Material Demand and Energy Saving Potential of Renovation of Norwegian Residential Buildings: *A Bottom-up Approach*

Material Demand and Energy Saving Potential of Renovation of Norwegian Residential Buildings*: A Bottom-up Approach*

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Abstract. As the stock of aging buildings increases, renovation is an alternative to demolition and new construction, reducing environmental impacts and material waste. Effective retrofitting should enhance thermal comfort, minimize energy demand, particularly for heating, cooling, and ventilation, and optimize material use. Building on our previous study of Norwegian residential archetypes, we evaluate three retrofit strategies using a bottom-up, physics-based approach. Our findings show that even minimal interventions, such as window replacement, significantly reduce heating demand. However, a more comprehensive retrofit—including external wall and roof insulation, window and door replacement, and balanced ventilation—achieves greater energy savings while maintaining indoor comfort.

1. Introduction

Raw materials and resources are limited, and their extraction and overconsumption have adverse environmental and social impacts [1]. European buildings consumed more than 40% of final energy and one-third of raw materials in 2024 [2], corresponding with 1.6 billion tonnes of annual material use for newly constructed and renovated buildings [3]. Given that more than 85% of Europe's current building stock is expected to still be standing by 2050 [4], reducing their environmental footprint is vital. This can be achieved through circular economy strategies, particularly by extending their lifespan. Renovating buildings for energy efficiency and higher use-intensity supports this goal by reducing resource consumption and delaying demolition.

In Norway, 37% of the building stock is residential, of which less than 30% are built after 2000 [5]. Norwegian dwellings account for 21% of total final energy consumption [6], of which more than 75% is in form of electricity [7]. Although the electricity generation in Norway is highly decarbonized by relying on hydropower [8], the electrification of industry, transport, and agriculture is rising the demand within a limited generation capacity [9]. This highlights the need for energy efficiency in buildings to make clean electricity available for industrial uses, replacing fossil fuels.

Although there are no precise accounts of in-use material stocks in Norwegian buildings, Bergsdal et al, [10] estimated the stock of concrete and wood in buildings to be almost 185 Mt in 2025 and to rise to more than 290 Mt by 2070. More recently, Rousseau et al. [11] estimated the current stock of materials in residential buildings of Greater Oslo region to be 91 Mt. These substantial figures indicate that renovating existing buildings is preferable to demolition, as it preserves material stocks, reduces landfill waste, and minimizes the need for new resource extraction and construction.

Literature on renovation of buildings in cold climates focus on increasing building envelope's thermal resistance by improving the insulation, windows, doors, and lowering infiltration. Several studies have explored the overheating risk of such strategies in new highly insulated and airtight buildings [12].

Renovation studies in cold climates, have mostly focused on energy saving potential or lifecycle emissions on single case study buildings [13–15]. Here, we aim to expand the study of renovation to understand the variety of retrofitting effects on various building types built in different decades, while accounting for both material use and energy saving by answering the following questions:

a) How much is the potential of energy saving in buildings across Norway, considering the climate variability?
b) How much material is needed to achieve the defined levels of energy efficiency in buildings with various typologies and construction cohorts?

We build upon our previous research, where we developed type and cohort-based archetypes of residential buildings in Norway, and assessed their useful heating energy demand and material composition [16]. By testing renovation strategies developed according to national Buildings Technical Regulations (TEK17) on these archetypes, we estimate both the energy-saving potential and the associated material requirements across Norway's various climate zones.

2. Methods

Twenty-one archetypes were developed in Amini et al. [16], representing single-family house (SFH), multi-family house (MFH), and apartment blocks (AB), built in seven construction cohorts, from pre-1955 to 2020. For archetypes whose heating demand exceeds TEK17's [17] maximum threshold for total energy demand (heating, cooling, lighting, and equipment), were further developed renovated versions.

We used the defined benchmarks for ventilation and thermal conductivity values (U-value) of the external envelope to develop retrofit strategies. Using DesignBuilder, a dynamic building energy simulation software [19], we calculated the needed thermal insulation thickness in each component to comply with TEK17. Three energy retrofit strategies were developed in an incremental manner, based on the building construction and implementation procedure details provided by Buildings Research documentation (Byggforsk) [20]. Consequently, we ended up with 360 archetypes, resulting from various combinations of building typologies, cohorts, retrofit strategies, and weather files. To simulate all these combinations and estimate material types and quantities input by each strategy, we used the BuildME Python package [21]. All retrofit strategies were initially modelled in DesignBuilder, exported as EnergyPlus Input Data Files (IDF), and input to BuildME for batch simulation under 6 weather files.

2.1 Renovated Archetypes

TEK17's maximum annual energy demand per unit of heated usable floor area (BRA) (kWh/m²) of SFHs and MFHs depends on their usable floor area, while for blocks of flats, the maximum demand is set on 95 kWh/m², regardless of their floor area, due to minimal variations among Norwegian ABs' energy performance [17]. The share of space heating demand varies across buildings; energy-efficient buildings typically have a lower heating-to-total energy ratio than less efficient ones. Since we focus solely on space heating, we adjusted TEK17's threshold by multiplying it with estimated heating-to-total energy ratios for different building types and cohorts [18] (see SI). Archetypes' space heating demand [16] is compared with resulting share of TEK17's values, according to their cohort and typology. Based on this, we retrofit all archetypes built before 2010, where their energy demand exceeds corrected TEK17's threshold.

Next, TEK17 provides benchmark values for infiltration rate, heat recovery rate of the ventilation system, and thermal conductivity of building envelope's components, i.e., external walls, windows, roof, floor, and doors. To develop and assess renovation strategies reflective of the Norwegian residential market, we analysed the 2012 survey [22] to determine upgrade shares for building components; the results show that respectively windows, walls, and roofs are the most commonly retrofitted elements. Therefore, we incorporated an incremental renovation approach in developing energy upgrading strategies, as shown in Table 1:

Table 1. Renovation strategies with TEK17 benchmarks

Strategies ↓	Maximum U-Value: Windows and Doors	Maximum U-Value: External Walls	Maximum U-Value: Roof	Balanced Ventilation, 80% Heat Recovery
Win	0.8	no change	no change	no change
Ren	0.8	0.18	0.13	no change
Vent	0.8	0.18	0.13	✓

Each strategy includes the prior strategy's characteristics, while adding an extra measure (Table 1). Under the Win strategy, windows and external doors are replaced with TEK17-approved units; the Ren strategy includes all Win measures plus re-insulation of external walls and roof to TEK17 thresholds; and the Vent strategy builds on Ren by also installing a balanced ventilation system with 80% heat recovery.

Improvement of the thermal conductivity of the envelope, if following standard construction guidelines including a continuous wind-barrier installation, will enhance the building's airtightness. The amount of this enhancement, however, depends on various measures including envelope's materials, geometry, weather, and most importantly, the continuity of the wind barrier layer, sealing all joints, intersections, and inlets [23]. Therefore, although the effect of air tightening of the envelope is estimated to be 15% to 30% of the energy demand [24], it is not possible to indicate a quantitative infiltration reduction value resulting from each renovation strategy. Ridley et al. [25] show the effect of windows' and doors' operability, area, fitting, and sealing on the air infiltration of dwellings, ranging between 16% to 44% of the envelope's infiltration in UK's dwellings. Langmans et al. [23] measured the airtightness of a wood-framed detached house in Ghent, Belgium in various stages of construction and showed a 90% reduction in average infiltration of the building. As a result, we applied a qualitative staged enhancement of airtightness by each of the renovation strategies in the archetypes' energy models, ranging from poor to excellent airtightness (see SI).

2.2 Materials for Renovation

2.2.1 Windows and Doors

External windows and doors are usually the weakest part of the building envelope, regarding heat loss, airtightness, and sound insulation [26]. Although it is not mandated to use products with TEK17-defined U-values, there are guidelines to ensure proper air and water-sealing during their installation, using common materials, e.g., polyurethane (PUR) foam, an elastic sealant, or a strip of the wind-barrier material [26]. Here, we selected a triple-glazed window with a 0,8 W/m².K U-value and a wooden frame. To account for the sealant materials used around openings, we manually calculated that based on the total perimeter of windows and doors (see SI).

The replaced doors are fire- and soundproof, with a total thickness of 80 mm. Their construction consists of multiple layers, from outside toward the center: a 20 mm pine wood board, a polyethylene moisture barrier, a 1.5 mm aluminum sheet, and a 35 mm mineral wool core. These layers are then mirrored on the other side, ensuring durability and insulation [27].

2.2.2 Walls and Roof

There are several methods of post-insulating walls and roof, including external, internal, and blow-in. In the external post-insulation method, the façade's cladding is removed, and insulation is installed on walls' core, covering thermal bridges and providing good moisture resistance and low heat loss [28–30]. However, it increases the walls' thickness from the outside, challenging its connection to the roof's overhang, rafter, and door/window openings. As in our second retrofit strategy, Ren, we assume post-insulation of walls and roof together with the replacement of windows and doors, external insulation is considered a viable option.

Depending on the condition of the walls' and roofs' cladding and owners' decision, external claddings could be reused or replaced. Here, we assumed that they will be reused and only a new mineral wool layer, as thermal insulation, and a sheet of bitumen-impregnated cardboard, as wind barrier, would be added as post-insulation. The thickness of the added mineral wool depends on the archetype's original insulation thickness, U-value, and material composition. The total insulation thickness in retrofitted archetypes, including original and added insulation thickness, range between 70 to 200 mm in walls and 290 to 350 mm in roofs (see SI).

2.2.3 Balanced Ventilation System

To estimate the material input for buildings under our third renovation strategy, Vent, we calculated the required ventilation system size for each archetype. TEK17 mandates a fresh air supply of at least 1.2 m^3/h per m^2 in common living spaces when occupied, with a higher requirement of 26 m^3/h per bedroom regardless of size [17,31]. Exhaust fans must efficiently remove 54 m^3/h in bathrooms and 36 m^3/h in kitchens, toilets, and laundry rooms [17,31]. The system size is determined by the highest value among the total fresh air supply, bedroom airflow and minimum total exhaust airflow [31]. We calculated each archetype's airflow values, based on their floor area, number of bedrooms, and number of kitchen and wet rooms, selecting the highest. Based on the results and archetype's number of dwellings, we assigned an individual unit for each dwelling in SFHs and MFHs, while in ABs, we assumed a shared ventilation unit for each 4 dwelling. Due to limited data on material types and quantities in HVAC units, we relied on an available Environmental Product Declarations (EPDs) for a system with the closest airflow value to our values for SFHs and MFHs. For ABs, we estimated the amount of each material by multiplying approximate shares of each by weight of the desired system (see SI).

The selected ventilation units for SFH and MFH weigh almost 33 kg, with a 40% share of plastic materials used for insulation and internal ductworks, followed by a 15% share of galvanized steel [32]. The selected unit for the ABs weighs 248 kg, due to its higher motor size covering 4 dwellings' airflow demand, and a 50% share of steel, followed by aluminum and plastics [33].

2.3 Climate

Energy demand in buildings for heating and cooling depends, among other things, on the climate and weather conditions. The Köppen-Geiger climate classification, a commonly used system for categorizing world's climates based on specific temperature and precipitation criteria, shows 4 major climate classes across Norway, including oceanic (Cfb), subarctic (Dfc), warm-summer humid continental (Dfb), and tundra (ET). In lieu of simulating archetypes under all municipalities' weather files, we selected six municipalities with large residential floor area in the different climate regions, and widely distributed across the country: Oslo, Bergen, Trondheim, Stavanger, Ringsaker, and Tromsø. Their EnergyPlus weather files (epw), obtained from [34], were used for the energy simulation of the base case and renovated archetypes.

2.4 Simulation process

Considering our 360 IDFs to simulate, resulting from various combinations of archetypes, renovation strategies, weather files, and climate scenarios, we used BuildME Python package [21] for the batch simulation of all IDFs. BuildME incorporates EnergyPlus simulation engine to calculate a building's space-heating demand and estimates a building's material quantity based on its IDF and geometry.

3. Results and discussions

As a result of our incremental approach in defining the strategies, the amount of glass input is equal among all retrofit strategies. Ren and Vent have equal amounts of glass and thermal insulation material inputs, with Vent's total intensity being slightly above Ren, due to the ventilation units' materials.

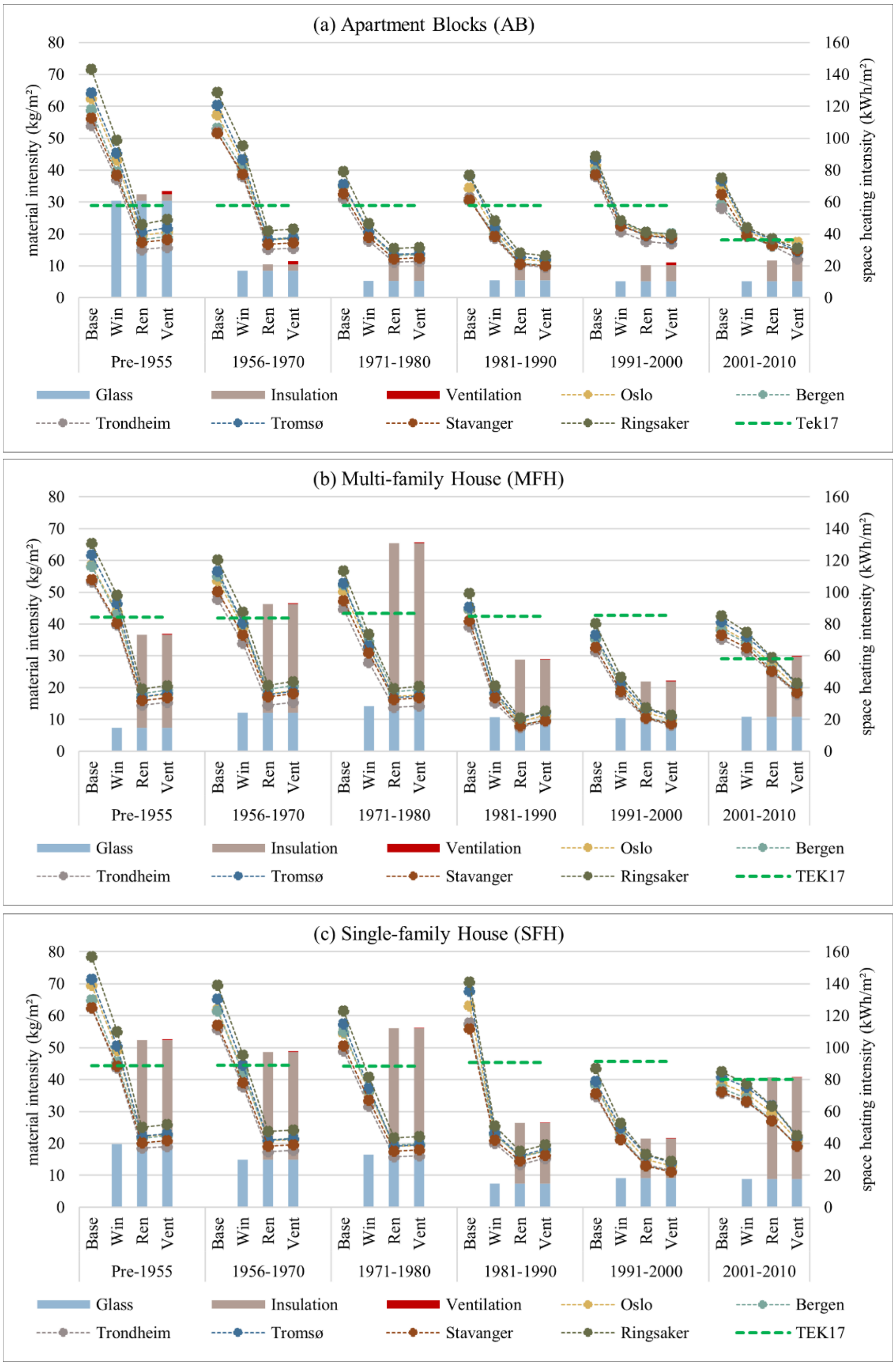

Figure 1. Material inputs and space heating demand in archetypes. Space heating intensity is the archetype's useful space heating demand intensity per conditioned floor area in each of the assessed weather stations in kWh/m².

In the pre-1955 AB (Figure 1.a), 30,3 kg/m² glass is needed to achieve TEK17's benchmark U-value of windows. This number drops to below 8,4 kg/m² in the proceeding ABs, as the archetype's window to wall ratio decreases from 25% in the first cohort to 10% after 1956 [16]. In the Ren strategy, the total amount of thermal insulation in the archetypes ranges between 2 to 5,5 kg/m². The ventilation system's material intensity in ABs is below 1 kg/m², barely noticeable in the Vent strategy's total material input intensity. Considering the installation of 2, 4, and 6 ventilation units in the first, second, and the post-1971 cohorts, respectively, the total weight of its materials increases; however, as the total conditioned floor area of apartments also increases in these cohorts, the intensity remains within the same range (see section 2.2.3). In MFH and SFH typologies (Figure 1.b, c), the thermal insulation material input intensity is predominant in the Vent strategy, where all other strategies are included. In MFHs, 11 to 51 kg/m², and in SFHs, 12 to 39 kg/m² thermal insulation materials are needed, based on the building's construction cohort, composition, and external walls and roof area. SFHs and MFHs built after 1981 had a more compact geometry regarding envelope to conditioned floor area ratio [16], driving the lower material input intensity in their cohorts (Figure 1.b, c).

All retrofit strategies significantly reduce the space heating demand in all representative weather stations. Among SFHs and MFHs built before 1990, Ren, Vent, and Win strategies are respectively most effective in reducing the demand (Figure 1.b, c); in these cohorts, the slight increase of the demand in Vent compared to Ren is due to the change from natural ventilation to mechanical ventilation. These archetypes did not include any type of mechanical ventilation, originally [16], and the added system introduces a new heating load for the required fresh air supply. However, in the following decades, 1991-2000 and 2001-2010, the base archetypes already include an exhaust and a balanced ventilation unit with 50% heat recovery, respectively. Therefore, by replacing them by a balanced ventilation with 80% heat recovery, the heating demand decreases. In original AB archetypes, use of exhaust ventilation was already common a decade sooner than in SFHs and MFHs [16]. Therefore, as the figure illustrates, Vent is the most effective strategy since 1981 (Figure 1.a).

The Win strategy, with the lowest level of intervention and material inputs, decreases the space heating demand in a range of 30% to 60% among all typologies, cohorts, and cities. Ren and Vent strategies lower the demand by 50% to 70% among all archetypes, being the most effective in the older cohorts (Figure 1).

Supplementary Information (SI)

Supplementary information is uploaded in the following link and will be updated after revisions and made publicly available upon publication:
https://osf.io/hsu6c/?view_only=7c413a9d61e14a208c6fbfe1c0e1edd8

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