



Retrofitting Norwegian residential buildings: an archetype-based dynamic stock model

RESEARCH

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ABSTRACT

The retrofit of buildings is essential to reduce their energy consumption and associated greenhouse gas (GHG) emissions. In this study, the resource use and energy performance of various retrofit options for Norway's residential buildings up to 2050 were quantified. A comprehensive analysis of the stock, encompassing all municipalities and using an archetype-based dynamic stock model, was developed. It was estimated that about 80% of Norway's buildings existing in 2023 will still be standing in 2050. If half of these buildings undertake a full retrofit of windows, roof and external walls and adoption of heat pumps, up to 101 TWh of energy and 13 MtCO₂-eq could be saved, which includes the GHG emissions expended from material production used for these retrofits. However, achieving such retrofit rates will require strong incentives, which would require tackling current economic challenges and energy policy debates.

POLICY RELEVANCE

Residential buildings have a long lifetime: around 80% of residential buildings existing in 2023 in Norway might still be standing in 2050. Many older buildings are highly energy inefficient and retrofitting these buildings is a necessity to reduce their energy consumption. This study demonstrates that in every Norwegian municipality a significant potential exists for energy savings and GHG emission reduction through retrofit and adoption of heat pumps, even when accounting for material production. Although the Norwegian electricity production system is highly decarbonised, it has a limited capacity. Reducing the electricity consumption of Norwegian residential buildings would therefore facilitate the electrification of fossil fuel-dependent sectors and contribute to a greater extent to climate change mitigation.

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In 2022, buildings accounted for 34% of global energy consumption and contributed to 37% of energy and process-related greenhouse gas (GHG) emissions (UNEP-Global ABC 2024), making the sector central to climate change mitigation efforts (IPCC 2023). Recent studies suggest that effective mitigation measures could reduce building emissions by up to 61% by 2050, with a focus on residential buildings due to their substantial contribution (Shukla et al. 2023).

The potential for emission reductions in residential buildings varies significantly between nations. Countries developing their built environment have a growing need to construct new, energy-efficient buildings using materials with low carbon footprints (Hertwich et al. 2020). In contrast, high-income nations with an existing, largely developed, built environment, such as in Europe, face the challenge of ageing and energy-inefficient building stocks (Andrić et al. 2019). Up to 90% of the buildings in high-income countries could still be part of the stock in 2050 (EEA 2022; IEA 2014), and only 0.05–0.10% of the European building stock is demolished and replaced annually (Huuhka & Lahdensivu 2016; Thomsen et al. 2011). Given the long lifetime of existing buildings, retrofitting is essential to reduce their operational GHG emissions (EEA 2022).

Building retrofits, involving systems and components upgrades for energy-efficient alternatives, can significantly reduce both energy demand and operational GHG emissions (Güçyeter & Günaydin 2012). However, retrofitting presents challenges as the process itself can have significant environmental costs. These upgrades require new material inputs to the existing buildings, as, for example, thermal insulation for the building envelope or new heating, ventilation and air-conditioning (HVAC) systems. The amount of materials needed to retrofit a building depends on its existing state, and its geometry and architecture (e.g. floor area, roof shape, opening ratio on facades), which are a function of construction regulation, common practices and the materials available when the building was constructed. To assess the net GHG emissions of retrofitting strategies, both the added embodied emissions from material production and the reduced operational emissions need to be accounted for.

In 2025, Norway's residential building stock (not including vacation homes) consisted of about 1.6 million buildings (Statistisk Sentralbyrå 2025b), among which about a quarter were built after the year 2000 (Statistisk Sentralbyrå 2025a). Older buildings, particularly those built before the 1980s, suffer from poor insulation and outdated mechanical systems, resulting in lower comfort and higher space heating demand (Amini et al. 2025a). In 2020, electricity accounted for about 85% of final energy consumption in Norway's residential buildings (Bøeng 2024). Given Norway's cold climate, where heating constitutes a major share of energy consumption, retrofitting efforts focused on insulation and HVAC upgrades are essential for reducing electricity use by residential buildings. This would allow other sectors (industry, transport and agriculture) to satisfy their increasing demand for electricity (Norges offentlige utredninger 2023). Regulations such as the Norwegian Energy Act (NVE-RME 2022), mandating efficiency standards and providing financial incentives, aim to support upgrades of Norway's ageing building stock.

The existing body of literature highlights the potential of retrofitting as a key strategy for reducing energy consumption and GHG emissions in Norwegian buildings, even with a low-carbon energy mix (Feliuss et al. 2020a). A selection of relevant literature studying the potential of retrofitting in reducing energy consumption and GHG emissions for buildings in Norway is presented in Table 1. The literature is divided into studies of individual buildings and those of the entire national building stock.

Both Pauliuk et al. (2013) and Sandberg et al. (2017) develop dynamic dwelling stock models to estimate energy consumption and retrofit of Norwegian dwellings at the national level. Sandberg et al.'s (2017) study, scoped for energy savings, provides neither estimates of the materials needed to perform the retrofits nor of GHG emissions. In contrast, Pauliuk et al. (2013) account for material requirements for two retrofit packages and estimate the resulting energy intensities using a comprehensive physical model of heating demand applied to building archetypes of various typologies and construction cohorts. However, the retrofit packages are not archetype specific as they assume a certain thickness of insulation added independently of the archetype retrofitted. They do not assess retrofit measures individually and the estimated energy intensities

PERSPECTIVE	STUDY	FINDINGS
Individual building(s)	Wrålsen et al. (2018)	Retrofitting of an apartment building to near-passive house standards (improved insulation, triple-glazed windows and modern ventilation) could reduce operational energy demand and environmental impact over 30 years by 56–96%
	Hrynyszyn & Felius (2019)	Upgrades of windows, insulation and ventilation following the EnerPHit Standard could reduce heating energy demand by nearly 80% in a 1960s wooden Norwegian house
	Chen et al. (2020)	Moderate retrofits were cost-effective, while extensive retrofits incorporating renewable energy yielded the greatest emissions reductions for residential buildings in Oslo
	Felius et al. (2020b)	Air-source heat pumps outperformed envelope retrofits alone. Combining these measures with building automation control systems achieved total energy savings of up to 57%
	Tian & Hrynyszyn (2020)	High airtightness increases overheating risks, while enhanced insulation slightly reduces overheating
	Rabani et al. (2021)	Retrofitting heating, ventilation and air-conditioning (HVAC) systems could cut emissions by up to 52% in office buildings
National building stock	Sartori et al. (2009)	Introducing retrofit measures combined with heat pumps for all buildings could save up to 17 TWh/yr between 2005 and 2035
	Pauliuk et al. (2013)	Retrofitting the residential building stock has lower upstream GHG emissions than demolishing existing buildings and replacing them with passive houses, due to the high emissions of building envelope construction
	Sandberg et al. (2017)	The use of heat pumps and on-site electricity production with solar panels could cut half of delivered energy, and further reduction (up to 65% compared with a baseline scenario) could be achieved with retrofit activities by 2050

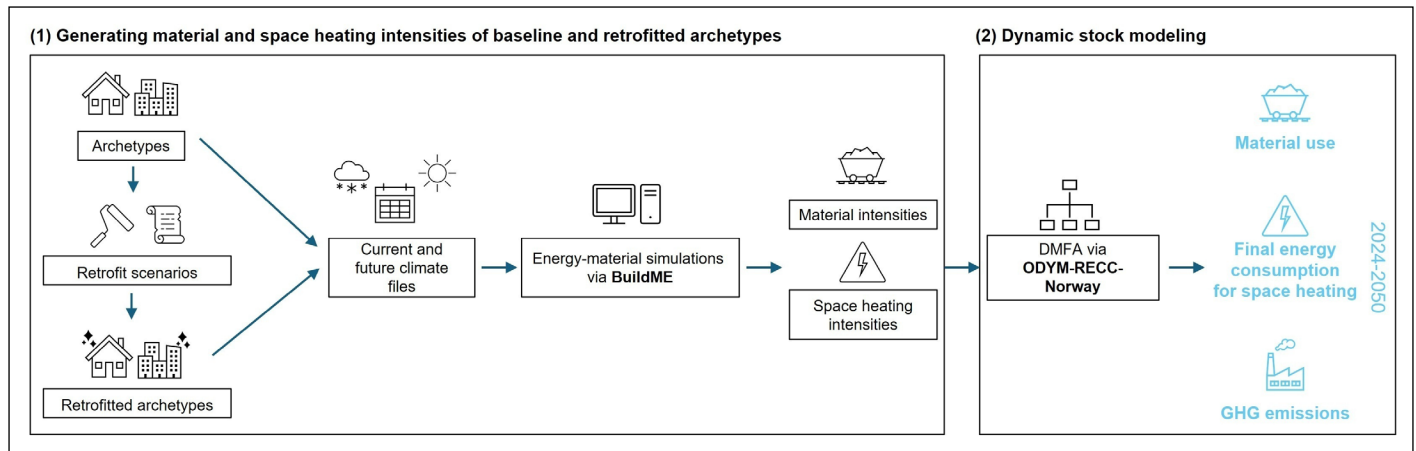
Table 1: A selection of relevant literature studying the potential of retrofitting in reducing energy consumption and greenhouse gas (GHG) emissions for buildings in Norway.

are constant national averages hindering consideration of Norway’s diverse climatic conditions (e.g. the heating degree-day value in Oslo is 4195, while it is 5033 in Tromsø; [Meteonorm, n.d.](#)) and changing climate in the future. In order to represent the interplay of material use in retrofit and the resulting energy demand reduction, physics-based building archetypes using dynamic energy modelling based on hourly energy simulation were developed ([Amini et al. 2025a](#)). In this way, material requirements for retrofit are tailored to archetypes’ characteristics and operational energy savings are derived from dynamic energy simulations of the archetypes under six major local climates up to 2050, rather than from static intensity factors. This approach takes into consideration the complexities of building geometry, various thermal zones in the buildings and the thermal inertia of thermal mass materials such as concrete or brick. This distinguishes the work from prior national stock studies in Norway and offers a more reliable basis for selecting effective retrofit strategies.

Moreover, there is a need for spatially disaggregated scenario analysis of Norwegian dwellings as Sartori et al. (2009), Pauliuk et al. (2013) and Sandberg et al. (2017) are national-based studies. Considering this research gap, this study evaluates retrofit options for Norway’s residential building stock up to 2050 in 357 municipalities, quantifying material use, space heating demand and GHG emissions under a set of various scenarios.

2. METHODS

The workflow was divided into two main phases: (1) material and space heating-related energy intensities were obtained using baseline and retrofitted archetypes; and (2) these intensities were inputs into a dynamic stock model where material use, energy consumption and GHG emissions were calculated between 2023 and 2050 ([Figure 1](#)).



2.1 ARCHETYPE-BASED RETROFIT MODELLING

Material and space heating intensities of residential buildings (single-family house—SFH, multi-family house—MFH, and apartment blocks—AB) in the 2023 stock were retrieved from Amini *et al.* (2025b). Based on these baseline archetypes, three retrofitting alternatives were modelled to reach the minimum requirements for energy efficiency, defined by the Norwegian Building Technical Regulations from 2017 (TEK-17) (Direktoratet for byggkvalitet 2017; Standards Norge n.d.):

- Win: replacing windows and external doors with TEK-17-compliant options as well as improving the airtightness of the openings.
- Ren: corresponding to Win plus replacing and increasing insulation for external walls and roof matching TEK-17 criteria as well as improving the airtightness of the whole building envelope.
- Vent: corresponding to Ren plus a balanced ventilation system with 80% heat recovery.

These retrofitted archetypes were built upon the work of Amini *et al.* (2025a) with the following interventions: while in Amini *et al.* the original cladding of walls and roofs were assumed to be reused in the Ren strategy, here the material demand for renewal of all external cladding was estimated, *i.e.* new timber cladding for external walls of wood-based archetypes, new clay tiles for slanted roofs and a new bitumen finish for flat roofs were estimated based on archetype's net external walls and roof area. Amounts of mineral wool (thermal insulation), bitumen-impregnated cardboard (wind barrier) and polyethylene sheet (vapour barrier) were taken directly from Amini *et al.*'s supplemental information. In the Vent strategy, Amini *et al.* only accounted for the materials used in the heat-recovery ventilation units, excluding the distribution ducts; here, the amount of galvanised steel used in circular ducts based on each archetype's plan dimensions, number of floors, number of rooms, kitchen, toilets and bathrooms, and their required airflow based on TEK-17 was estimated (see **Section S1** in the supplemental data online).

To account for the various climate and weather conditions over Norway and their effect on buildings' space heating demand, six municipalities with the largest residential floor area were identified to use their weather data in energy simulations: Oslo, Bergen, Trondheim, Stavanger, Ringsaker and Tromsø. The weather data in these six municipalities were then used as a proxy for estimating space heating demand in other Norwegian municipalities depending on their geographical location and climate zone (for details, see **Section S2.2** in the supplemental data online). Future weather patterns may impact the energy performance of baseline and retrofitted buildings. Therefore, future weather files based on the Intergovernmental Panel on Climate Change's (IPCC) A1B scenario were developed by using the Meteonorm software (Bernstein *et al.* 2008; Meteonorm n.d.). The space heating intensities of existing and retrofitted buildings for 2050 were calculated and used to estimate changing intensities in the future.

Figure 1: Methodological framework and its different phases, including modelling, simulation, scenario development and comparison.

Note: Only space heating-related energy demand was considered as the retrofit activities modelled in this research focus on buildings' construction.

DMFA = dynamic material flow analysis.

The future residential building stock was modelled using ODYM-RECC-Norway,¹ a minimal version of the Open Dynamic Material Systems Model for Resource Efficiency and Climate Change Mitigation (ODYM-RECC) originally developed by Pauliuk et al. (2021a). In ODYM-RECC, in-use stocks and flows of products (here, residential buildings of different typologies and cohorts) are driven by population and floor area per capita (FAPC). Material production, final energy consumption and their associated GHG emissions are then estimated using material, energy and GHG intensities. The framework can also be used to estimate the long-term effects of different retrofitting scenarios on energy consumption and emissions. As an open-source tool, there are variants and branches of ODYM-RECC (Napiontek et al. 2025; Pauliuk et al. 2021a, 2021b, 2024; Rousseau et al. 2025; Vélez-Henao & Pauliuk 2025) as well as a streamlined version established by Akin et al. (2025) excluding the vehicle-related model, and the energy demands associated with demolition and waste treatment. ODYM-RECC-Norway, focusing on building retrofits in Norway, was derived from that streamlined version and introduced features specific to this research, such as modelling retrofit and the adoption of heat pumps (HPs).

The input parameters for ODYM-RECC-Norway model are distributed across numerous spreadsheets and cover each of the 357 Norwegian municipalities. These include demographic trends, FAPC, electricity production mix, GHG emission factors for material and energy production, retrofit rates, and material and energy intensities of baseline building archetypes along with their retrofitted versions under different future climate files. Most of these inputs stem from archetype simulations (Amini et al. 2025a, 2025b) and external sources such as population projections (Statistisk Sentralbyrå 2023, 2024a), utility FAPC (estimated based on dwellings' statistics) (Statistisk Sentralbyrå 2024b) or electricity production mix (Ember 2023). Some of the parameters are municipality specific, such as future population, while others are valid for the entire country, such as electricity mix.

At its core, the dynamic stock model builds on building lifespan—an average of 125 years (Bohne et al. 2006) whose variation is partially captured using a normal distribution, with a standard deviation of 37.5 years—FAPC and share of building types in new construction (both assumed to stay constant in line with 2023 values) and retrofit rate. The lifetime of retrofitted buildings was extended using the Dynamic Lifetime Model (Krych et al. 2025) (see **Section S3** in the supplemental data online) assuming that retrofit extends buildings' lifetime. The GHG emissions of materials were estimated according to a business-as-usual scenario (Pauliuk 2023), i.e. changes in background systems follow the Shared Socioeconomic Pathway 2 (SSP2) scenario (O'Neill et al. 2014; Riahi et al. 2017). For more details about the input parameters, see **Section S1** online; and in the Zenodo repository containing the database.²

2.3 SCENARIOS

Retrofitting consists of measures addressing passive and active components. Measures targeting passive components focus on enhancing building's thermal resistance by improving insulation, airtightness and glazing. These measures reduce the rate of heat transfer, thereby lowering heating demands (Konstantinou & Hoces 2018). On the other hand, retrofitting active components involves upgrading HVAC systems to optimise energy usage. Examples include installing HPs, energy-efficient appliances and developing district heating-compatible systems (Lund et al. 2014; Tettey et al. 2017). In Norway, electricity is the dominant space heating fuel, with electric heaters and boilers covering 65% of space heating demand in SFH/MFH and 75% in AB, and HPs covering 22.5% in SFH/MFH and 5% in AB (Sartori et al. 2022). Wood stoves cover the rest in SFH/MFH (12.5%) and district heating in AB (20%).

The scenarios analysis encompassed 10 scenarios (Table 2): a baseline scenario without any retrofit (NoRen), scenarios focusing on passive building components only (Win, Ren) and combined with active strategies (Vent) using the retrofitted archetypes described in Section 2.1, a scenario with a widespread adoption of HPs, and scenarios combining Win, Rent and Vent with HPs'

adoption (Win_HP, Ren_HP, Vent_HP). In all the scenarios involving retrofit, 1.89% of the buildings built before 2010 are retrofitted each year (for details about this retrofit rate, see **Section S1** in the supplemental data online). In scenarios involving retrofit of the windows (Win, Win_HP), the lifetime of retrofitted buildings is extended by 25 years; and in scenarios involving retrofit of the buildings' envelope (Ren, Vent, Ren_HP, Vent_HP), the lifetime of retrofitted buildings is extended by 50 years (Egerlid et al. 2025) (for the modelling, see **Section S3** online).

In the NoRen and retrofit scenarios, the population projection follows the main projection alternative of the scenarios by Statistics Norway (Statistisk Sentralbyrå 2023, 2024a). The electricity production mix is as of 2023, i.e. 88.5% hydropower, 9.7% wind power, 0.3% other renewables and 1.5% fossil (Ember 2023). A sensitivity analysis was performed to test a high-projection scenario for population (high growth of population as per Statistisk Sentralbyrå 2024a) and the Nordic production mix, i.e. the weighted average of Sweden, Denmark, Finland and Norway for 2023 (37% hydropower, 27% wind power, 18% nuclear, 13% other renewables and 5% fossil) (Ember 2023), as an alternative electricity mix.

SCENARIO	RETROFIT OF ENVELOPES	RETROFIT OF ENERGY SYSTEM	POPULATION SCENARIO	ELECTRICITY PRODUCTION MIX
NoRen (baseline)	None	None	Mid	Norway
Win	Win	None	Mid	Norway
Ren	Ren	None	Mid	Norway
Vent	Vent	None	Mid	Norway
HP	None	Heat pumps	Mid	Norway
Win_HP	Win	Heat pumps	Mid	Norway
Ren_HP	Ren	Heat pumps	Mid	Norway
Vent_HP	Vent	Heat pumps	Mid	Norway
NoRen_HighPop	None	None	High	Norway
NoRen_NordicEl	None	None	Mid	Nordic

Table 2: Scenarios.

Note: Win = replacing the windows and external doors with TEK-17-compliant options as well as improving the airtightness of the openings; Ren = Win plus replacing and increasing the insulation for external walls and roof matching TEK-17 criteria as well as improving the airtightness of the whole building envelop; and Vent = Ren plus a balanced ventilation system with 80% heat recovery.

3. RESULTS

3.1 RETROFITTED ARCHETYPES

Replacing windows and doors with TEK-17-compliant components (Win strategy) requires 1.8–10.9 kg/m² glass in new windows and 0.14–0.60 kg/m² aluminium in the external door's layers (Figure 2a). The variation in glass intensity among archetypes is attributed to the window-to-wall ratio (WWR), which is up to 25% in pre-1955 archetypes, decreasing to 6% on some facades in more recent cohorts (Amini et al. 2025a). The space heating intensity in the Win strategy decreases by 11–65% (Figure 2b), relative to both the WWR and the original thermal conductivity and infiltration value of the openings. These results demonstrate larger potential for space intensity reductions in older archetypes and limited savings by Win in post-2000 ones.

To achieve the Ren strategy, 40–70 kg of material per m² are needed in SFH and MFH, with thermal insulation making at least 40% of materials needed (Figure 2a). Gypsum, used as finish material and a component of the wind barrier layer in walls and ceilings, together with clay tiles, used as roofing finish, are the next predominant materials required in this retrofit strategy. It is worth highlighting that material demand intensity for retrofitting ABs is almost half of SFHs and MFHs, with 20–30 kg/m², due to lower external walls-to-floor area ratios. In ABs, the share of thermal insulation materials is lower, as glass in AB1955 and bitumen in post-1970 ABs take up significant shares of the material intensity due to their much higher densities. In AB1955 and AB5670, as the external walls have a masonry finish, cement is used as the finish over the added insulation layer to provide an architecturally compatible material for the building. The Ren strategy lowers the space heating demand down to a range of 20–40 kWh/m² (Figure 2b). A comparison of the

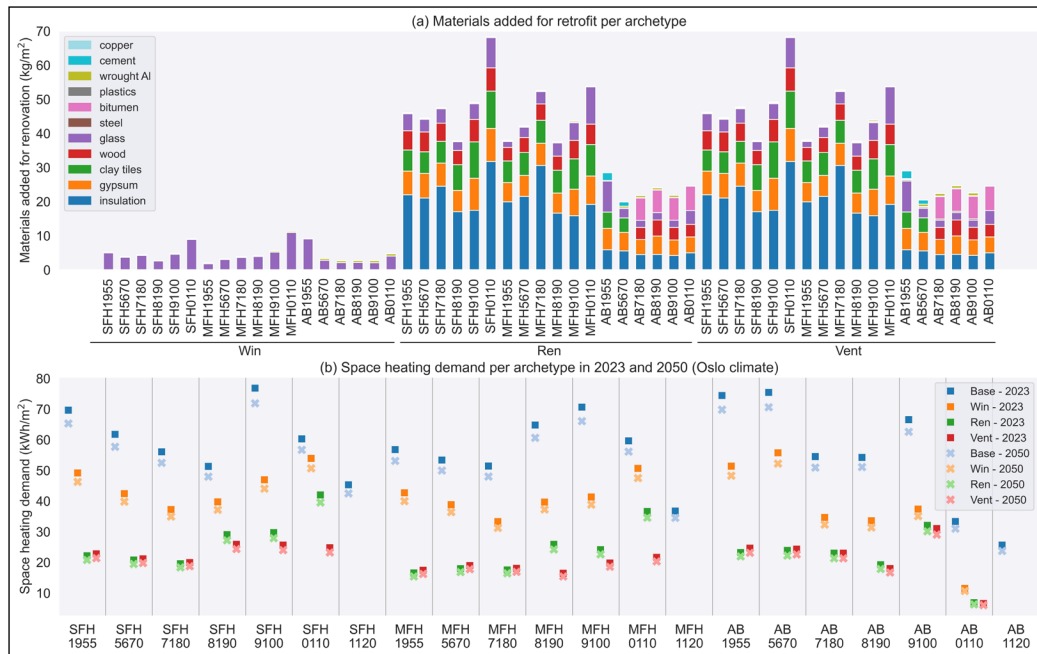


Figure 2: (a) Quantities of materials added for the three types of retrofit (Win, Ren and Vent); and **(b)** space heating demand for the base case and the three types of retrofit (Win, Ren and Vent) in 2023 and 2050 (simulated under an Oslo climate) per archetype classified by typology.

Note: SFH = single-family house; MFH = multi-family house; AB = apartment block. Construction cohort (1955, pre-1955; 5670, 1956–70; 7180, 1971–80; 8190, 1981–90; 9100, 1991–2000; 0110, 2001–10; and 1120, 2011–20). The results are presented per m² of utility floor area (area within the outer walls). Space heating demand for other climate zones is not shown but available with underlying data.

archetypes suggests that Ren is more effective on older archetypes than post-2000 ones. This can be attributed to the architectural features of the more recent archetypes, with taller ceilings and less compact design.

Finally, the material demand intensity in the Vent strategy follows the same trend as in the Ren strategy with less than 1 kg/m² added to the material needed for retrofit due to ventilation unit and its distribution ducts (Figure 2a). Although the added mass is insignificant compared with other materials, they are emission intensive, e.g. steel, copper, aluminium and plastics. This demonstrates the importance of accounting for their share in mass and net emission saving calculations. The space heating demand under the Vent strategy increases slightly in pre-1980 SFHs and MFHs and pre-1970 ABs compared with the Ren strategy, due to the energy consumed by the added ventilation unit to heat the ventilated fresh air and recirculated air to reach the set-point temperature, providing better indoor air quality (Figure 2b). The space heating demand, however, decreases in the more recent cohorts, with the lowest saving in ABs and highest savings in SFHs, followed by MFHs. The savings are attributed to the new ventilation system's higher heat recovery rates and efficiency factors compared with the existing systems in place (Amini et al. 2025a).

The comparison of the space heating demand using 2023 and 2050 weather conditions shows up to 5 kWh/m² lower demand in base case archetypes, shrinking to less than 2 kWh/m² in the retrofitted archetypes. As the simulated future weather files under the SSP2 scenario show, the average air temperature is expected to increase in the next decades, resulting in slightly lower space heating demand across all archetypes. It is relevant to point out that the space heating demand presented in Figure 2b was estimated under the Oslo conditions in 2023 and 2050, but the trends are relatively similar for the three retrofit strategies when simulated under the other five cities' weather files (see the supplemental data within the underlying data for Figure 2b).

3.2 FUTURE TRAJECTORIES BY 2050 IN THE BASELINE SCENARIO

The Norwegian residential buildings stock is expected to grow from 329 million m² in 2023 to 363 million m² in 2050 (Figure 3a). Given the assumption of new building constructions following the same typologies' share as in 2023, the share of AB slightly increases in the stock, from 16% in 2023 to 21%, while the share of SFH slightly decreases, from 65% to 59%. The construction of new residential buildings and the demolition of older less energy-efficient ones will result in a decrease of the yearly final energy consumption for space heating by around 10% (Figure 3b). However, the use of materials for new construction, mostly aggregates (64%), wood (17%), cement (13%) and steel (3%), will increase towards 2050 (Figure 3c). Overall, a reduction of annual GHG emissions by 6% is observed (Figure 3d).

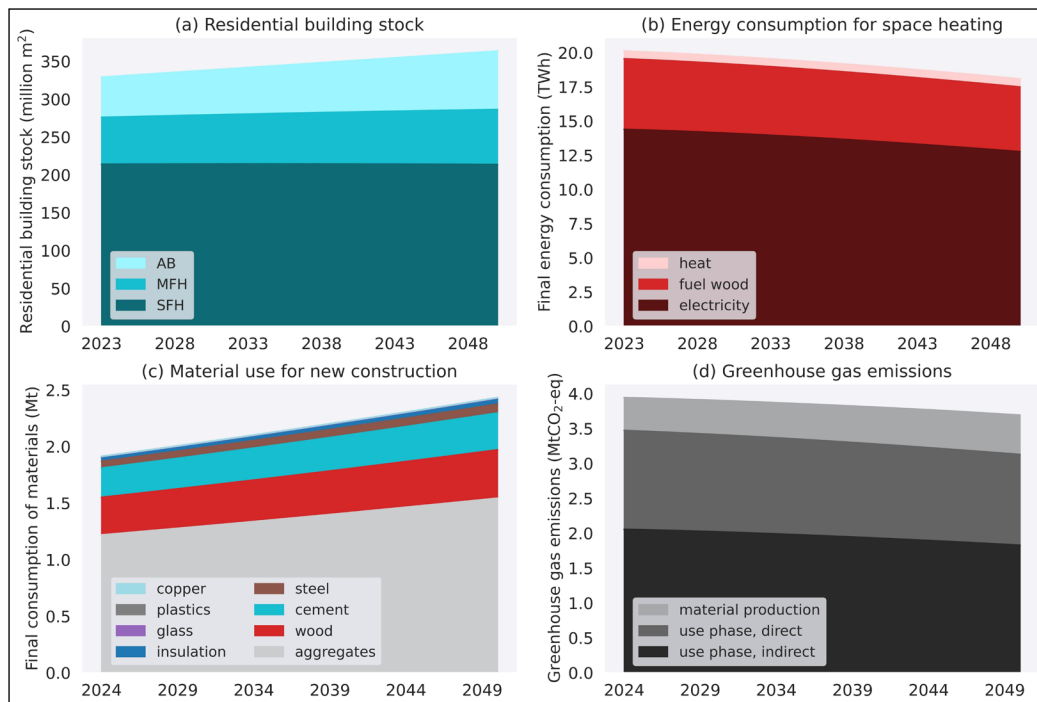


Figure 3: (a) Residential building stock by type; (b) final energy consumption for space heating by energy carrier; (c) material use (final consumption of materials) for new construction by material type; and (d) greenhouse gas (GHG) emissions by source of emissions of Norwegian residential buildings between 2023 and 2050 following the baseline scenario.

Note: Material production and GHG emissions are estimated only from 2024.

SFH = single-family house; MFH = multi-family house; AB = apartment block.

3.3 ENERGY AND MATERIAL USE WITH RETROFIT

Without any retrofit, new residential buildings built from 2024 form 20% of the stock in 2050 (Figure 4a). In the case of only energy systems being retrofitted, the share of new buildings is unchanged (20%), and retrofitted buildings, heated with HPs, represent 36% of the stock (Figure 4b). When retrofit of the envelope is enforced, resulting in lifetime extension of the retrofitted buildings, by 2050, the stock consists of 18% new construction and 37% retrofit (Figure 4c).

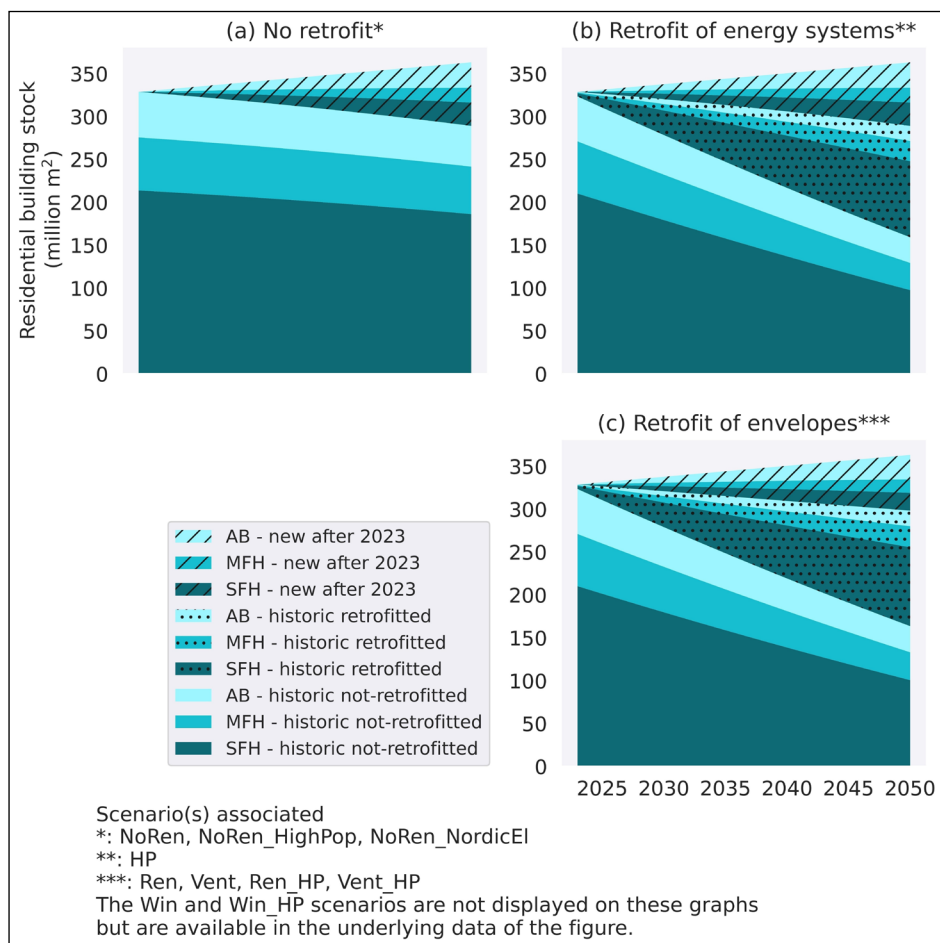


Figure 4: Composition of residential building stock between 2023 and 2050 for (a) a scenario with no retrofit, (b) scenarios with retrofit of energy systems and (c) scenarios with retrofit of envelopes.

Across all scenarios of retrofit and HP adoption, the cumulative final energy consumption (2023–50) is composed of about 70% of electricity, 25% of wood and 3% of district heating (Figure 5a). Electricity production is responsible for nearly 60% of the GHG emissions, wood for over 40% and district heating for 0.2% (Figure 5c). The cumulative final energy consumption is reduced by 6% with the adoption of HPs, 7% with changing windows (Win), and 14% with a full retrofit without or with balanced ventilation (Ren and Vent) compared with the baseline scenario (Figure 5a). If HPs are combined with the retrofit of windows or the envelope, final energy consumption is reduced by another 4–5%. About 0.6 Mt of glass and 2.6 Mt of insulation material are needed to achieve such reductions in energy consumption (Figure 5b). Moreover, gypsum (0.94 Mt), clay tiles (0.9 Mt), wood (0.67 Mt), and other materials (such as bitumen and cement) are also needed for reconstruction of the facade and roof after installation of the new insulation. In addition, 0.08 Mt of stainless steel for HPs are estimated in scenarios comprising their adoption. Insulation material makes more than 50% of the GHG emissions when envelopes are retrofitted, and glass, steel and aluminium are also large contributors to emissions (Figure 5d).

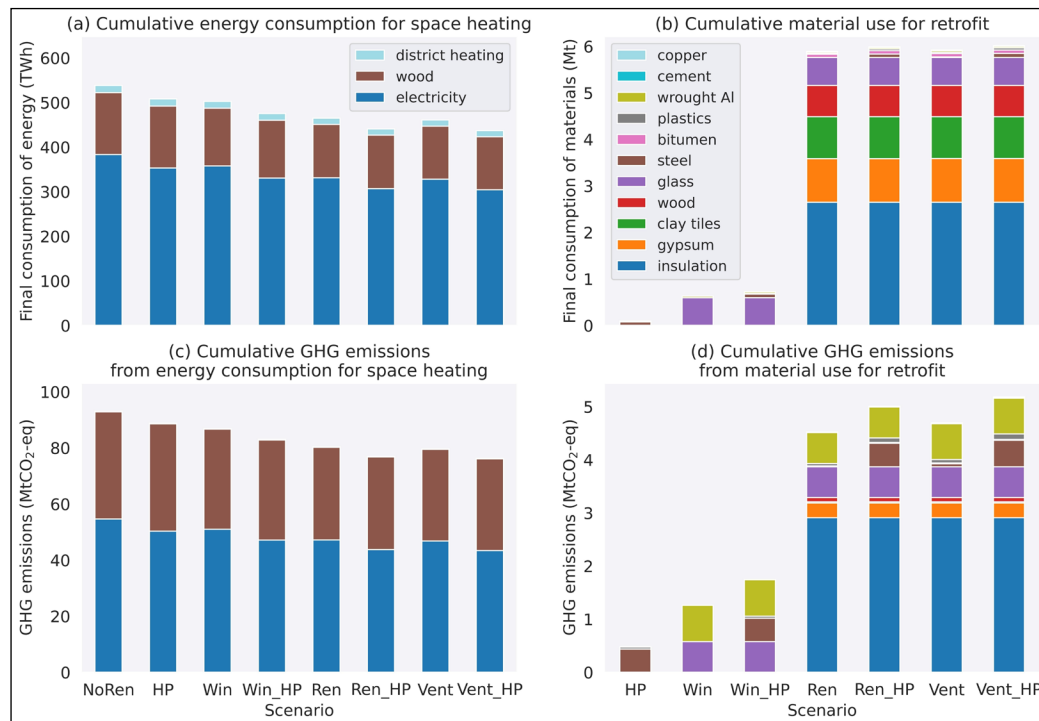


Figure 5: (a) Cumulative final energy consumption for space heating between 2023 and 2050; (b) cumulative material use (final consumption of materials) for retrofit between 2024 and 2050; (c) cumulative greenhouse gas (GHG) emissions from energy consumption for space heating between 2023 and 2050; and (d) cumulative GHG emissions from material use for retrofit between 2024 and 2050.

Note: Cumulative material use for new construction and the associated GHG emissions from production are not shown.

The annual final energy consumption and associated GHG emissions following a full retrofit and HP adoption (Ren_HP and Vent_HP) are reduced by around 8 TWh in 2050 compared with 2023 (Figure 6a) i.e. from 20 TWh in 2023 to 12 TWh in 2050. This results in saving cumulatively up to 101 TWh by 2050, i.e. on average 3.6 TWh/year. Despite the large use of materials in the early years of the analysis, the material use in these two scenarios becomes lower than the one in the baseline and HP scenarios around in the second half of 2030s (Figure 6b). Indeed, the Ren, Vent, Ren_HP and Vent_HP scenarios initially need larger material quantities for retrofit but thanks to the lifetime extension, lower material quantities are needed for new construction. Even if the materials needed are GHG intensive (Figure 6d), the two scenarios Ren_HP and Vent_HP quickly become the best scenarios due the significant reduction in GHG emissions from energy consumption (Figure 6c, e). Cumulatively, up to 13 MtCO₂-eq, i.e. on average 0.5 MtCO₂-eq/year are saved.

At the municipal and per capita level, the reduction in final energy consumption for space heating is not homogenous (Figure 7) as the residential building composition (building types and construction year) differs among municipalities. The lowest energy consumption for space heating per capita is in the region of Oslo and its neighbouring municipalities. Bergen and Trondheim, two populous municipalities, are also in the top 10 of lowest energy consumption for space heating per capita. In 2023, the median energy consumption was around 4600 kWh per capita, while it ranges between

2600 (Vent_HP) and 3900 (baseline) kWh per capita in 2050. With retrofit, the energy consumption per capita becomes more uniform across municipalities toward 2050 with a standard deviation that reduced from 930 kWh per capita in 2023 to 510 (vent_HP)–840 (baseline) kWh per capita.

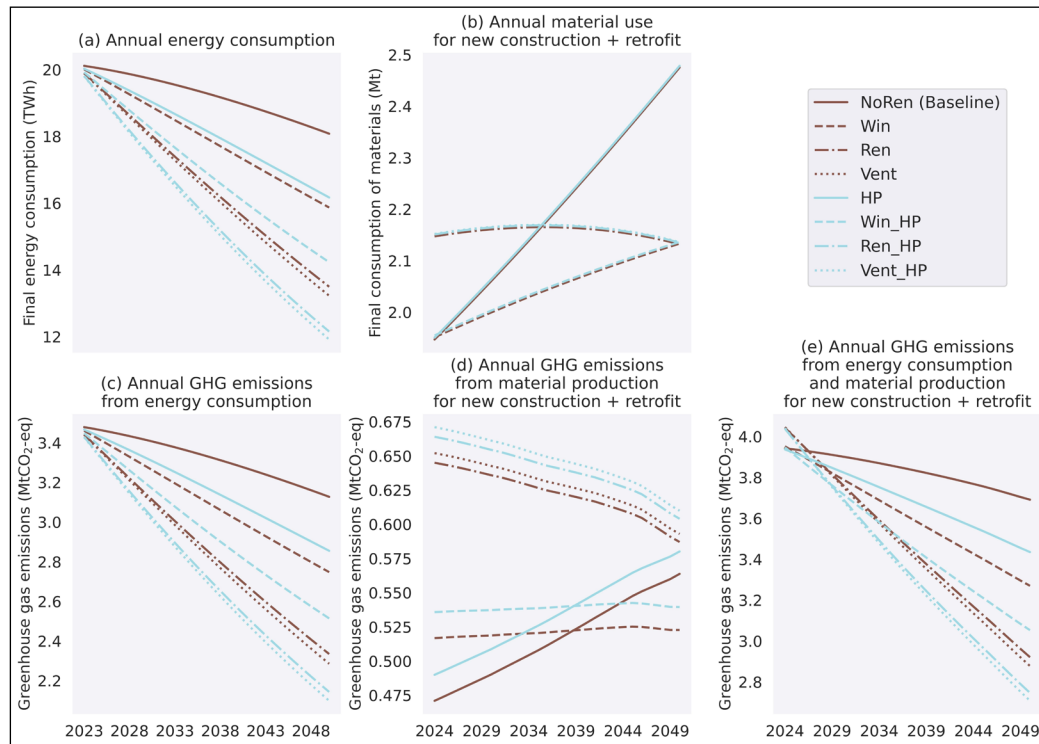


Figure 6: (a) Annual final energy consumption for space heating in residential buildings; (b) annual material use (final material consumption) for new construction and retrofit of residential buildings; (c) annual greenhouse gas (GHG) emissions from energy consumption for space heating in residential buildings; (d) annual GHG emissions for production of materials for new construction and retrofit of residential buildings; and (e) annual GHG emissions for the combination of energy consumption and production of materials.

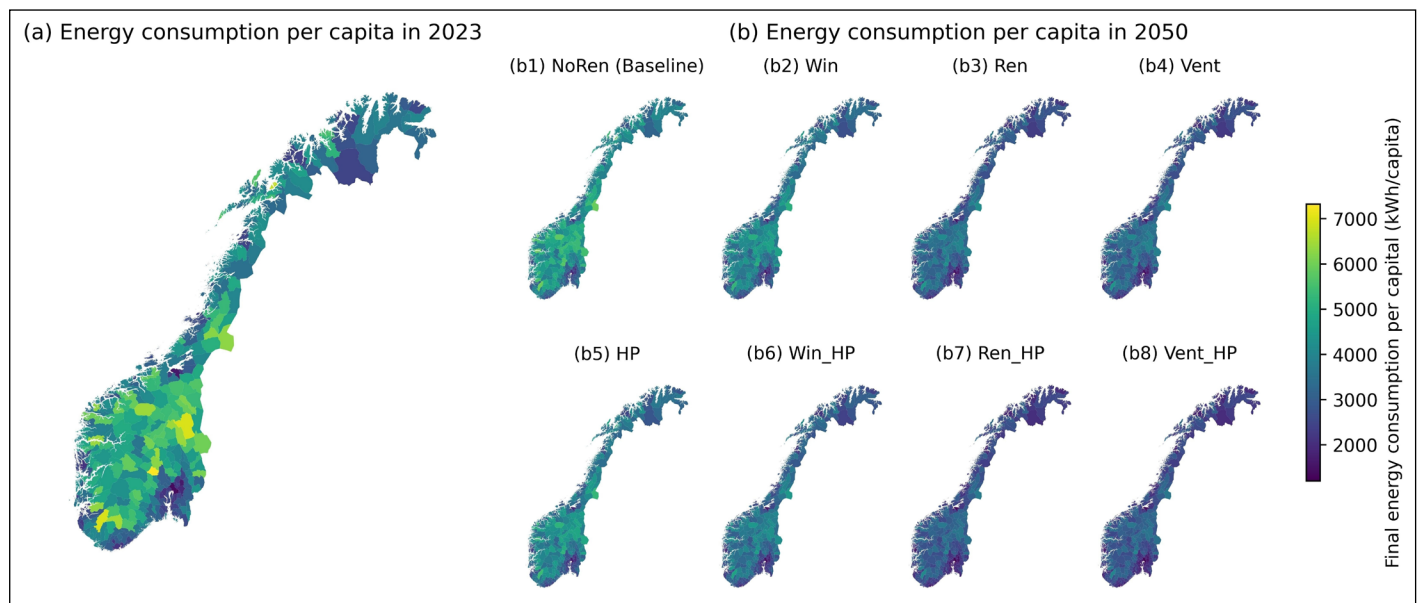


Figure 7: Final energy consumption per capita for space heating in residential buildings for individual Norwegian municipalities in 2023 and 2050 (with the associated scenario).

Note: For an enlarged version of the figure, see **Figure S4** in the supplemental data online.

To achieve the final energy consumption reductions in the individual municipalities presented in [Figure 7](#), the 6 Mt of cumulative material needed for retrofit by 2050 ([Figure 5b](#)) would need to be distributed to Oslo (0.42 Mt, i.e. 7%), Bergen (0.26 Mt, i.e. 4.4%), Trondheim (0.18 Mt, i.e. 3%) and the rest of the country.

3.4 SENSITIVITY ANALYSIS

The results of the sensitivity analysis ([Table 3](#)) show that with a high growth of population, the residential building stock is projected to surpass 400 million m² in 2050 (+11.6% compared with 2050's stock following a medium growth of population). However, the cumulative final energy

consumption does not increase as much (a 3% increase) as new construction is energy efficient. Regarding the cumulative GHG emissions due to energy consumption for space heating in residential buildings, the choice of electricity mix can significantly affect the results. With a Nordic electricity mix, the cumulative emissions are estimated to be 28% higher than with the Norwegian electricity mix.

SCENARIO	RESIDENTIAL BUILDING STOCK IN 2050 (millions m ²)	CUMULATIVE FINAL ENERGY CONSUMPTION BY RESIDENTIAL BUILDINGS BETWEEN 2023 AND 2050 (TWh)	CUMULATIVE GREENHOUSE GAS EMISSIONS DUE TO FINAL ENERGY CONSUMPTION BY RESIDENTIAL BUILDINGS BETWEEN 2023 AND 2050 (MtCO ₂ -eq)
NoRen (baseline)	363	538	93
NoRen_HighPop	406	555	119
NoRen_NordicEl	363	538	96

Table 3: Results of the sensitivity analysis with high growth of population and a Nordic electricity mix.

4. DISCUSSION AND CONCLUSIONS

4.1 RETROFITTING RESIDENTIAL BUILDINGS AND ENERGY SAVINGS

Residential buildings of all typologies and construction cohorts present a significant potential in reducing space heating demand after retrofit. For most archetypes, changing the windows and doors has the potential to cut around 50% of space heating demand, and for some buildings, a larger reduction is possible. It is important to note that these reductions are only possible if airtightness improvements happen as presumed in the archetype modelling of Amini et al. (2025a). Many building retrofit studies assess window retrofits primarily through thermal conductivity (*U*-value), solar-gain metrics and visible transmittance, with a fixed or simple infiltration value (Moghaddam et al. 2023). In Amini et al. (2025a), window and door changes are interconnected with air infiltration reduction by improving airtightness. Buildings' energy demand is highly sensitive to its airtightness, a parameter that is strongly dependent on how the retrofit work is executed. This implies that even if changing windows and doors appears as a simple strategy, it requires professional execution, where guidelines on sealing joints are carefully followed. However, for single-family houses (SFHs) and multi-family houses (MFHs) built after the year 2000, this strategy does not appear to be sufficient to reduce space heating demand. Hence, retrofitting the envelope and improving the ventilation efficiency would be necessary.

In older buildings, where only natural ventilation is in place (pre-1980 SFH/MFHs and pre-1970 apartment buildings—ABs), installing a balanced ventilation system with an 80% heat recovery rate would slightly increase space heating demand, while increasing thermal comfort and improving indoor air quality.

Although retrofit happens at the individual building level, the dynamic stock model in this study aimed to provide an understanding of the potential of various retrofit strategies in saving energy for space heating and reducing greenhouse gas (GHG) emissions at the national scale. Energy savings and GHG emissions reduction are observed in baseline scenarios which are in line with previous research: Pauliuk et al. (2013) observed a reduction in annual energy demand and carbon footprint; Sandberg et al. (2017) estimated that the final energy is reduced by 23% between 2016 and 2050.

The full retrofit and heat pump (HP) adoption scenario in this study has the potential to reduce annual final energy consumption by up to 40% between 2023 and 2050. This reduction is comparable with the 46% reduction in energy demand estimated in the scenario of retrofit with an increasing share of HPs and alternative heating by Pauliuk et al. (2013), and with the 35% reduction in final energy estimated in the scenario of combining advanced and frequent retrofit by Sandberg et al. (2017).

The direct comparison with Pauliuk *et al.*'s (2013) and Sandberg *et al.*'s (2017) results reveals the consistency of this study with previous national studies. While assessments at the national scale provide a valuable overview of future material use and energy consumption, generating results for all municipalities individually is an opportunity to inform local decision-makers. Knowing when and how much material is expected to enter or leave the built stock at this finer scale can directly inform local strategies in mitigating GHG emissions. Spatially explicit results may help local decision-makers anticipate construction activity and the amounts of materials required for retrofit. Such information could be used to support retrofit activities through financial incentives or energy auditing programmes.

4.2 ECONOMIC CHALLENGES AND ENERGY POLICY DEBATES

Jowkar *et al.* (2022) identify economic constraints as the main barrier to building retrofits for homeowners in Trondheim. They find that stronger financial incentives are critical enablers for wider adoption. The government-owned enterprise responsible for energy, Enova, provides advice and financial support for energy upgrades of residential buildings (Enova 2025b). Since autumn 2025, the process requires an application, and once it is approved, the financial support will be provided after the retrofit work is completed and documented through invoices. While this new scheme guarantees financial support for those whose application has been approved, these are based on actual receipts, so the scheme requires homeowners to prepay the entire amount. Moreover, the financial support covers 25% of the costs up to defined maximum amounts.

Even if economic constraints are highlighted as a barrier to energy retrofit, newspapers described Norwegians as champions in home renovation (Mårdalen 2019), with large amounts of money spent on kitchen and bathroom renovations. While such measures might provide immediate functional and aesthetic improvements, passive retrofit strategies' effects, such as in Win and Ren, are not immediately visible, unless improving the building's energy rating, providing a documented proof of energy efficiency. The energy rating system is defined by an energy label (A–G) and a heating rating (a colour scale from green to red) (Direktoratet for byggkvalitet 2018). The energy label indicates the range of delivered energy consumption per heated floor area, including heating, ventilation, lighting and equipment's energy use (Enova 2025c). Therefore, active systems' energy efficiency rates and the building's floor area affect the energy label. There is an approximate 10–15 kWh/m² heated floor area gap between the A and B labels, while the individual gaps between the B and C, C and D, D and E, and E and F labels are larger (40–60 kWh/m² heated floor area), suggesting a need for more drastic changes to upgrade the labels of less energy-efficient or older homes and a disregard for the indoor air quality improvements by retrofit. If one considers the standard energy use of lighting systems, equipment and hot water in residential units at around 60 kWh/m² heated floor area (Standards Norge 2023), the space heating energy consumption needs to be less than about 25 kWh/m² heated floor area to achieve the energy label A and less than 35 kWh/m² heated floor area to achieve the energy label B. Among the simulated retrofit strategies, the Ren strategy has the highest potential for reducing space heating by more than 40 kWh/m² heated floor area in pre-2000 archetypes and perhaps give a better energy label to the dwelling. The heating rating, on the other hand, determines the share of space heating and hot water energy that is sourced from non-renewable resources, e.g. gas and electricity. Therefore, no change of rating would be achieved by passive retrofit strategies, and only a change of active heating systems to HPs, district heating systems or biofuels could move the rating on the scale from red towards green.

Electricity prices (in purchasing power standard) in Norway are low compared with other European countries (Eurostat 2025). However, there are large regional disparities and temporal oscillations in electricity prices within the country (Nord Pool 2025), becoming a major political issue in the past years. As a result, the Norwegian government implemented a set of electricity subsidies (Regjeringen 2025). Electricity prices are market dependent, and therefore as soon as the demand rises and outstrips supply, electricity prices shoot up as do the electricity subsidies paid by the government. If instead these funds were used for retrofitting, electricity demand would decrease, alleviating the market and prices and allowing other sectors to use electricity as an alternative

energy source. A reduction of nearly 5 TWh in final electricity consumption in 2050 in the Vent_HP scenario compared with final electricity consumption in 2050 in the baseline scenario was estimated. This corresponds to a reduction of 0.7 MtCO₂-eq in GHG emissions in 2050. If the saved electricity were used to produce green ammonia, one of the intended uses of electricity according to Norwegian policy, GHG emissions in 2050 could be reduced by over 2 MtCO₂-eq. If it were to replace fossil process heat in industry, savings could be over 7 MtCO₂-eq (Mayer et al. 2023).

4.3 CONTRIBUTIONS, LIMITATIONS AND FUTURE RESEARCH

Although the two previous sections were focused on discussing the results from a Norwegian context, this study contributes to the literature in a more general way. It is another example of how an open-source software such as Open Dynamic Material Systems Model for Resource Efficiency and Climate Change Mitigation (ODYM-RECC), or here in this study its streamlined version, can be adapted to various geographical scope and research questions. For example, the extended service life of the retrofitted buildings was modelled. The parameters and code were also adapted to include space heating demand under future climate data. Knowledge about buildings from a local perspective is needed to understand how buildings are built and how they consume energy. Physics-based building archetypes enable a greater understanding of energy consumption after retrofit.

Improvements in passive and active systems alone are not sufficient to reliably reduce final energy consumption. Comfort and socio-economic factors must also be accounted for as they are the primary driver of energy consumption (Perez-Bezos et al. 2023; Stazi et al. 2017). Final energy consumption in older buildings, despite their lower technical efficiency (as described by the energy label), may in some cases be similar to the final energy consumption in newer buildings with higher energy efficiency (Mathiesen Gjerde et al. 2025). Such effects known as the rebound and preboun effects were not considered in this study. Sandberg et al. (2017) estimated that accounting for these effects can significantly affect the findings: in the scenario combining advanced and frequent retrofit, the final energy consumption would decrease by only 20% instead of 35%.

The emissions attributed with the energy consumption of the retrofit activities themselves, e.g. equipment used for new facade installation, were neglected. For a complete estimation of the net emissions savings by retrofit measures, as described in the B4 (replacement) stage of the construction life cycle assessment method, the energy consumption by the equipment used for execution of replacement activities should be accounted for (Standards Norge 2023).

Buildings have a long lifetime, and retrofit strategies have a key role to play to reduce energy consumption because increasing demolition for rebuilding increases material use and their GHG emissions (Pauliuk et al. 2013). Based on the findings, changing windows or installing HPs could lead to reducing space heating demand without significant increases in GHG emissions, and this could be rather easily implemented without causing major disturbances in the buildings due to wall or roof retrofitting. Enova also advises the installation of systems to automatically control heating in older buildings (Enova 2025a).

In addition to retrofit, supply- and demand-side-mitigation measures are needed (Creutzig et al. 2018; Hertwich et al. 2019). In this study, GHG intensity factors of materials account for changes in energy mixes used in their production, but besides aluminium, GHG intensity factors are not estimated to decrease significantly as they are for conventional materials. Decarbonisation of material production, especially of materials with high GHG intensities such as insulation material, glass and steel, could contribute to decreasing GHG emissions from material use for retrofit. Additionally, for lower GHG emissions in the entire residential building stock, the size of dwellings and number of inhabitants matter (Pauliuk et al. 2013, 2021b). Smaller dwellings would require less material not only at construction but also during retrofit. If combined with more people per dwelling, i.e. less floor area per capita, it would contribute to lowering the national final energy consumption. These strategies are low hanging fruits for future research.

- 1 See <https://github.com/LolaRousseau/ODYM-RECC-Norway>
- 2 See <https://doi.org/10.5281/zenodo.19886444>
- 3 See note 1
- 4 See <https://zenodo.org/records/20594798/>

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AI DECLARATION

The research and writing are the authors' work and not generated or written by programs using artificial intelligence. Such programs were used in a limited manner to refine language (synonyms, alternative phrasing), and all content was reviewed and edited by the authors.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA ACCESSIBILITY

The ODYM-RECC-Norway database used for this study builds on the databases ODYM-RECC-WN (<https://doi.org/10.5281/zenodo.13117670>), ODYM-RECC-VN1.0 (<https://doi.org/10.5281/>

zenodo.14200001) and some of the results from the RECC v2.5 model (<https://doi.org/10.5281/zenodo.12752349>). The ODYM-RECC-Norway database, output results and underlying data for the figures are available on Zenodo (<https://doi.org/10.5281/zenodo.19886444>). The ODYM-RECC-Norway code is made available on GitHub³ and archived on Zenodo.⁴ Additional data and results that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPLEMENTAL DATA

Supplemental data for this article, which contains a description of the ODYM-RECC-Norway parameters and modelling assumptions, can be accessed at: <https://doi.org/10.5334/bc.785.s1>

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