statistics and from personal interviews with experts. Two major components from previous studies are: 1) dynamic building simulation with multi-objective optimization (Hirvonen et al., 2018) and 2) national building stock modelling (Kurvinen et al., 2021). These are used to analyze the socio-economic impact of national-scale deep energy retrofitting of the Finnish apartment building stock, as shown in Fig. 1.

No new building simulations were performed during this study. Instead, building energy demands generated in a previous optimization study on apartment building retrofit optimization (Hirvonen et al., 2018) were used as inputs for this study. Fig. 1 shows the basic idea: The Finnish apartment building stock was divided into four age classes according to the energy efficiency requirements in the building code of their construction years. Hourly heating and electricity demands were obtained using dynamic building simulation with the IDA-ICE software. The buildings were retrofitted using passive methods, such as additional thermal insulation and upgraded windows and active methods, such as heat pumps, solar panels and heat recovery systems. An evolutionary algorithm was used in the MOBO tool to do multi-objective optimization and to find retrofit solutions with minimal cost and CO_2 emissions for each of the different apartment buildings. More details are shown in Section 2.3. For a detailed account of the simulation and optimization process, refer to (Hirvonen et al., 2018).

Parallel to this, the QuantiStock model (Kurvinen et al., 2021) was used to calculate the distribution of heating systems and the amount of apartment buildings of each age category in the current building stock (in 2020) and in the future building stock (in 2050), as presented in Fig. 1. More details are presented in Section 2.4. The building stock energy consumption was generated according to the building stock composition and retrofitting actions and used as an input for the socio-economic impact model. The retrofitting scenarios were chosen based on (Hirvonen et al., 2021), with a focus on cost-effectiveness or high CO_2 impact. Since the calculations extend to 2050 and beyond, climate change was also expected to reduce heating demand, as in (Hirvonen et al., 2021). The heating energy consumption of the buildings was thus adjusted according to the estimated impacts of climate change (Jylhä et al., 2015), with linear progression between the

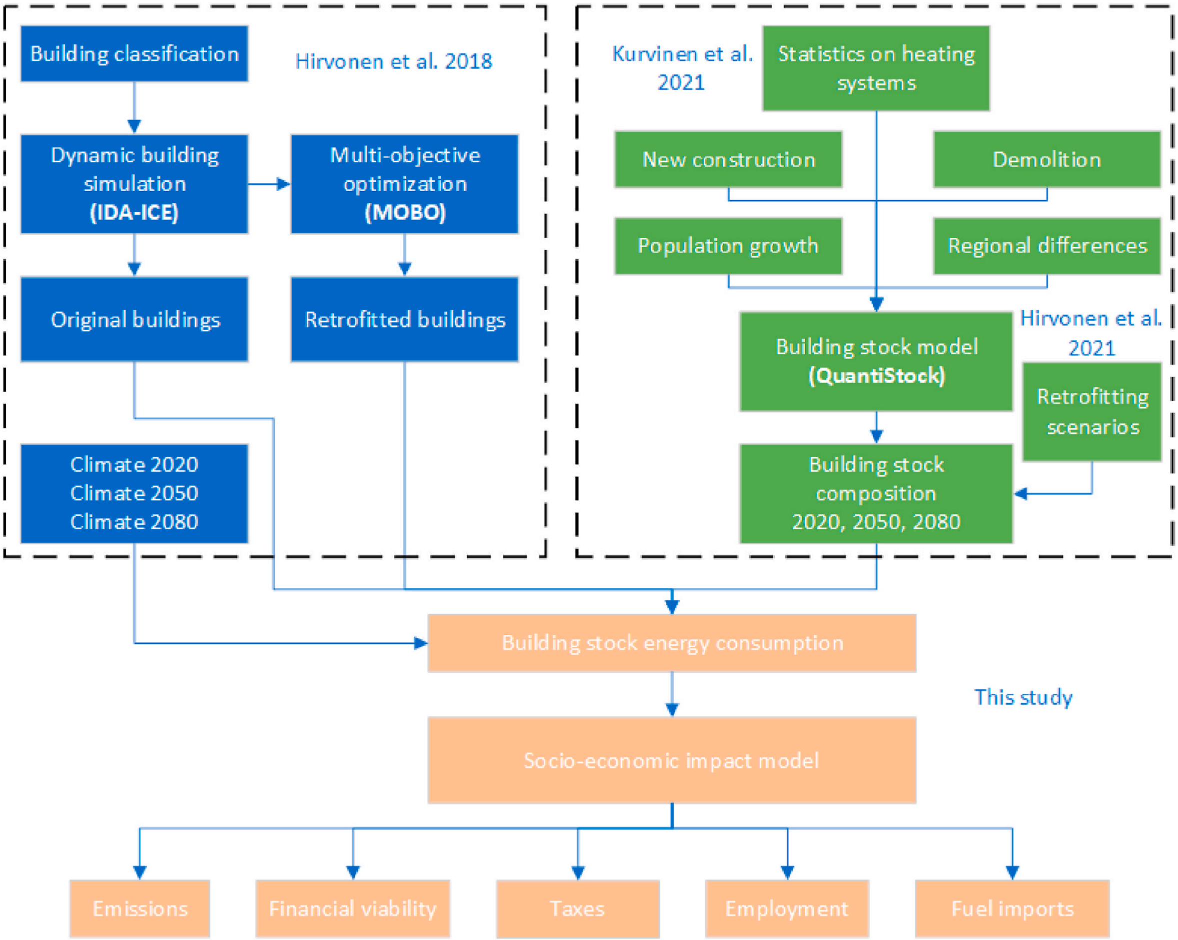

Fig. 1. The models and tools used in the study. Models and results from previous studies (Hirvonen et al., 2018 (Hirvonen et al., 2018), Hirvonen et al., 2021 (Hirvonen et al., 2021), Kurvinen et al., 2021 (Kurvinen et al., 2021)) were used as input data for the socio-economic impact modelling in this study.

landmark years 2050 and 2080.

The process and components of the calculation of societal impacts of large-scale deep retrofitting campaign are shown in Fig. 2. The green boxes and their connections represent direct relations between stages of the national retrofitting process. The orange boxes are external influences that can change the input values, but are not controlled by the process. Investment decisions are first done on the individual building owner level. Different measures of retrofit will reduce energy consumption and emissions significantly (28–82%) in the buildings, some of it profitably (Hirvonen et al., 2018). When scaled up, these actions will impact the society by reducing energy consumption in the whole building stock. This will influence CO_2 emissions and economic matters on the national level, as retrofitting incurs cash flows at related to salaries, equipment and taxes. The following sections will describe the elements of Fig. 2 in more detail.

2.1. Resources

Various resources are needed for the operation and retrofitting of buildings. The building owner must pay the investment cost, which is about evenly split between labor cost and material cost. If there are lots of simultaneous investments, labor shortages might become an issue. Materials include things like thermal insulation and windows as well as heat pumps and other electronic devices. Domestic vs. foreign production can make a difference in the security of supply and cost inflation. Energy consumption of district heating, fuels and electricity changes after retrofitting, depending on the scale of the investments. This can in turn influence the potential of future investments depending on the available energy resources.

Apartment buildings in Finland are currently mostly heated by district heating (90%). A smaller fraction of buildings are heated by on-site oil-boilers (7%). Some apartment buildings also utilize electric heating (heat pumps or direct electric boilers) or wood-burning boilers, but the share of each of these systems is nowadays only about 1% (Statistics Finland, 2015). The share of oil heating is decreasing, while the share of ambient heat is increasing, as 800 M€ per year is invested in heat pumps in Finland (Finnish Heat Pump Association SULPU, 2022).

2.2. Expenses

Retrofit investments include costs of worker salaries (on-site and factory work) and the installed equipment. Part of this cost are government taxes. Taxes are paid on both labor and materials (income tax, pension fees, value added tax). Energy expenses include the cost of district heating and electricity, which is further divided between the spot market price and distribution costs. Energy expenses also involve taxes (value added tax, electricity tax) and tax-like expenses (the EU emission allowance cost).

2.2.1. Labor cost

The labor costs for the client were estimated assuming two worker roles: 15% of the labor was salaried design and management work (4000

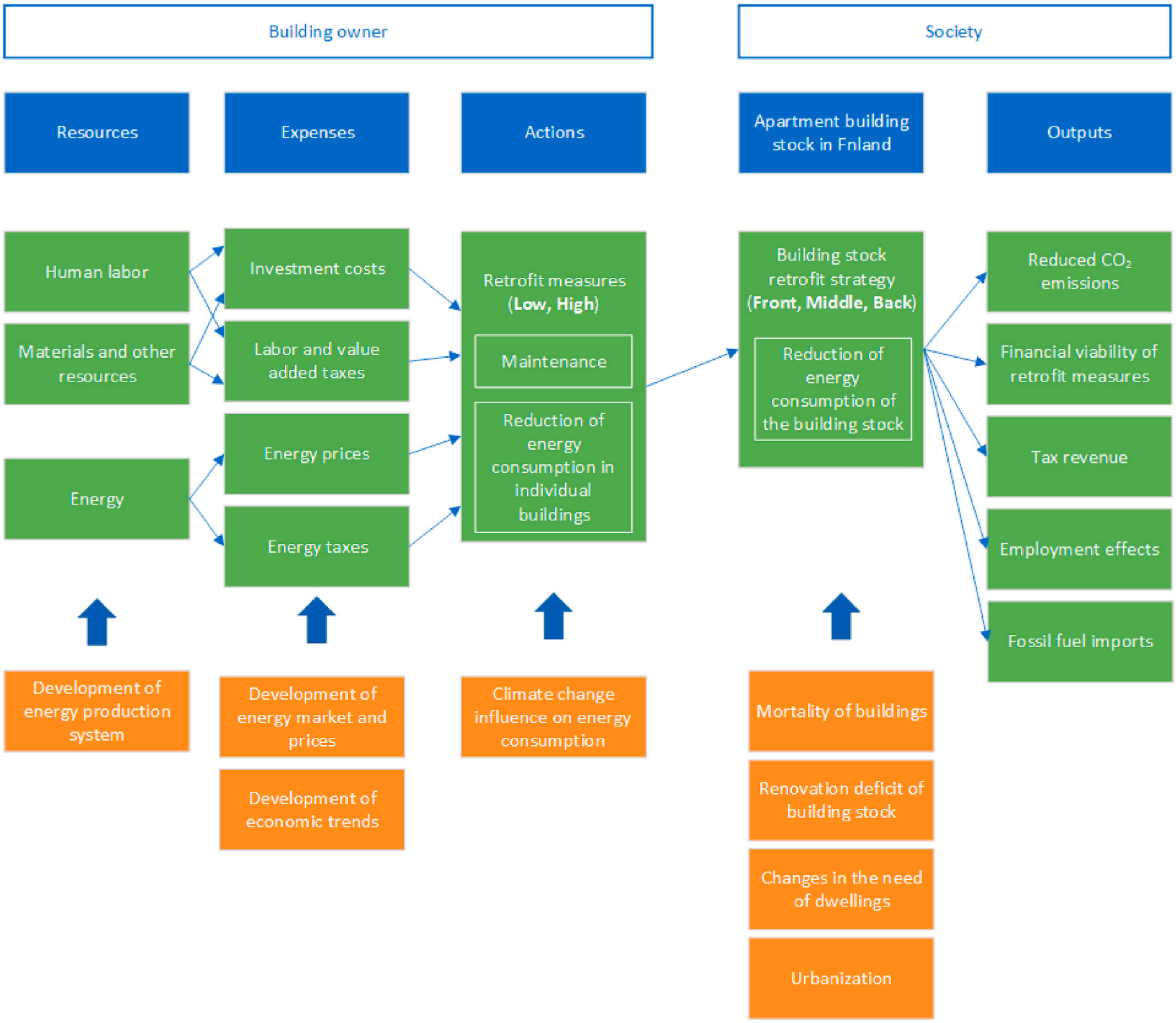

Fig. 2. Calculation process and its elements. Actions performed at the individual level are combined to create society level impacts.

€/month) and 85% of the labor was hourly paid field work such as construction and installation (18 €/h (Statistics Finland, 2021a), 153 h/month). In addition, 34% extra was added for employer costs such as pension payments and paid vacations (Finnish Centre for Pensions, 2021). The monthly labor costs were accounted for 11 months of each year, amounting to a combined average cost of 43 350 €/year for each worker. The share of labor out of the total investment was assumed to be 50%. In addition to the initial installation task, there is also ongoing maintenance work.

2.2.2. Energy cost

District heating costs in Finland are different for each municipality and contain different pricing schemes, such as consumption-based seasonal or fixed pricing and availability-based capacity/connection costs. Here, national average district heating prices were used, with a single annual consumption-based price (Statistics Finland, 2020a). This value combines the variable energy consumption costs and the fixed capacity costs that are paid based on annual peak heating power consumption.

Electricity cost also includes several components, such as the energy market price (based on the Nord Pool spot market), the distribution cost, the electricity tax and fixed monthly fees. All the numbers were combined for an average total electricity price.

Table 1 shows the consumption-based prices for each utilized energy source along with the impact of taxes.

2.2.3. Taxation

Taxes are collected in all stages of the retrofitting process life cycle. All fossil fuel -based energy generation (district heating, electricity, oil boilers) are subject to varying taxes, such as the energy content tax, carbon tax and security of supply tax, as well as the electricity tax and value added tax. The investments are subject to labor income taxation and pension payments as well as the value added tax and the corporate tax.

2.3. Actions: energy saving measures

The configuration of a deep energy retrofit changes depending on the desired level of energy efficiency improvement. The retrofit measures considered here were taken from an earlier study which focused on finding optimal energy retrofit configurations in Finnish apartment buildings (Hirvonen et al., 2018). Dynamic simulations with IDA-ICE (EQUA Simulation and IDA ICE - Simulation Software, 2019) were performed in (Hirvonen et al., 2018) to obtain the energy demand of the reference buildings. The simulation tool was connected to MOBO (Palonen et al., 2013), to perform multi-objective optimization to minimize the life cycle cost and CO_2 emissions in the buildings. From the many Pareto optimal solutions presented in the study, two sets of results were utilized here: low impact, cost-neutral building retrofits (Low) and high impact, non-profitable building retrofits (High). Two heating technologies were utilized: district heating (DH) and ground-source heat pumps (GSHP). Low impact retrofits using DH could reduce CO_2 emissions by 28–42%, while high impact retrofits using GSHP could reduce CO_2 emissions by 70–84%. The retrofit calculations of individual apartment buildings were finally combined at the building stock level, to provide two basic retrofitting scenarios, DH Low and HP High. The building stock was formed using four building archetypes from construction periods with different building codes. The retrofit configurations included improvements to the building envelope and changes to the ventilation and energy generation systems. More details can be read from Appendix A and the original publication (Hirvonen et al., 2018).

Table 1
The purchase price of different energy sources for Finnish apartment buildings.

Energy source	Price without tax (€/MWh)	Price with tax (€/MWh)	Tax rate (%)
District heating	56 (Statistics Finland, 2020a)	77	39 (Tiitinen, 2021)
Electricity	133 (Energy Authority, 2019)	201	51
Oil	51 (Statistics Finland, 2022)	100	97 (Verohallinto, 2021)
Wood	40 (Oy, 2022)	50	24 (Tiitinen, 2021)

2.4. Building stock

The building retrofits were assumed to happen gradually over the period 2020–2050. The investment lifetime was 30 years, so the impact of retrofits can reach up to 2080. During this time, part of the currently existing buildings are demolished. New buildings are also constructed, but in this study we focus only on the currently existing buildings (year 2020). The changes in the building stock caused by building mortality were calculated using the QuantiStock model (Kurvinen et al., 2021), which can account for building renewal and demolition as well as regional differences and change of purpose. The changes in the building stock are shown in Table 2. By 2050, 76% of the current residential building stock is still in use with the rest being replaced by new construction. In 2080, only 48% of the current residential buildings are in use. Demolition of buildings is done only in the oldest age category (AB1, built before 1976). In the business-as-usual (BAU) case, the currently existing buildings remain in their original condition, considering energy efficiency. In the retrofitting scenarios, 98% of the remaining old buildings are retrofitted to be more energy efficient. The lifetime of the retrofit investments is 30 years, so most investments will have an impact even after the retrofitting period ends in 2050. For example, the retrofits performed in 2050 will have an impact until 2080. The calculations in this study only account for the currently existing buildings. New buildings constructed after 2020 are disregarded.

Two retrofitting strategies presented in (Hirvonen et al., 2021) were implemented in this study: a low impact, cost-neutral strategy, with a focus on district heating (DH Low) and a high impact, unprofitable strategy with a focus on heat pumps (DH GSHP). In the DH Low scenarios, 50% of oil boiler heating systems are converted to DH, while the other 50% is converted to GSHP. Other heating systems remain as they are. In the GSHP High scenarios, 100% of buildings with oil heating and 1/3 of buildings with district heating are converted to GSHP. Other heating systems remain the same. The DH Low scenario represents a case where the currently dominant district heating system remains in place and investments are done economically. The HP High scenario represents a case where much of the dominant DH systems get replaced by heat pumps and investments are done primarily for environmental reasons. These scenarios were used to show the range of possible economic effects of varying investment levels and were not intended to be recommendations for the best courses of action.

The retrofitting of the building stock was assumed to happen gradually over the 2020–2050 period. In principle, acting sooner would have a stronger cumulative economic and environmental impact in the long-term, but the availability of material resources and human workforce may be an obstacle. In practice, the national retrofitting strategy needs to planned in such a way that the required resources are available and price inflation due to overheating markets is avoided. Three retrofit timeline scenarios were tested for both retrofitting strategies. The retrofit rates and schedules were not intended as optimal or

Table 2
Floor area of the apartment building stock.

Building class	Building stock size (million-m^2)				
	2020 Reference	2050 BAU	2080 BAU	2050 Retrofit	2080 Retrofit
Original	102.2	77.7	49.3	1.9	0.7
Retrofitted	0	0	0	75.7	48.6
Demolished	0	−24.5	−52.8	−24.5	−52.8

recommended strategies, but the aim was to gain a big picture view and simply show how much impact there could be in the end result when the retrofitting timeline is hurried or delayed. In the front-loaded scenario (Front), the retrofitting of buildings starts at full speed in the year 2020 (5.5% of original buildings retrofitted per year) and is gradually scaled down by 2050 (1%/a). Most investments will be done in the first decade. This is the environmentally ideal scenario, which maximizes the retrofit impact while the CO_2 emissions of grid energy are still high. In the middle-focused scenario (Middle), the investments start at low pace (1%/a) and are scaled up until the middle of the examined period in 2035 (5.5%/a), at which point they will be gradually reduced until 2050. This is considered the most realistic scenario, where the ramp-up of retrofits takes some time (to train the workforce and increase manufacturing capacity), but once most of the work is done, the retrofitting efforts start to scale back. In the back-loaded scenario (Back), it is assumed that it will take a long time to scale up the retrofits, which is why retrofitting rate starts at a low level (1%/a) and will gradually increase until reaching the peak at 2050 (5.5%/a). This scenario represents a pessimistic case with delayed retrofitting plans. These three scenarios are visualized in Fig. 3. Part A of the figure shows how the annual retrofitting rate changes over the 30 year examination period under each retrofitting schedule. Part B shows how the cumulative retrofit operations are divided over the decades.

2.5. Outputs

The retrofits will reduce significantly the energy consumption of the whole building stock. This will reduce the energy expenses of the building owners, but will also reduce the energy-related tax revenue of the government. On the other hand, investments into the retrofit will provide employment for construction and industrial workers and new tax revenue for the government both from income taxation, corporate taxation, and value added taxes. Thus, two outputs of the model are the financial viability of the retrofit investments from the owner's point-of-view and the net tax revenue for the government.

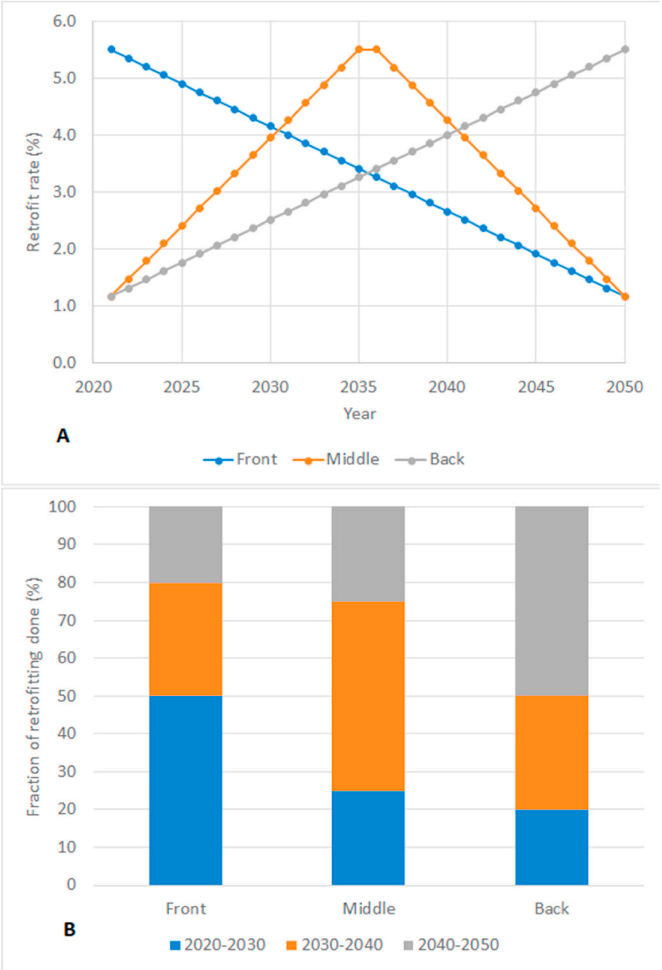

Fig. 3. The annual retrofitting rate (A) and time distribution of retrofits (B) for each scenario.

Reduced energy consumption will also influence the emissions of energy production and one output is the amount of CO_2 emissions released by the building stock. The number of new jobs will be presented in the form of labor-years. Finally, retrofitting will reduce the amount of imported fossil fuels, according to the current Finnish energy production mix. This will change the foreign trade balance and leave more money for domestic consumption.

The retrofits investments are done gradually over a 30 year period and all investments were assumed to have a 30 year lifetime. This means that the benefits of the retrofit actions will continue up to 2080, even after the investments stop in 2050.

2.5.1. CO_2 emissions

The CO_2 emissions were calculated using the annual energy consumption values of the buildings and the average emissions factors of electricity, district heating, oil and wood (Table 3). The Finnish plans for decarbonizing the energy system were accounted for by gradually reducing the emission factors of electricity and district heating in accordance with the estimates of the Finnish Ministry of the Environment (Ministry of the Environment, 2019). To obtain the cumulative CO_2 emissions, annual emissions were summed up year by year according to the variable retrofitting rates in each scenario. While wood combustion as such has rather high CO_2 emissions, they are assumed 0 as is the practice for renewable fuels. CO_2 emissions from the material phase and construction of the retrofit measures (embodied CO_2) were not taken into account in this study.

2.5.2. Financial viability

The financial viability of deep retrofitting for the building owners was determined using the net present value of the combined costs. This includes the annual investments from the period 2020–2050 and the maintenance costs and energy cost savings from the extended 2020–2080 period. Investments stop at the 30 year mark, but the economical benefits of each annual investment round will keep running for a 30 year period. The net present value was calculated using Equation 1

$$NPV = \sum_{n=1}^{60} \frac{E_n(1+r_e)^n - I_n - M_n}{(1+r)^n} \tag{1}$$

where E_n is the energy cost savings obtained in year n, I_n is the retrofit investment made in year n, M_n is the cost of maintenance in year n. In addition, r is the real interest rate and r_e the energy price escalation above the general inflation rate.

The default values for discounting were 3% for the real interest rate and 2% for the energy price escalation above general inflation. The investment costs were based on (Niemelä et al., 2017a), (Niemelä et al.,

Table 3
Emission factors of different forms of energy during different decades (Ministry of the Environment, 2019).

	Emission factors during different years (kg-CO_2/MWh)						
	2020	2030	2040	2050	2060	2070	2080
Electricity	121	57	30	18	14	7	4
District heating	130	93	63	37	33	22	15
Oil	260	260	260	260	260	260	260
Wood	0	0	0	0	0	0	0

2017b) and (Saari and Airaksinen, 2012) with non-energy related costs deducted and prices increased by a 19% construction offer price index correction (Haahtela-yhtiöt, 2022). Annual maintenance costs were assumed to be 0.5% of the initial investment.

2.5.3. *Tax impact*

Tax effects were also calculated using the present value method and same discounting factors as for financial viability. Taxes were collected from the salaries of workers taking part in building renovations and later maintenance work. Based on the salary levels of the workers (see section 2.2.1), the tax rate was 15.7% (Finnish Tax Administration, 2022). Companies involved in renovation work pay a 20% corporate tax on their profits. Value added tax of 24% is charged on materials (heat pumps, insulation etc.) and renovation services, to be paid by the building owner.

Taxes are also paid on consumed energy. The tax rates vary based on the form of energy. The average tax on district heating is 39%, which includes the excise tax and the VAT (Tiitinen, 2021). The district heat price and tax calculation also includes the capacity fee. The average tax on electricity is 51%, including the electricity tax and VAT. This was calculated for the total price, which includes the electricity market price and the distribution cost (Vattenfall, 2022). The 50% oil tax rate was based on the taxes of light heating oil and includes also the VAT. The tax on wood was just the 24% VAT. Fig. 4 visualizes the calculation process of the tax impacts.

2.5.4. *Employment impact*

To calculate the jobs created by the retrofitting, the share of domestic labor out of the total cost needs to be determined. First, the amount of foreign costs were deducted. This was taken as 20%, according to the Finnish construction statistics (Statistics Finland, 2020b). According to (Kaivonen and Ratia, 1995), the share of labor costs out of all taxable renovation costs is 49–62%. Here, labor costs include direct costs of work on site, management costs, design costs, and project management costs. The additional costs listed above include the cost of labor used in the manufacture of construction materials. As energy retrofitting contains large amounts of installation of equipment, the share of labor was chosen from the low end of the range, as 50% of total cost. The cost of one year of labor was estimated as 43 350 € (see section 2.2.1).

The potential cost of unemployment was calculated assuming that no retrofitting is performed and that all people not employed by those projects, would remain unemployed, thus providing an upper estimate for the cost. The annual cost of unemployment was 13 500 €/person. This is composed of the direct unemployment benefit of 725 €/person/month and the housing allowance of 400 €/person/month (Social Insurance Institution of Finland, 2022). The unemployment benefits were not directly included in the tax impact calculations, but are shown in Fig. 4 as a potential influencer.

2.5.5. *Fossil fuel imports*

About 25% of Finnish primary energy comes from foreign fossil fuels: coal, oil and natural gas (Statistics Finland, 2019a). Other fossil fuels are also used, but in addition to domestic peat, they are waste fuels and

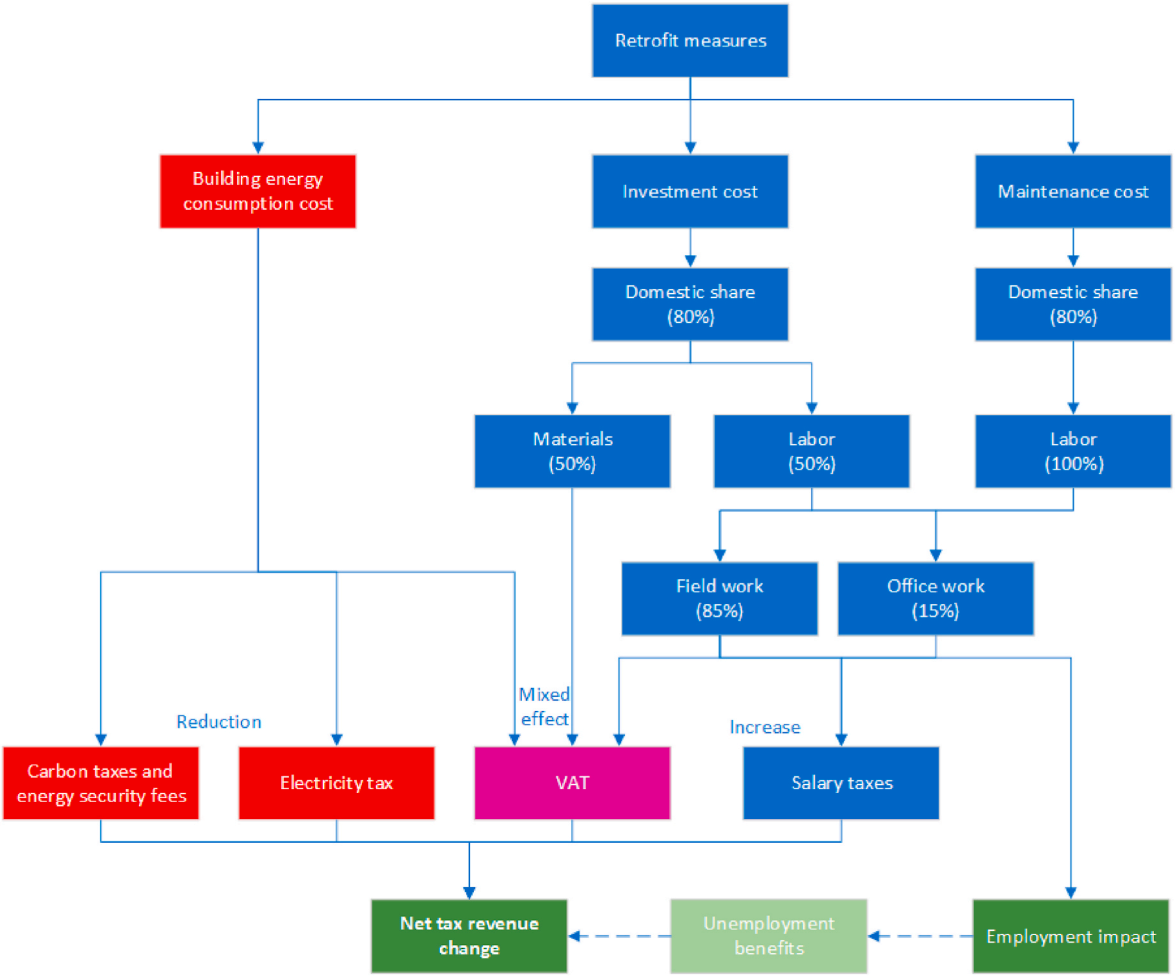

Fig. 4. Tax and employment impact calculation process. Effects of unemployment benefits were not included in the net tax revenue, but they have a potentially large impact.

industrial byproducts, which have not been imported for energy generation and have therefore been excluded from the analysis. Large-scale retrofitting reduces national energy consumption and consequently also the imports of foreign fuels. This is relevant from the point-of-view of national energy security and trade balance. Fig. 5 shows the input parameters and the calculation process for the value of the fuel imports. The share of different fuels in district heating and electricity generation was used to count the cost of imported fossil fuels per unit of energy. The energy generation statistics are from 2019. Total national district heating generation included combined heat and power and heat-only boilers, but excluded industrial heat, giving a total DH generation of 38.1 TWh (Statistics Finland, 2019a). Electricity generation was the total Finnish electricity generation of 66.0 TWh (Statistics Finland, 2019b), including non-combustion based energy, but excluding imported electricity. Oil import price was based on the price of heavy fuel oil (Statistics Finland, 2021b). Hard coal and natural gas prices were used for the other fossil fuels (Statistics Finland, 2021c). Different building retrofit scenarios and energy consumption values were used to calculate the total fuel cost of the building stock. Average imported fossil fuel cost was calculated as the weighted average price of individual fuels, according to the fuel consumed per unit of energy generation, as presented in Equation 2

$$P_{fossil} = P_{coal}{}^{*}f_{coal} + P_{oil}{}^{*}f_{oil} + P_{gas}{}^{*}f_{gas} \tag{2}$$

where P is the import price of each fuel per unit of energy and f is the share of the fuel in district heating or electricity generation (as shown in Fig. 5). The average share of foreign fossil fuel cost was 16.0 €/MWh in district heat generation and 7.4 €/MWh in electricity generation.

Over the calculation period, the Finnish energy generation mix is expected to change and the CO_2 emissions reduced in tandem. Therefore, the share of fossil fuels in district heating and electricity generation was assumed to change with the same ratio as emissions are reduced (according to Table 3). This means that the share of fossil fuels in 2050 is reduced by 72% in DH generation and by 85% in electricity generation, reducing the average imported fuel cost per unit of energy by the same fractions.

3. Results

3.1. CO_2 emissions

CO_2 emissions of the apartment building stock in the different scenarios are presented in Fig. 6 as cumulative emissions over the period of 2020–2080. This shows how the different retrofit schedules affect the changes in emissions and how the benefits of retrofitting start to saturate as the emission factors in the energy grid also get lower. In Fig. 6, the 30-year investment lifetime of the retrofits is ignored and the emission reducing effects have an impact all the way to 2080. The total accumulated emissions by 2050 were reduced by 15% in the DH Low Middle scenario and by 23% in the HP High scenario. However, the difference in additional emissions over the 2051–2080 period gets larger, as a fully retrofitted building stock is compared to the totally unretrofitted building stock. In the HP High Middle scenario only 1.5 Mt of CO_2

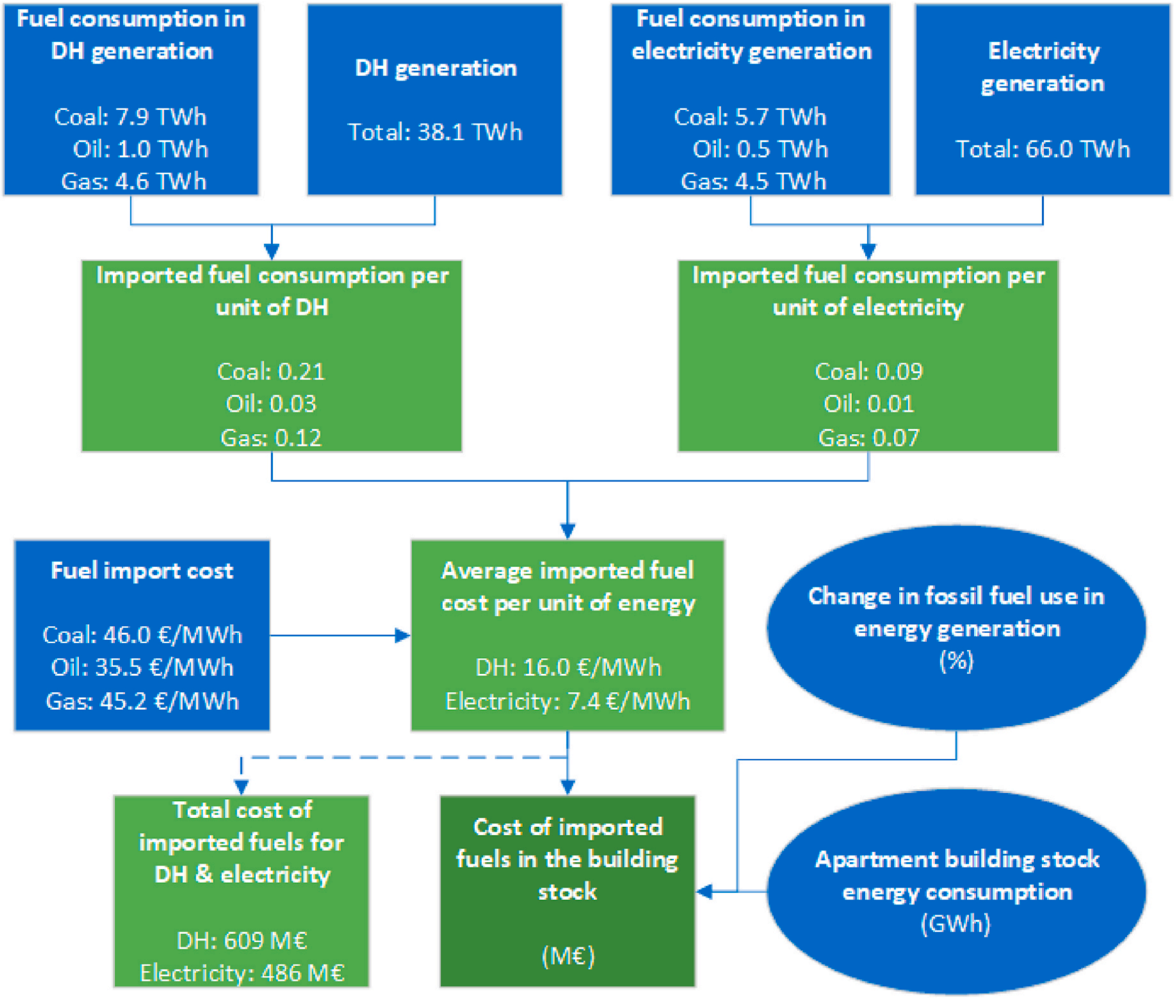

Fig. 5. Calculation of imported fossil fuel cost.

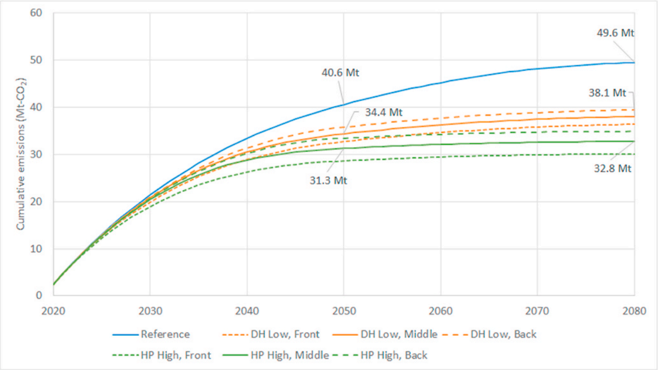

Fig. 6. Cumulative CO_2 emissions of the apartment building stock in each scenario. Investment lifetimes are ignored.

emissions were accumulated, while 9 Mt were added in the Reference scenario. The annual CO_2 emissions in 2050 were 0.33 Mt lower than Reference in the DH Low scenarios and 0.45 Mt lower in the HP High scenarios.

Fig. 6 showed the annual emission accumulation under the assumption that all retrofit impacts are permanent. Fig. 7 continues the analysis by showing the accumulated emission cuts resulting from the retrofitting compared to the Reference scenario, when limited investment lifetimes are considered. This means that after 30 years, each retrofitted building will stop providing emission cuts. The emission cuts were split into two parts: 1) the 2020–2050 period, when retrofits are made according to the annual schedule, 2) the 2050–2080 post-period, when no more energy saving measures are implemented in the building stock. The latter period helps to take into account the effect of retrofits done in the later part of the first period, as otherwise their cost-to-impact ratio would be very high. However, accounting for the 30-year investment lifetime prevents early retrofits from having a very long impact period compared to later retrofits.

In all scenarios, 74% of the original building stock was retrofitted by 2050. At the same time, 24% of the original building stock was demolished, so almost all of the original buildings remaining were retrofitted. The impact of retrofitting scheduling on the accumulation of CO_2 emissions was noticeable, but limited by the concurrent reduction in the emission factors of the energy grid. As shown in Fig. 7, in the DH Low Front scenario, where retrofitting was mostly done early, by 2050 the CO_2 emissions were reduced by 7.9 Mt (19%) compared to the unretrofitted reference scenario in 2050. In the DH Low Back scenario, where most retrofitting was delayed, the emission accumulation was only reduced by 4.8 Mt (12%). The emission benefits continued even after 2050, so further reductions of 29–42% were accounted for the 2051–2080 period. However, the higher relative values are due to the low absolute emissions in the reference scenario. The values for emission cuts ignore the cuts made after the 30-year lifetime of each retrofit investment has passed. In the HP High scenarios, the emission cuts were greater. In the Front scenario, by 2050 the emissions were cut by 30%, while in the Back scenario they were cut by 18%. The results from the two figures are also compiled into Table A1 in the Appendix.

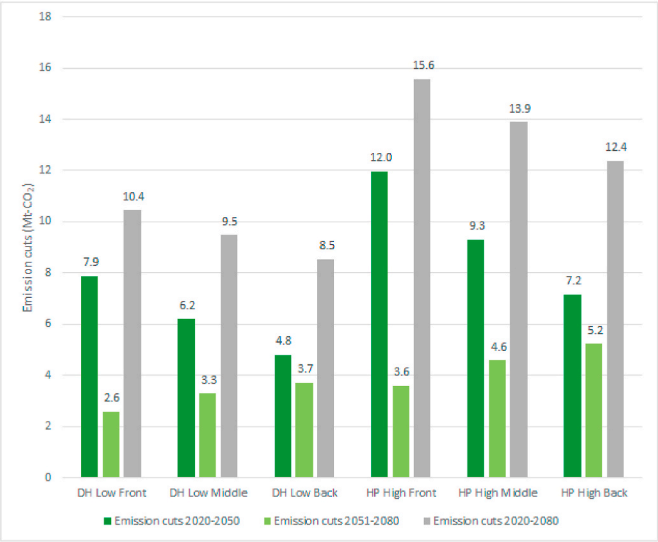

Fig. 7. Cumulative CO_2 emissions cuts of the apartment building stock. Emissions cuts are only counted during the 30-year investment lifetime.

Fig. 8 shows how the emission cuts of large-scale apartment building retrofitting campaigns would change using different emission factors of electricity and district heating. The values show the total cuts over the 2020–2080 period, taking into account the 30-year investment period, which limits the impact of individual retrofit actions. Under the No decarbonization plan, the fossil fuel content of the energy mix is assumed to stay at its current levels for the whole calculation period. In the Slow decarbonization plan the decarbonization of the energy system follows Table 3, but is delayed by 10 years, so the average fossil fuel use increases. In the Fast decarbonization plan, the progress in Table 3 is expedited by 10 years. Under the current energy generation mix, the cumulative emissions cuts of the DH Low retrofitting scenarios would increase to about 17 $Mt\text{-}CO_2$, and the emission cuts of the HP High scenarios would increase to about 29 $Mt\text{-}CO_2$. The differences between the different retrofitting schedules are relatively larger in the other cases, since the changing emission factors amplify the impact of the schedules. In the Slow decarbonization scenario, the emissions cuts varied from 10.0 to 19.3 $Mt\text{-}CO_2$ between all the cases, while in the Fast scenario the savings were 7.4–12.7 $Mt\text{-}CO_2$.

3.2. *Life cycle economy*

Fig. 9 shows the non-discounted annual energy costs in each scenario over the whole calculation period. The energy costs of the apartment building stock go down in the reference scenario mainly due to reduced size of the building stock (−21%, see section 2.4.), but also because of the lower heating demand induced by climate change (−13%). By 2050, the annual costs compared to the reference are down 34% in the DH Low scenarios and by 62% in the HP High scenarios. The maximum differences between the different retrofitting schedules are rather small in the DH Low scenarios, but large in the HP High scenarios. The end result in 2050 is the same using each schedule, however.

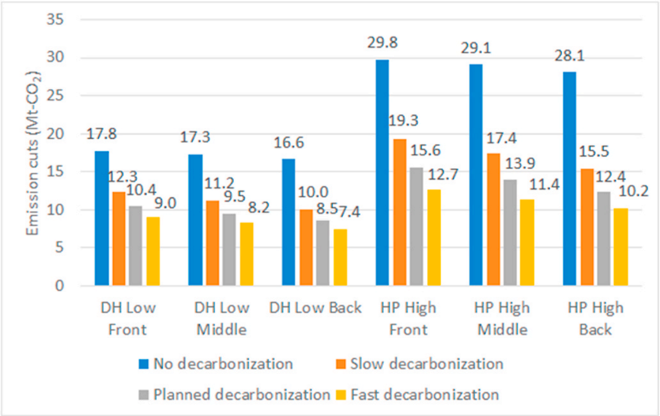

Fig. 8. Sensitivity of cumulative emission cuts over the 2020–2080 period to the emission factors of national energy generation. No decarbonization: current energy mix. Slow decarbonization: Decarbonization delayed by 10 years. Planned decarbonization: Default development, Fast decarbonization: Decarbonization speeded up by 10 years.

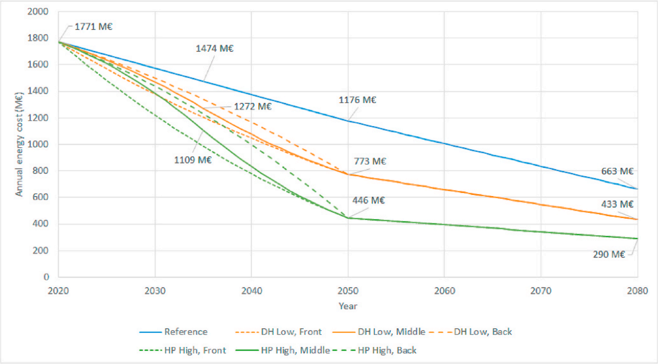

Fig. 9. Total end-users' cost of energy use in the apartment building stock, before discounting.

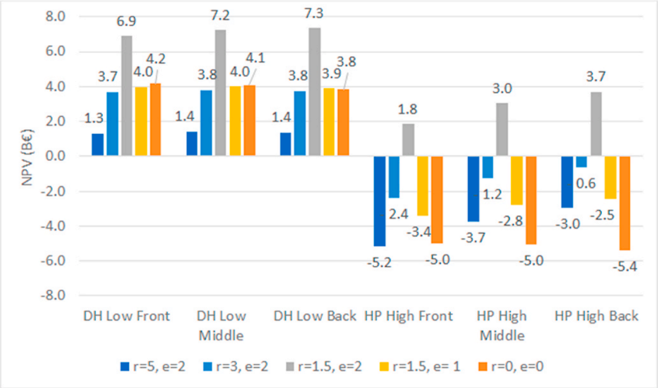

Fig. 11. Sensitivity analysis of economic impact of retrofits from the owner's point-of-view using various discounting rates. The symbol r is the real interest rate (%) and e is the energy price escalation above inflation (%).

Fig. 10 shows the present value of the investment costs, the ongoing maintenance costs and the energy savings in each retrofit scenario. From the building owner's point of view, the DH Low retrofits were profitable in the long-term and the net present value of retrofitting was 3.7–3.8 B€ over the investment period, including the residual value realized after 2050 In the Middle and Back scenarios, the investment and maintenance costs were pushed into the future and discounting reduced their impact compared to the Front scenario. Similarly, the energy cost savings were shifted from the 2020–2050 period to the 2051–2080 period. None of the HP High scenarios were profitable, as was expected. In the HP High retrofits, the differences between the scenarios were much greater, with net present value rising from −2.4 B€ to −0.6 B€ from the Front scenario to the Back scenario, respectively. The discounting had a bigger effect in the more investment heavy scenarios. In the HP High scenarios, the investment costs were 3.5 times higher than in the DH Low scenarios, but the resulting energy cost savings were less than doubled, showing the difference in cost-effectiveness.

Fig. 11 shows sensitivity analysis of the life cycle economy using variable values for real interest rate *r* and the energy price escalation *e*. The shown value is the NPV of the whole 2020–2080 period. In the DH Low scenarios, all of them were profitable for the building owner, regardless of the interest rates. The NPV remained close to 4 B€ under three different discounting combinations ($r = 3$, $e = 2$; $r = 1.5$, $e = 1$; $r = 0$, $e = 0$). However, when the energy price escalation *e* was fixed to 2%, lowering the real interest rate *r* from 5 to 3 and 1.5% caused the NPV to rise. Lowering the *r* from 1% above e, to 0.5% below e, raised the NPV by about 90%. In the DH Low cases, the impact of the retrofitting schedules had only a low impact on the NPV under the different discounting scenarios. In the investment heavy HP High scenarios, the retrofitting schedule had a much bigger impact. Delaying the investments increased the NPV in all cases except the $r = 0$, $e = 0$ cases. The only profitable cases were the ones with $r = 1.5\%$ and $e = 2\%$, where the energy price escalation rate was higher than the real interest rate.

3.3. *Tax effect*

The effect of large-scale retrofits on the government's tax revenues were opposite to the building owner's view. Fig. 12 shows the change in collected taxes in all retrofit scenarios compared to the reference scenario. When the NPV of the retrofits increased, the net tax collection decreased. Taxation of the labor related to investments and maintenance increased tax revenues, while the reduced energy consumption lowered consumption-based tax revenues. Thus, the net tax collection was lower than the reference in all examined scenarios. Tax collection rates were the highest in the Front-loaded scenarios and the lowest in the Back-loaded scenarios.

The impact of different discounting rates is shown in Fig. 13. For the DH Low scenarios, less taxes are collected than without retrofits under

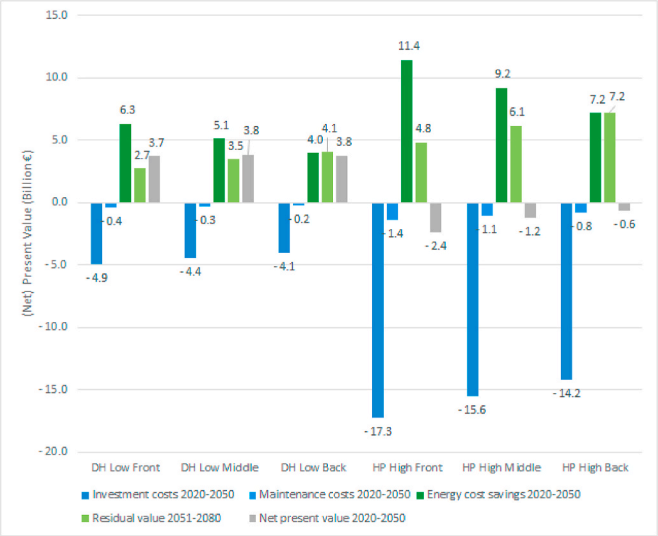

Fig. 10. Life cycle economy during 2020–2050. Used real interest rate is 3% and energy price escalation is 2%.

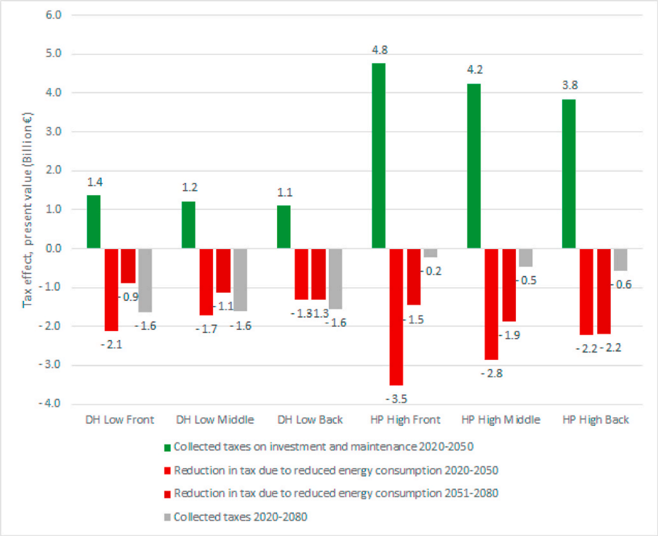

Fig. 12. Impact of retrofitting strategy on cumulative tax revenues. Used real interest rate is 3% and energy price escalation is 2%.

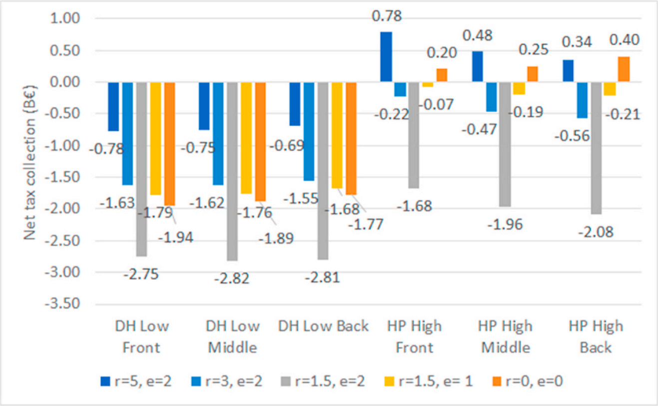

Fig. 13. Sensitivity analysis of net tax collection under different retrofit scenarios and discounting rates. The symbol r is the real interest rate (%) and e is the energy price escalation above inflation (%).

all discounting rate and retrofitting schedules. Like with the NPV calculations, the schedule has little impact on the final result. However, higher real interest rates increase the amount of taxes collected. In the investment-heavy HP High scenarios, the net tax revenues are higher than in the corresponding DH Low scenarios. The cases with higher tax revenues than in the reference are the cases with high real interest rate $r = 5$, $e = 2$ and the undiscounted cases with $r = 0$, $e = 0$. This follows logically from the previous observation that the energy impact per invested money is lower in the HP High scenarios. Thus, more money goes into job-generating investments while relatively less consumption-based tax revenues are lost through energy efficiency. Comparing the results to Fig. 11, the results for taxes are inversely correlated with the financial viability calculations for building owners. The cases with highest NPVs have the lowest tax revenues and vice versa.

3.4. Employment

The energy retrofitting of each building is a laborious process, which employs many different professionals. Fig. 14 shows the impact of apartment building retrofitting on employment and potential savings in unemployment benefits.

When the retrofits are performed in large quantities, the low impact retrofits and the resulting maintenance work provided about 72 000 person-years of work over a 30-year period. In addition, the jobs have an indirect benefit of reducing unemployment costs. Assuming that all the employed people would be unemployed, the present value savings in the DH Low cases would be 712 M€ in the front-loaded scenario and 564 M€ in the back-loaded scenario.

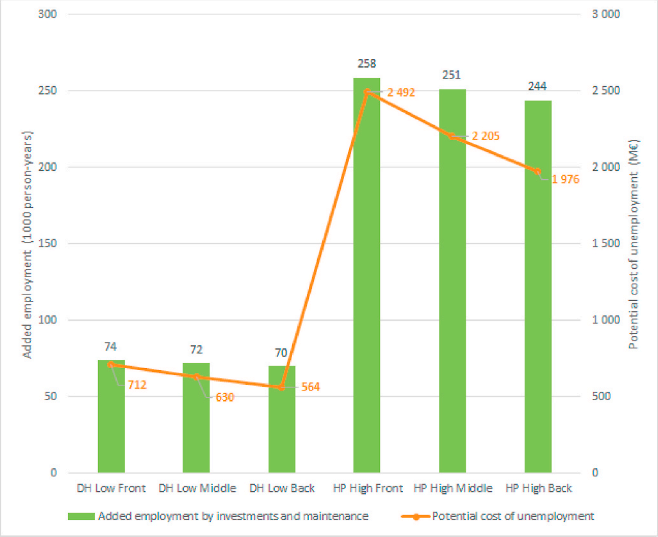

Fig. 14. Left axis: Added employment due to labor related to retrofit investments and maintenance. Right axis: Potential cost of unemployment benefits.

The high impact scenarios more than tripled the employment compared to the low impact scenarios. In the HP High scenarios the average employment gain was 251 000 person-years over 30 years. The potential government savings in unemployment benefit payments were 2492 M€ in the front-loaded scenario and 1976 M€ in the back-loaded scenario. The utilized real interest rate was 3%.

3.5. Imported fossil fuels

Fig. 15 shows the cumulative cost of imported fossil fuels in each scenario. It includes the annually reducing fossil fuel content of the Finnish energy mix as presented in Table 3. This reveals the rate of change and saturation of emissions, as the whole energy grid is decarbonizing during the retrofitting campaign.

Fig. 16 shows the discounted value of the fossil fuels imported for the needs of the building stock. During the investment period, the cumulative value of fossil fuel imports was reduced by 12–19% in the DH Low scenarios and by 16–30% in the HP High scenarios, compared to the Reference scenario. However, the decarbonization of the national energy infrastructure and the demolition of a major fraction of the existing buildings has an even bigger impact. Even in the Reference scenario, the fuel imports of the apartment building stock in the 2051–2080 period are 82% lower than in the 2020–2050 period. The potential impact of the apartment building retrofitting on foreign fossil fuel imports is thus a 1 to 2 billion € reduction over the whole 2020–2080 period, assuming the decarbonization targets of the energy system are reached. The initial import value was 276 M€/a in 2020 for the apartment building stock. Due to the decarbonizing energy grid and partial demolition of the existing building stock (Table 2), by 2050 this was estimated to go down to 50 M€/a even without any retrofitting measures. With retrofits the 2050 estimate was 19 M€/a for the DH Low scenarios and 7 M€/a for the HP High scenarios.

Fig. 17 presents sensitivity analysis of fossil fuel imports under different decarbonization plans. The Planned decarbonization utilizes the energy mix presented in Table 3 and Fig. 16. Under the No decarbonization plan, the fossil fuel content of the energy mix is assumed to stay at its current levels. In the Slow decarbonization plan the decarbonization of the energy system follows Table 3, but is delayed by 10 years, so the average fossil fuel use increases. In the Fast decarbonization plan, the progress in Table 3 is expedited by 10 years. Fig. 17 shows that the importance of building retrofitting is directly correlated with the

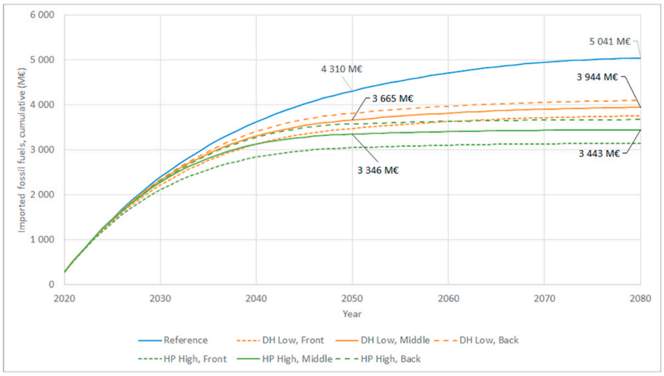

Fig. 15. The cumulative cost of imported fossil fuels used to meet the energy demand of the apartment building stock. Used real interest rate is 3% and energy price escalation is 2%.

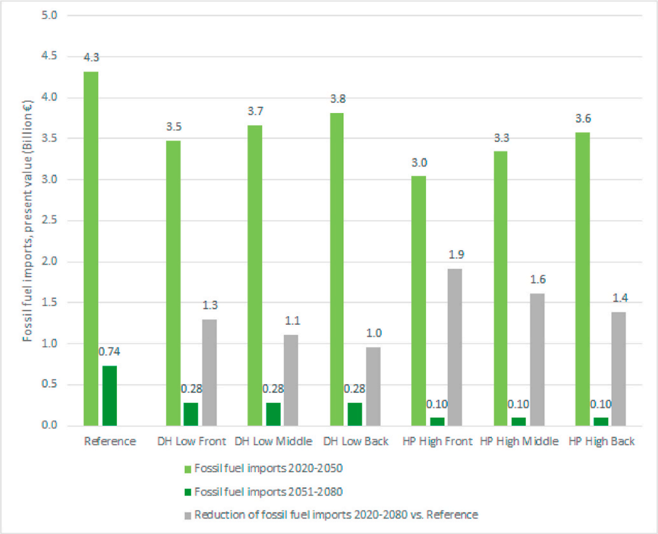

Fig. 16. Fossil fuel imports during and after the investment period. The green bars show the cumulative value of imported fossil fuels used by the current apartment building. The grey bars show the total cost savings of lower fossil fuel imports due to apartment building deep energy retrofitting. The used real interest rate was 3% and energy price escalation was 2%.

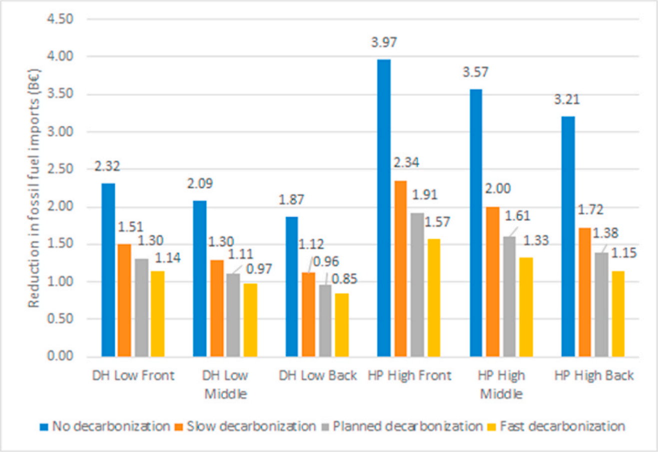

Fig. 17. The discounted savings in imported fossil fuels during the 2020–2080 period under different energy grid decarbonization plans and retrofitting campaigns. No decarbonization: current energy mix. Slow decarbonization: Decarbonization delayed by 10 years. Planned decarbonization: Default development, Fast decarbonization: Decarbonization speeded up by 10 years. Used real interest rate was 3% and energy price escalation was 2%.

fossil fuel content of the energy mix. If no decarbonization of the grid were done, the fossil fuel importing cost savings were 78–94% higher under the DH Low retrofitting and 107–132% higher under the HP High retrofitting plan. Slow decarbonization increased the impact of retrofitting by 16–24% and fast decarbonization reduced the impact by 12–18%.

4. Discussion

This study accounted for various environmental and economic impacts of two deep retrofit concepts on both private and public sectors: CO_2 emissions, trade balance of imported fossil fuels, the cost of investments and maintenance, savings in energy costs, job creation and net tax revenue. The results show that while retrofitting of the building stock can result in significant reduction in CO_2 emissions, this benefit is reduced notably by simultaneous decarbonizing actions in the district heating and electricity generation sectors. Energy savings in buildings can make the retrofit actions profitable for building owners, but this also results in reduction in the revenues of consumption-based taxes such as the VAT, electricity tax and carbon taxes. In fact, the more cost-effective the measures were for the building owners, the higher were the losses of net tax revenues for the government, despite increased tax revenues from retrofitting-related jobs. This is a novel finding not found in other publications. On the other hand, the new employment can also reduce government expenses by removing the need for unemployment benefit payments, which can turn the net tax losses into gains.

CO_2 emission impacts Climate change is caused by changes in the atmospheric CO_2 concentration or the accumulated CO_2. Building stock level retrofitting actions are not instantaneous, which is why this study focused on cumulative emissions over the long term. The cumulative CO_2 emission reduction was 5–8 Mt (11–19%) by 2050 in the DH Low scenarios and 7 to 12 Mt (18–30%) in the HP High scenarios. About 66% more emissions were cut with the front-loaded retrofitting actions compared to the delayed action of the back-loaded scenarios. This shows the importance of acting early. When the decarbonization of the energy grid was delayed by 10 years, the emission cuts of building retrofits were raised to 25–48% relative to the Reference scenario. Thus, building energy retrofitting can mitigate the emission impacts of a failure to reach climate targets in the energy grid. This is especially important to Finland, in case there is a change to the zero emission status of wood-based fuels in the EU emission regulations, as is currently being discussed.

However, the climate impact of building retrofitting is usually presented as changes in annual emissions. For example, in a previous study on decarbonization of the Finnish building stock (single family homes, apartment buildings and commercial buildings), total annual Finnish CO_2 emissions were reduced by 3–5% after 20 years of retrofitting and new construction (Tuominen et al., 2013). In the present study, the annual emission reduction after 20 years was 0.4%–1.0%, depending on the retrofitting level and schedule. However, only currently existing apartment buildings were included in the analysis. The building stock was also reduced in size over the years due to demolition and new construction was ignored. The starting emission factors of both district heating and electricity generation were also lower due to the major changes in Finnish energy mix over the 2000s and 2010s. However, if apartment buildings are roughly estimated to cause a third of the building stock emissions, the emission impacts are on the same scale as in the previous Finnish study. In a study on the Swiss residential building stock, the CO_2 emission impacts were reported with respect to the building stock itself (Streicher et al., 2020). By 2050, the annual emissions of the building stock were reduced cost-effectively by 1%, 13% or 65%, depending on what share of non-energy related renovation costs were accounted for. In the present study, 60% reduction in annual emissions with respect to the non-retrofitted building stock was obtained in 2050 in the cost-effective DH Low scenarios and 82% reduction in the expensive HP High scenarios. However, cumulative emission reductions were much lower, due to the gradual progress of building retrofitting on the national scale. This highlights the importance of rapid retrofitting strategy and short-term milestone targets in addition to the 2050 climate targets, as climate measures enacted now have a higher cumulative impact than similar measures enacted later.

4.1. Fossil fuel imports

Fossil fuels are used by every country on Earth, but the use cases can be very different. In Finland, some fossil fuels are used in apartment buildings directly in on-site boilers, but mainly they are utilized indirectly through the district heating and electricity grids. This study provided an estimate for the change in the value of imported fossil fuels as a result of deep retrofitting of the building stock. Such estimates were not found in other retrofitting studies, which typically only report the change in energy consumption or emissions. The reduction in fossil fuel import value was 1.0–1.9 B€ over the 30 year lifetime of all the performed retrofits. This is equivalent to 4–7 years of imports at the starting level of 2020. In all scenarios at least 50% of the building stock retrofitting was done after 2030, when the fossil fuel share of the energy sector was already significantly lowered, which reduced the impact of the building-side measures. Reduction of fossil fuel imports has the additional benefit of improving domestic energy security and it can also prevent the funding of regimes guilty of atrocities and severe human rights violations.

4.2. Economic effects

The previous study on Finnish building stock retrofitting also looked into the GDP and employment effects (Tuominen et al., 2013). However, it did not describe the tax impacts. The total employment impact on the national level was −0.06% after 5 years and +0.03% after 20 years. In the present study, the average annual employment related to retrofitting was 2400 person years in the low impact scenarios and 8370 person years in the high impact scenarios. Compared to the 2.37 million employed people in Finland (2019) (Statistics Finland, 2020c), this represents a maximum increase of 0.1–0.35%. Dynamic cross-sector effects were not considered, only the required workforce to meet the investment needs. On the other hand, the economic background assumptions of the previous study were not presented for comparison. In the present study, the retrofitting investments created 15 to 17 jobs per million euros invested. This was similar to the results found for deep retrofitting in Estonia, where 17 jobs per million euros were created (Kamal et al., 2019). In Croatia, as many as 32 jobs per million euros were created by retrofitting (Mikulić et al., 2020). However, this included direct, indirect and induced effects across different sectors.

In this study, there was an inverse relation between retrofit profitability and the impact on net tax revenue. The cost-effective retrofits required less labor per unit of achieved energy efficiency than the more expensive retrofits. Thus, in the cost-effective retrofits the improved energy efficiency reduced energy-related tax revenues more than the retrofitting process generated new tax revenues through salary taxes and VAT of materials. In the more expensive retrofits, the ratio shifted and tax revenue losses were much lower. If the potentially avoided unemployment benefits were also accounted for, the tax revenues would turn greatly positive for the HP High scenarios, but remain negative in the DH Low scenarios. However, it is likely that part of the workforce would just be shifting jobs, reducing this theoretical maximum gain.

Tax impacts were considered in a study on Estonian building renovation projects (Pikas et al., 2015). A 33% tax return was obtained, which could be used to fund retrofitting subsidies in a tax-neutral way. However, the study did not account for the loss of energy-related taxes. In the present study, this loss makes the retrofits harmful for government budgets and leaves no room for tax neutral subsidies. Reduced fossil fuel imports would likely have unaccounted benefits on tax revenues as well, since more money would remain in Finland for other kind of consumption and investments. Especially in the HP High scenarios, the fossil fuel cashflow changes were significantly higher than the tax deficit reported here. Alternative sources for tax revenue will be needed in the future. One source could be property taxes, as increased energy efficiency will reduce daily living expenses and thus increase the value of the apartment. For example in Denmark, as much as 77% of renovation expenses were transferred to the value of the house (Bjørneboe et al., 2017), which would also increase property tax revenues.

4.3. Implications

In Finland, as well as in Sweden and Denmark, the share of district heating is very high, while Norway is dominated by electric heating (Patronen et al., 2017). These heating systems are part of the EU ETS and their emissions are controlled by the municipal or national energy infrastructure. The vast majority of Finnish apartment buildings in particular are connected to district heating. Thus, emissions of the building stock will be reduced even without any actions on the building sites themselves, although energy efficiency measures will reduce the need for investments in the energy sector. In this study, majority of the emission reductions resulted from non-retrofit-related events.

If embodied emissions of retrofitting materials are also accounted for, building retrofitting will seemingly provide only a limited additional environmental benefit. However, the role of buildings will likely be emphasized through the demand response services needed to control the future energy system based on variable renewables. The relative benefits of grid improvements vs. building improvements may also change depending on the share of renewables in the system. Specifically for Finland, the role of buildings will be more important if there are changes to the greenhouse gas accounting of biofuels, which the Finnish district heating system is significantly based on. However, compared to countries with mostly on-site gas boilers, much lower environmental impacts of deep retrofitting can be obtained, especially as the grid decarbonization progresses. In central and southern Europe, on-site gas boilers are much more common (32% of final energy consumption in the EU) and the importance of building energy retrofits is amplified. New EU legislation is underway to implement a parallel emission trading system for heating (and transportation) fuels (European Commission, 2021b), which is likely to lead to increased heating costs. The EU aims to address this with a Social Climate Fund, that could be used both to compensate for increased expenses and to fund investments into energy efficiency (European Commission, 2021c). Because of district heating, the proposed extension of the EU ETS to cover building heating systems will likely have only a limited effect in Finland. Biggest CO_2 impacts can be obtained by fast retrofitting action during this decade.

The net negative tax revenues caused by building energy efficiency could be a major issue for the Finnish government, which has been running a deficit since 2009. The government is currently providing highly popular subsidies for building renovation, which will speed up this tax loss accumulation. Thus, alternative tax revenue sources need to be devised. This could mean higher taxes for domestic wood-based energy or energy in general. Reduced fossil fuel imports are likely to reflect positively on the local economy and together with reduced unemployment benefit payments can still turn the tax revenue balance into a positive for the government. In Finland, electricity and district heating at the end-user level are taxed regardless of the carbon content.

The societal impacts of building energy retrofits take effect over many decades. This entails a lot of uncertainty due to discounting and energy price development. The long time is also an issue for funding of the retrofits. If low-interest loans are available in large quantities, the retrofitting can be done even with long payback periods. However, if interest rates were to rise, this could significantly slow down retrofitting rate. At the beginning of 2022, the Finnish government could still obtain 10 year loans at very low interest rates (Pankki, 2022). Investing such funds into building retrofitting would stimulate the economy and be a low cost emission reduction measure for the government, as loans need to be paid back, unlike direct stimulus payments. This could be done through government loan guarantees, similar to ones given for student loans and home mortgages.

4.4. Limitations

The CO_2 emissions were calculated only from the operational period. If the embodied emissions of materials were also included, the GHG benefits would be smaller. The CO_2 emissions of the bio-based energy prevalent in the Finnish energy grid were assumed to be zero according to common rules. In practice, however, the immediate emissions of biomass are comparable to coal and accounting for this would increase the GHG benefits of building stock retrofitting.

From the economical side, the induced economic effects of changing cashflows were not considered. Employment of previously unemployed people would increase national economic activity, while labor competition with other sectors could also cause labor shortages or cost increases. The capacity of the market to absorb the demand of significantly increased retrofitting was not estimated. However, the utilized gradual increases to the retrofitting rates were intended to simulate the improving labor and material capacity in the market. A single value of labor vs. material cost ratio was used for both high and low level retrofitting. In practice, this could change as a function of increased target energy efficiency.

Retrofitting of buildings can improve indoor air quality and thermal comfort, such as by increasing ventilation rates or reducing draught. These comfort enhancements have not been accounted for and could have an effect on public health as the risk of overheating is increasing due to climate change (Velashjerdi Farahani et al., 2021).

4.5. *Recommendations*

The presented results paint a somewhat negative picture of the effects of retrofitting for the government. More in-depth studies should be performed on the induced economic effects of retrofitting, to account for the indirect benefits of improved trade balance and employment situation. It is also important to understand how a major increase in retrofitting affects the supply chains and the labor market, especially when parallel retrofitting strategies are implemented in all other EU countries, tightening the availability of the international workforce. Building retrofitting allows the addition of demand response technology, which will have major impact on the utility of variable renewable energy sources. High resolution analysis of large-scale demand response potential needs to be done. Such analysis should examine sector coupling and capacity pricing and how the building sector can influence the demand and prices of both power and energy. In addition, scenario-studies should be performed for cases where biomass is not considered a carbon neutral fuel, as this would have major implications on many bioenergy-dependent economies in the EU, especially Finland.

5. Conclusions

This study examined the economic and environmental impacts of large-scale deep energy retrofitting of Finnish apartment buildings. This was done using two retrofitting strategies (low cost and high cost) and three long-term retrofitting timelines (early vs. delayed retrofitting).

> RQ1. How does the time distribution of energy retrofits affect the cumulative CO_2 emissions of the building stock over the long-term?

The retrofitting scenarios were examined under the assumption that the decarbonization of the Finnish energy sector progresses according to the government's targets. This reduced the impact of the building retrofitting actions. The cumulative CO_2 emission reduction was 5–8 Mt by 2050 in the DH Low scenarios and 7 to 12 Mt in the HP High scenarios, which means a 12–30% reduction compared to the Reference scenario. About 66% more emissions were cut with the front-loaded retrofitting actions compared to the delayed action of the back-loaded scenarios. This shows the importance of acting early. When the decarbonization of the energy grid was delayed by 10 years, the emission cuts of building retrofits were raised to 25–48% relative to the Reference scenario. Thus, building energy retrofitting can mitigate the emission impacts of a failure to reach climate targets in the energy grid. This is especially important to Finland, in case there is a change to the zero emission status of wood-based fuels in the EU emission regulations, as is currently being discussed.

> RQ2. What are the employment benefits generated by building energy retrofitting?

For every million euros invested into building retrofitting, 15 to 17 jobs were created. The number of jobs created was about 3.5 times higher in the HP High scenarios compared to the DH Low scenarios due to much higher investments. If all the retrofitting workers would otherwise be unemployed, the government would save on unemployment benefit payments, saving it 600–2500 M€ over a 30 year period. Induced employment which could result from the increased economic activity of large-scale retrofitting was not accounted for, but this would likely be a positive additional effect.

> *RQ3. How do building energy retrofits reduce the value of imported fossil fuels?*

Compared to the reference non-retrofitting scenario, by 2050, the cumulative value of imported fossil fuels was reduced by 500–800 M€ in the DH Low scenarios and by 700–1300 M€ in the HP High scenarios, depending on the retrofitting schedule. The import value reduction was limited due to the major forecasted reduction of fossil fuel fraction in the Finnish energy mix. However, the cost of fossil fuel imports was 35–38% higher in the Back scenarios vs. the Front scenarios, showing again the importance of fast decarbonization. If the decarbonization of the energy grid is slower than anticipated, the cost of the imports could rise by 16–24%. The sudden price increases of fossil fuels in 2021–2022 were not accounted for, but this would raise the impact of retrofits on imported fuel value.

> RQ4. How do large-scale investments into building energy retrofits influence tax revenues?

Building retrofitting created new tax revenues through salaries related to employment in design, installation and maintenance work. At the same time, improved energy efficiency lowered the tax revenues from consumption-based taxes (carbon tax, electricity tax and VAT). In the retrofits that were most cost-effective for the building owners (DH Low scenarios), the lost tax revenues greatly exceeded the tax gains from retrofitting investments. In the higher cost scenarios (HP High), the tax impacts were still negative, but less so. This reveals a conflict of interest: For a government that gains taxes from energy consumption, it is more useful to have labor-intensive and costly energy retrofitting where the energy efficiency improvement per invested capital is low than to oversee retrofits that are more cost-effective for the building owners. Sensitivity analysis using different real interest and energy price escalation rates showed an inverse correlation between building owner profitability and tax revenues. High interest rates reduced investment profitability, but increased tax revenues relative to the reference scenario.

If the potentially avoided unemployment benefits were also accounted for, the tax revenues would turn greatly positive for the HP High scenarios, but remain negative in the DH Low scenarios. However, it is likely that part of the workforce would just be shifting jobs, reducing this theoretical gain. Reduced fossil fuel imports would likely have unaccounted benefits on tax revenues as well, since more money would remain in Finland for other kind of consumption and investments. Especially in the HP High scenarios, the fossil fuel cashflow changes were significantly higher than the tax deficit reported here.

5.1. *Future outlook*

The reduced tax revenues as a result of the retrofitting pose a problem for public financing. Energy efficiency subsidies might not pay for themselves, but could instead cause an additional drain on the government financing. New tax revenues are needed to replace those lost from consumption-based taxes. One possible revenue source would be increased property taxes. Of course, energy efficiency of buildings also provides additional energy security and reduces the risk of energy-based sanctions or trade wars.

Further study on the topic could focus on the induced employment effects and total trade balance of large-scale retrofitting. What is the economic impact of local component manufacturing and what kind of positive economic feedback do the directly created jobs generate? How would the importance of building energy retrofits change if wood-based biofuels are no longer counted as zero-emission in EU accounting? More attention needs to be given to the ways that the government can compensate for the lost energy tax revenues.

CRediT authorship contribution statement

Janne Hirvonen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Arto Saari:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Juha Jokisalo:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Risto Kosonen:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Building retrofit configurations

The apartment building stock was divided into four age categories according to changes in the energy regulation (Ministry of the Environment, 2017). The oldest buildings in category AB1 were built before 1976, while the somewhat better insulated category AB2 was built between 1976 and 2002. Insulation levels were further improved in AB3 (2003–2009), which also introduced mandatory ventilation heat recovery. The newest category AB4 (built in 2010 or later) had the highest energy efficiency, with even stronger requirements on the thermal insulation of the envelope as well as increased requirements for the ventilation heat recovery efficiency.

Retrofit options used in the apartment buildings were improvement of the thermal insulation of external walls and roof, installation of more energy efficiency windows and doors, the use of solar thermal (ST) or electric (PV) systems, replacement of district heating with ground-source heat pumps (GSHP), installation of mechanical balanced ventilation with heat recovery and demand-based ventilation controls, switching to low temperature radiators and the installation of sewage heat recovery. A summary of the design of the reference and retrofitted buildings is shown in Table A1, while the energy performance of the buildings is shown in Table A2. The energy consumption of the reference buildings is given for buildings with district heating. Heat generation using on-site boilers was assumed to be less effective and was adjusted according to efficiency factors of 86% for oil boilers and 75% for wood boilers. For electric heating, the DH demand was converted directly to electricity.

Table A1
Features of the structures and system of the apartment buildings before and after deep retrofitting.Values are from (Hirvonen et al., 2018).

	U-values (W/m^2,K)				(m^2)	(kW$_p$)	(kW$_{th}$)		(°C/°C)	
Building class	Walls	Roof	Doors	Windows	ST	PV	HP[1]	Ventilation	Dim. temp. of radiators	Sewage HR
Reference: Original buildings before retrofitting										
AB1 Ref	0.81	0.47	2.2	1.7	0	0	0	Mech. exh.	70/40	–
AB2 Ref	0.34	0.26	1.4	1.7	0	0	0	Mech. exh.	70/40	–
AB3 Ref	0.25	0.17	1.4	1.7	0	0	0	Balanced (60%)[2]	70/40	–
AB4 Ref	0.17	0.09	1.0	1.4	0	0	0	Balanced (65%)	45/35	–
DH Low: Buildings retrofitted in a cost-effective manner, used in the DH-focused scenario										
AB1 DH C	0.81	0.08	2.2	0.7	55	30	0	Mech. exh.	70/40	HP[4]
AB1 GSHP C	0.36	0.08	0.7	0.7	60	35	110	Mech. exh.	45/35	HP
AB2 DH C	0.34	0.26	0.7	1	100	25	0	Mech. exh.	70/40	HX[5]
AB2 GSHP C	0.34	0.26	1.4	0.7	25	35	35	Balanced (70%), VAV[3]	65/40	HP
AB3 DH C	0.25	0.07	1.4	1.4	50	15	0	Balanced (60%), VAV	70/40	HX
AB3 GSHP C	0.25	0.1	1.4	1.4	60	20	25	Balanced (60%), VAV	70/40	HX
AB4 DH C	0.17	0.09	1	1	45	15	0	Balanced (65%), VAV	45/35	HX
AB4 GSHP C	0.17	0.09	1	1	30	25	25	Balanced (65%), VAV	45/35	HX
HP High: Building retrofitted for high emission reduction, used in the HP-focused scenario										
AB1 DH B	0.36	0.08	2.2	0.8	55	30	0	Balanced (70%), VAV	70/40	HX
AB1 GSHP B	0.23	0.1	0.7	0.8	0	35	115	Balanced (70%), VAV	45/35	HX
AB2 DH B	0.34	0.1	0.7	0.7	100	25	0	Balanced (70%), VAV	70/40	HP
AB2 GSHP B	0.34	0.1	0.7	0.7	90	35	60	Balanced (70%), VAV	45/35	HX
AB3 DH B	0.25	0.06	0.7	1.4	95	15	0	Balanced (60%), VAV	70/40	HP
AB3 GSHP B	0.25	0.06	0.7	1.4	65	20	60	Balanced (60%), VAV	45/35	HX
AB4 DH B	0.17	0.06	0.7	1	95	15	0	Balanced (65%), VAV	45/35	HP
AB4 GSHP B	0.17	0.06	0.7	0.6	95	15	35	Balanced (65%), VAV	45/35	HX

[1] Design power of GSHP.
[2] Temperature efficiency of ventilation heat recovery.
[3] Demand-based variable air volume ventilation.
[4] Sewage heat recovery with heat pump.
[5] Sewage heat recovery with heat exchanger.

Table A2

Annual energy use in the apartment buildings before (reference) and after deep retrofits (DH Low and HP High).

Building	DH use (kWh/m^2,a)	Electricity use (kWh/m^2,a)
Reference		
AB1 Ref	172	30
AB2 Ref	124	28
AB3 Ref	81	37
AB4 Ref	65	35
DH Low		
AB1 DH Low	118.6	27.6
AB1 GSHP Low	0	48.3
AB2 DH Low	74.3	22.3
AB2 GSHP Low	0	32.2
AB3 DH Low	41.7	28.1
AB3 GSHP Low	0	40.1
AB4 DH Low	31.8	27.1
AB4 GSHP Low	0	35.6
HP High		
AB1 DH High	73.1	21.9
AB1 GSHP High	0	38.6
AB2 DH High	24.0	21.8
AB2 GSHP High	0	27.5
AB3 DH High	26.8	30.9
AB3 GSHP High	0	37.4
AB4 DH High	17.6	29.8
AB4 GSHP High	0	34.0

Appendix B. Cumulative CO_2 emissions

Table B1

Emission impacts of different retrofitting scenarios. Cumulative emissions assume unlimited lifetimes for all retrofit actions. Conversely, emission cuts for 2050–2080 ignore CO_2 savings obtained through building retrofits after the 30-year investment lifetime.

	Cumulative emissions (unlimited lifetime) (Mt-CO_2)			Cumulative emission cuts (30-year lifetime) (Mt-CO_2)			Cumulative emission cuts (30-year lifetime) (%)		
Scenario	2020–2050	2051–2080	2020–2080	2020–2050	2051–2080	2020–2080	2020–2050	2051–2080	2020–2080
Reference	40.6	8.9	49.6						
DH Low Front	32.8	3.7	36.4	7.9	2.6	10.4	19.4	28.8	21.1
DH Low Middle	34.4	3.7	38.1	6.2	3.3	9.5	15.3	36.7	19.1
DH Low Back	35.8	3.7	39.5	4.8	3.7	8.5	11.8	41.6	17.2
HP High Front	28.6	1.5	30.1	12.0	3.6	15.6	29.5	40.3	31.4
HP High Middle	31.3	1.5	32.8	9.3	4.6	13.9	22.9	51.3	28.0
HP High Back	33.5	1.5	34.9	7.2	5.2	12.4	17.6	58.4	25.0

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