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Geo-referenced building stock analysis as a basis for local-level energy and climate mitigation strategies

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ABSTRACT

A geo-referenced building stock model was used to analyse the energy and climate performance of the Knowledge Axis in Trondheim, Norway, by 2050. Strategies for energy upgrades, construction of more energy-efficient new constructions, changes in heating technologies, and their implications in terms of energy savings and greenhouse gas (GHG) emissions associated with energy and materials are assessed through various scenarios.

Thematic maps were used to display the development of the total floor area and energy use. Compared to the baseline scenario for the same year, the energy savings range from 2 to 9%, 2–14%, and 2–19% in 2030, 2040, and 2050, respectively. New passive house constructions combined with energy upgrades in renovation projects and the maximum use of heat pumps have the greatest energy-saving potential.

Our results displayed a large variation in the total net GHG emissions as a result of the alternative emission factors. The total net GHG emissions are primarily affected by the energy savings (amplified by assuming fossil fuel as the marginal mix), electricity mix (Norwegian or European), and allocation chosen for the incinerated waste to feed the district heating system.

1. Introduction

Deep reductions in emissions in all sectors of the economy, combined with rapid, far-reaching, and unprecedented changes in all aspects of society, are required to limit global warming to a safe level of 1.5 °C [1]. Buildings account for 40 % of the energy use and 36 % of the energy-related greenhouse gas (GHG) emissions in Europe [2]. Given that 75 % of the European building stock is not energy efficient and that 85–95 % of the current existing building stock will still be in use in 2050, renovation is essential to reduce both the energy-use and related GHG emissions [3]. For new construction, it is essential to apply low-energy use standards to avoid undesirable technological lock-in because of the building's long lifetime.

Demand-side material efficiency strategies are complementary to those obtained through the decarbonisation of our energy system, and may offer substantial GHG mitigation potential [4,5]. For the building sector, energy demand should be reduced and the energy sector should be decarbonised, and strategies should be implemented to reduce life-cycle GHG emissions from materials [2]. Legislative proposals from the European Commission, such as the Renovation Wave (as part of the Green Deal [6]), acknowledge the important potential synergies between reducing the material footprint and GHG emissions. The implementation of material efficiency strategies at different points in time has shown tremendous mitigation potential [7].

In recent years, energy use has garnered increased focus on energy use at the district level, such as sustainable positive energy neighbourhoods (SPENs), positive energy districts (PEDs), and net-zero-emission neighbourhoods (nZEN) [8]. The terminology used to refer to the same concept varies across studies, but these concepts refer to a geographically defined area with annual net zero energy import, and net zero GHG emission, working towards the annual local surplus production of renewable energy. PEDs are part of an urban and regional energy system that ensures the security and flexibility of supply and storage [9].

Building stock models are powerful for assessing individual buildings as part of a larger built environment, for example, a SPEN or nZEN. Building stock models can be used to conduct historical scenario analyses to understand the effects of various factors on historical development, such as the total energy consumption. This is the case for Norway from 1960 to 2015 [10] and Sweden from 1970 to 2000 [11]. However, building stock models are seldom used to assess historical developments. Building stock models can help predict the heat demand of buildings in large regions

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[12], track material use over time, for example, from 2000 to 2015 in China [13], and help estimate the carbon emission peak at the city [14] or national scale [15], for example, for China by 2050. The building stock model can also help predict future potential pathways through global scenarios for housing, mobility, and material efficiency at the global [16] and national scales [17].

The outputs of building stock models are useful inputs for policy strategies. At the national level, potential energy savings from the large-scale implementation of low-energy use buildings, for instance, the Norwegian 'zero emission buildings' in the national building stock [18] have been shown to offset the increase in energy demand by 2050. For Switzerland, Heeren and Hellweg [19] geo-referenced and tracked the construction material over space and time to investigate the impacts of material stocks in the residential building stock using data at the building level. This approach can support the development of tailored strategies to reduce the material footprint and environmental impacts of buildings and settlements.

Geo-referencing building stock models using geographic information system (GIS) models adds a spatial dimension that enables the use of thematic maps for urban sustainability [20,21]. Through thematic maps, the evaluation of spatial distribution of buildings, their related energy use, and material availability can provide a better understanding of the spatial distributions of the input and output parameters of the building stock models. Geo-referenced building stocks can aid in determining the average material use intensity [22,23], predicting future renovation needs [24,25], and decision support for building energy retrofit [26–28].

The use of cadastral data in geo-referenced building stock models can provide useful insights for local climate mitigation strategies, such as reducing the energy use and related GHG emissions. This study employs this approach to provide insight into the building stock of an area called the Knowledge Axis in Trondheim, Norway. First, the current energy performance of the building stock (residential and service buildings) was assessed and displayed through thematic maps in terms of the building type distribution and calculated energy use. Scenarios were then simulated to assess the different strategies for the energy upgrading of the existing stock, more energy-efficient new constructions, changes in heating technologies and their implications in terms of energy savings and associated energy and material GHG emissions. By drawing scenarios that reflect the composition of the existing and planned building stock of a delimited area in the municipality of Trondheim, the energy conditions, potential energy savings, and energy-upgrades can be described. By employing an integrated approach for the deep decarbonisation of the building stock, we assessed the decarbonisation of both the energy and material use.

The aim of this study was to provide a geo-referenced knowledge-based model that can be used to develop recommendations on possible development pathways of a built area for a timeline that coinciding with the long-term climate goals of 2050. The geo-referencing of the building stock can help in visualising these recommendations through thematic maps, wherein information of different types, such as the distribution of the different archetypes (in m^2), the total energy use distributed by energy carriers, and the GHG emissions related to energy and material use, can be displayed.

2. Methods

2.1. Case study

The case study, the Knowledge Axis, is located in Trondheim, Norway. The Knowledge Axis is geographically defined and covers an area of 5.3 km^2, comprising a mix of residential and service buildings and includes the city centre and central parts of the city. It lies at the 63° N latitude. Thus, the heating demand during the winter is high; a map of the Knowledge Axis is shown in Fig. 1.

2.2. Model

The model used in this study is shown in Fig. 2. The model is generic and can, in principle, be applied to any neighbourhood or region. The description below explains the input data applied in the case study for the Knowledge axis.

2.2.1. Geographic information system

GIS is used to collect, manage and analyse spatially or geographically referred data [29]. The GIS model used in this study was based on cadastral maps from 2021 [30], including data on the building type, year of construction and floor area for the existing building stock. Existing buildings at the NTNU campus, Gløshaugen, lacking information on the gross internal area, have been manually updated based on data provided by Næss et al. [31].

To model future scenarios in GIS, plans for development within the study area were provided by the municipality of Trondheim [32,33]. These plans include new buildings at Brattøra, Midtbyen and Sluppen. Building footprints were extracted from 3D models or manually drawn based on the geo-referenced raster images. The new buildings are divided into three construction periods based on information from the municipality (2021–2030, 2031–2040, and 2041–2050). The demolition activity follows the same period and is handled in the model by scheduling the demolition of existing buildings when a new building is planned at the same location.

2.2.2. Building stock

The buildings were distributed into segments defined by their building type (three residential building types and eight types of service buildings) and cohort (construction period <2010, 2011–2020, and >2021). The amount of renovation in various segments of the stock is estimated based on previous modelling of the dynamic development of the Norwegian building stock [18,34]. The extent of renovation is modelled with the same assumptions throughout the period, but the resulting rates slightly vary with variations in the stock composition over time. The resulting renovation rate is approximately 1.5 % for service buildings and 1 % for the residential building stock, with a larger share of the renovation activity occurring in old buildings.

Renovation may or may not include energy upgrades. Currently, approximately 20 % of renovations in Europe include energy upgrades [35]. In this model, we estimated the overall shares of each segment that is renovated and energy upgraded at various points in time according to various scenarios, and applied a weighted average energy intensity for the entire segment.

2.2.3. Energy demand

The energy demand requirements for the 11 building types were derived from PROFet [36,37] and were provided as annual averages for the three energy efficiency levels (1 Regular,2 Efficient, and 3 Very Efficient), as summarised in Table A1 in the Appendix. PROFet is an aggregated load profile generator that is based on measurement data and can predict the hourly load profiles for both thermal (space heating, and heating of domestic hot water) and electric loads, based solely on the outdoor temperatures and building area.

Level '1 Regular' is an average of buildings constructed before 2010 that have not undergone energy upgrades. Level '2 Efficient' corresponds to the technical requirements of buildings constructed after 2010 and level '3 Very Efficient' refers to the passive house standard. Renovation with energy upgrades was assumed to move

Fig. 1. The Knowledge axis, Trondheim, Norway.

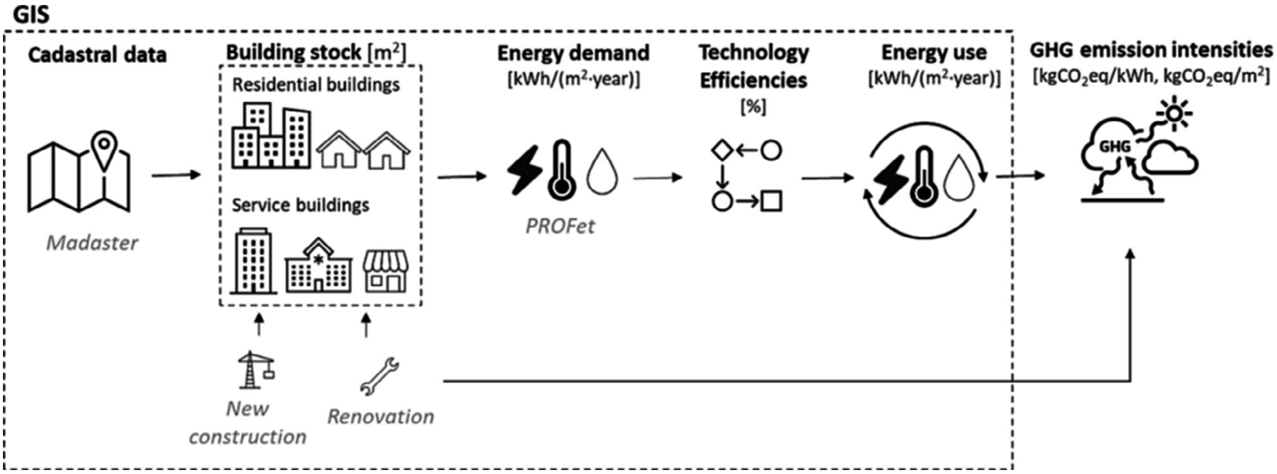

Fig. 2. Model description.

the building from levels 1 to 2. The weighted average energy demand for each segment for 2020 and 2050 is presented in Tables A3–A5 in the Appendix.

2.2.4. Heating technology efficiencies - energy use

The energy demand for space heating and domestic hot water heating is met by one of the following heating technologies, wherein the combined efficiencies [34] for space heating and domestic hot water provided in brackets: district heating (86.6 %), heat pumps (seasonal coefficient of performance (SCOP) 194 %), wood stove (64 %, small house only), bio boilers (60 %), and direct electric heating (88.2 %). The efficiency of electric loads was assumed to be 100 %.

The Knowledge axis lies entirely inside the district heating concession area, where all new buildings are to be connected to the district heating system. A district heating grid was established in this area during 1987–91. All the buildings inside the district heating area constructed after 1990 were assumed to have district heating. The share of heating technologies in buildings constructed before 1990 was assumed to be equal to the national average [34]. The average technology share in 2020 is summarized in Table A6. Heating technologies in new buildings (constructed after 2020) and renovated buildings depend on the scenario.

Buildings can be equipped with photovoltaic (PV) solar panels. The annual electricity generation was retrieved from EPISCOPE [38], calculated in relation to the floor area, and was at a maximum of 28 kWh/(m^2·year) for small houses and 14 kWh/(m^2·year) for apartment blocks and service buildings (assumed to be the same as for apartment blocks). On-site energy generation is a part of the energy generation system and not the energy demand system; and therefore, this is calculated to indicate its potential, but is not included in the energy-use calculations.

The energy use was computed by multiplying the floor area by the energy demand presented in Tables A3–A5, and the corresponding energy efficiencies are presented in Table A6.

2.2.5. GHG emission intensities

The GHG emissions resulting from energy use in Knowledge Axis are computed by multiplying the energy use by the corresponding energy carrier GHG emission intensities. The emission intensities to be used are under debate, and we applied a set of six alternative emission intensities to determine whether conclusions can be drawn from different emission intensities. The set of intensities includes 1) assuming the electricity mix of Norwegian or Europe combined with 2) the emissions from waste incineration being distributed to the waste producer, the district heating producer, or 50 % to each. The marginal electricity mix assigned to the emission benefits gained from energy savings is fossil–based consisting of natural gas. The GHG emission intensities also varied over time owing to the decarbonisation of the electricity mix. The intensities are listed in Table A2 in the Appendix.

Material GHG emissions are attributed to new construction and energy upgrade measures, namely, the emissions from the materials in the standing building stock built before 2020 are not included. The material–related GHG emission intensities were based on a comprehensive review by Wiik et al. [39] for Norwegian conditions. The 'as built' values proposed by them are used. In this review, values are given as lumped values for the product (A1–A3) and replacement (B4) stages (according to the Norwegian standard NS3720:2018 'Method for greenhouse gas calculations for buildings'). To delineate the product stage (A1–A3) and median values of the shares of different life-cycle stages, we used data from another European review by Moncaster et al. [40].

The computed values for the product (A1–A3) and replacement (B4) stages for 2020 were 315 and 117 $kgCO_2eq/m^2$ for residential buildings and 274 and 102 $kgCO_2eq/m^2$ for service buildings, respectively. To account for technological improvements and the decarbonisation of the energy mix that will lead to emission reductions over time, the emission intensities were multiplied by technology factors of 0.9 for 2030, 0.7 for 2040 and 0.4 for 2050, as used by Lausselet and Brattebø [5] and Resch et al. [41] based on the figures provided by ESU and IFEU [42].

2.3. Scenarios

After describing the current energy performance of the building stock in the Knowledge Axis, scenarios are drawn to assess the different strategies for energy upgrades of the existing stock, construction of more energy-efficient new constructions, changes in heating technologies, and their implications in terms of energy savings and associated energy and material GHG emissions. Scenarios are defined to investigate whether the Knowledge axis could become a zero emission neighbourhood by 2050, wherein the cumulated omitted GHG emissions are larger than the GHG emissions from energy and material use. Moreover, we evaluated the aspects required to achieve this in terms of improvements in the buildings' energy level by upgrading existing buildings and construction efficient new buildings and/or changes in the heating system technologies. Additionally, district heating scenarios are investigated to understand the local specificities of the Knowledge axis, which is part of the district heating concession area.

As a baseline, we assume future construction to be in accordance with the current technical standard TEK17 (between levels 2 and 3). In the energy–efficiency scenarios, new constructions were assumed to be passive houses (level 3). Renovation in this model is to assumed to be a comprehensive renovation of the building envelope, including façades, roofs, windows, and doors. The amount of renovation was the same in all scenarios. However, buildings could be renovated with or without energy upgrades. For renovations under 'business as usual' scenarios, we assume that 80 % of the renovated floor area did not involve energy upgrades, while the remaining 20 % involved energy upgrades, transitioning from levels 1 to 2 [35]. For 'ambitious' renovations, 100 % of the renovations involved energy upgrades and transitioned from levels 1 to 2. For both 'business as usual' and 'ambitious' renovation types, renovations of buildings in levels 2 and 3 remained at the same energy level.

Renovation also involves changing the heating technologies, and in particular, installing a waterborne heating system in buildings that was previously absent. This was considered in our max heat pump (HP) scenarios. These scenarios are presented in detail in Table 1. The details of the technology share are listed in Table A6.

3. Results

Thematic maps showing the building stock according to the building type and cohort for various years are shown in Fig. 3. The total floor area of the building stock in 2020 was 3.2 million m^2. The building stock was predicted to increase by 28 % by 2050, with increases of 17, 4 and 7 in 2030, from 2031 to 2040, and from 2041 to 2050, respctively. Service buildings dominate the building stock with shares of 68–73 %., followed by apartments at 21–27 %, and finally by houses with 6–8 %. Nationally, detached houses, apartments, and service buildings comprise 57, 12, 31 % of the total floor area, respectively [46]. Thus, the Knowledge Axis has an atypical building stock in the Norwegian context. The share of the oldest cohort (<2010) declined over the years from 85 % in 2020 to 62 % in 2050. The newest cohort holds shares of 5–8 %. Fig. 3 indicates a significant new activity in this part of the city in the following decades, and the activity is particularly concentrated in the Brattøra, Gløshaugen and Sluppen districts (Fig. 1).

The total energy use by energy carriers and building types (residential and commercial buildings) in 2020, 2030, 2040, and 2050 are shown in Fig. 4 and listed in Table A7. Service buildings are the dominant building type in the building stock and thus naturally dominate the total energy use. Electricity is the main energy carrier used for space heating in Norway and the Knowledge axis is no exception. However, district heating also plays an important role in energy supply because the Knowledge axis lies in the district heating concession area. Bio-energy carriers play a minor role in this process. PV production is not included in any scenario, but is displayed on the right-hand side of Fig. 4 to indicate its potential.

For all scenarios, the total energy use increased from 2020 to 2030, induced by the growth of the building stock. The first benefits of energy upgrades were observed in 2030.

Compared to the energy use in the baseline scenarios for the same year, the total energy use in the other scenarios reduced by 2–9 % in 2030, 2–14 % in 2040, and 2–19 % in 2050, as shown in Fig. 4 and presented in Table A6.

Fig. 5 shows the total energy use for each scenario for the years 2021–2030, 2031–2040 and 2041–2050 with a grid resolution of 100 × 100 m. The maps of scenarios 1b, 2a, 2b, 3a, and 3b show differences compared to scenario 1a for the same period. Corresponding graphs for the energy–use carriers are depicted in the Appendix: electricity in Fig. A1, district heating in Fig. A2 and bio in Fig. A3. The scenarios where the new constructions follow the passive house standard and where a high share of the building stock is renovated with energy upgrades clearly showed the largest energy savings. The scenarios using more district heating have a lower overall decrease in the energy use, but a greater decrease in the electricity use.

The life-cycle GHG emission of each scenario cumulated over the assessment period are shown in Fig. 6. The results are shown for each life-cycle stage (product (A1–A3), replacement (B4), and operational energy use (B6) stages). Across the scenarios, 4–30 %, 2–11 %, and 59–94 % of the total GHG emissions were allocated to the product stage of the new constructions (A1–A3), replacement of materials (B4) occurring during renovation activities, and to energy use (B6), respectively. Within energy use (B6), electricity, district heating, and bio resulted in 13–85 %, 4–73 %, and 1–3 % of the emissions. The share of energy use (B6) in the total is correlated to the emission intensity of the electricity mix and the allocation chosen for the district heat waste fraction.

Important emission savings (orange bars below the × axis in Fig. 6) were observed in the energy efficiency scenarios, wherein the energy use is decreased by energy upgrading the existing stock and passive house new construction. Furthermore, maximising the use of district heating, particularly heat pumps, resulted in further

Table 1
Description of scenarios (DH = district heating, HP = heat pump, and PV = photovoltaic solar panel).

			Energy standard		
			New construction	**Renovation**	**Technology shares**
Scenarios	**1a**	**Baseline**	TEK 17	Business as usual	Today's shares. No change in heating technologies when buildings are renovated
	1b	**Energy efficiency**	Passive house	Ambitious	
	2a	**Baseline + max DH**	TEK 17	Business as usual	100 % district heating in renovated buildings and new buildings (2020–2050)
	2b	**Energy efficiency + max DH**	Passive house	Ambitious	
	3a	**Baseline + max HP**	TEK 17	Business as usual	100 % heat pump in renovated buildings and new buildings (2020–2050)
	3b	**Energy efficiency + max HP**	Passive house	Ambitious	

New construction
TEK17: Current national technical standard [43]
Passive house: According to NS 3700:2013 "Criteria for passive houses and low energy buildings - Residential buildings" [44] and NS 3701:2012 Criteria for passive houses and low energy buildings - Non-residential buildings [45]
Renovation
Business as usual: Renovation from Level 1: 80 % unchanged, 20 % energy upgraded to Level 2. Renovation from Level 2 and 3: unchanged.
Ambitious: Renovation from Level 1: 100 % energy upgraded to Level 2. Renovation from Level 2 and 3: unchanged.
(Level 1: Regular, Level 2: Efficient, Level 3: Very efficient, ref. Tables A3–A5)

savings. Emissions from energy use varied according to the applied emission intensities.

Across the scenarios and for the same electricity mix (NO or EU), the percentage of the total GHG emissions increase (from an original value of 0 %) by 65–101 % when emissions from waste incineration are allocated as 50 % each to the energy and waste producer, and by 129–203 % when 100 % of emissions are allocated to the energy producer. For the same waste incineration allocation method, the total GHG emissions increase by 313–357 % when transitioning from a Norwegian electricity mix to a European one.

When accounting for the emission benefits gained by the displacement of fossil fuels due to the energy savings, the net totals reduced by 7–173 %. The three scenarios achieved a net-zero GHG emission balance in 2050 under certain variants of the emission intensities: Scenario 2b (NO-0 %), Scenario 3a (NO – 0 %, and NO – 50 %/50 %), and Scenario 3b (NO – 0 %, NO – 50 %/50 %, and NO – 100 %). This indicates the difficulty in choosing a strategy that does not include other factors (e.g., utilisation of an existing waste heat resource or possible need for expansion of parts of the energy system or local energy production) or investigating which emission factors are most likely and/or politically determined.

4. Discussion

4.1. Comparison with previous studies

In the present study, we found that energy upgrade measures combined with more energy efficient heating technology options could reduce the overall energy use by 2–19 %. The high-end of the range is found when new constructions are of the passive house standard, energy upgrades occur in a high share of the building stock, and heat pumps are deployed at their maximum level. This is because given that there are no secondary effects on the local energy system (electricity and district heating), such as major upgrades to the electricity grid and transformers in the municipality. However, switching from district heating to a heat pump in a concession area is both controversial and unrealistic. Additionally, it is probably not desirable to replace district heating with heat pumps in this way, because it will increase the need for electricity in other sectors of society as they will be electrified.

For the same climatic context but at a national scale, Sandberg et al. [18] found energy savings of 10–50 % compared to a baseline scenario for the same year during 2020–2050, which were induced by the same factors as those in our study. The energy savings of the present study are lower because of the important new construction activities that increased the floor area of the Knowledge axis by 28 % from 2020 to 2050, in addition to the large percentage of buildings connected to district heating; 23–42 % for the Knowledge axis compared to 7–18 % in reference [18] across all scenarios and years. For a European continental context, Mastrucci et al. [47] estimated that the theoretical potential energy savings in residential buildings of the Rotterdam city were 45 % and ranged from 41 to 68 % for dwellings built before 1964, 5–12 % for those between 1992 and 2005, and null for those after 2005. The results of the present study are consistent with those of previous studies on similar energy retrofit measures, for example, energy saving at the district or city scale.

Energy use (B6) contributes 59–94 % of the total GHG emissions during 2020–2050. This range does not align with a typical profile for Norwegian dwellings, wherein the product stages (A1–A3) dominates the total GHG emissions [48]. The emissions from the materials in the standing building stock constructed before 2020 are not included here, and the GHG emissions from energy use (B6) therefore dominates the total GHG emissions. The low end of the range is close to a typical Norwegian profile [48,49] with a renewable energy mix, and the high end of the range is close to a European profile with a less decarbonised energy mix [50].

Renovation (B4) contributed 2–11 % of the total GHG emissions. This range is consistent with that of 4–16 % from Mastrucci et al. [51], who developed a spatially explicit LCA framework to evaluate the environmental impact of urban building stocks and renovation scenarios using a building-by-building approach, as done in this study. Additionally, the buildings in review conducted by Wiik et al. [39] in Norway were constructed over the past 10 years and are thus of high energy standards. Thus, it is reasonable to use their values for the renovation (B4) as representative of the GHG emissions related to the energy upgrades computed throughout the scenarios of this study. The values for renovation are in line with Moschetti and Brattebø [52] for similar conditions and can be seen as conservative because they overestimated the GHG emissions from older buildings that, by definition, cannot reach the

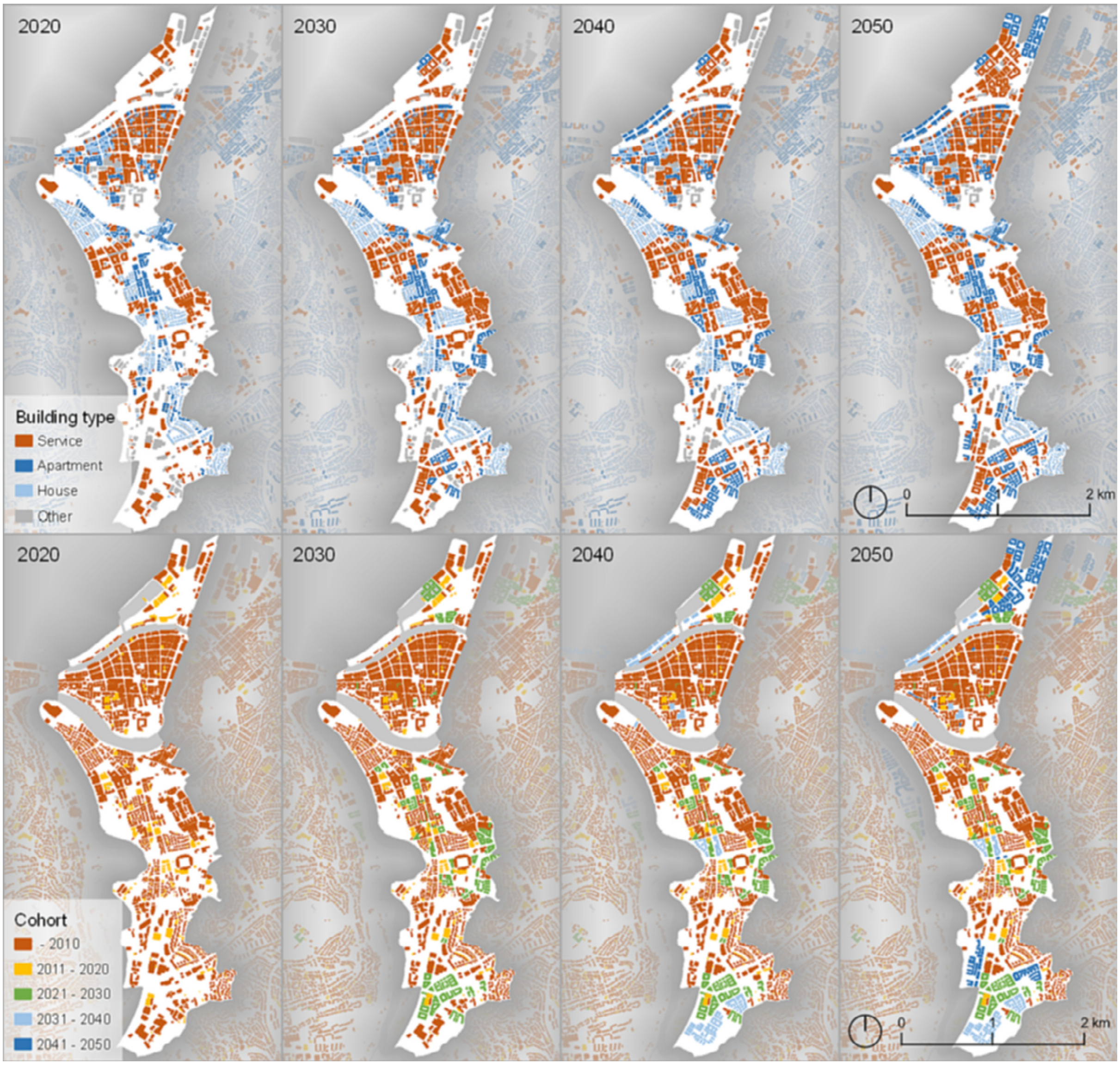

Fig. 3. Building stock displayed by building types and cohort.

same of energy efficiency level as new cohorts, and thus do not have the same material requirements [53].

Material-intensive retrofit strategies were shown to be effective under current Dutch energy mix conditions by de Oliveira Fernandes et al. [54]. The authors warned that this emission balance potentially shifts as the energy mix transitions towards more renewables. This was also shown in our study by exploring different assumption concerning the energy mix for both electricity and district heat over time.

4.2. Uncertainties

Uncertainty was found in the different parts of the model and analysis. First, uncertainty is embedded in the building stock model that predicts the development of the Knowledge axis over a long period of time and is thus inherent in a model assessing long timeframes. Second, the energy profiles are the average yearly energy–use profiles for the given building types and energy levels. In reality, energy use varies between buildings, and is highly influenced by user behaviour. Third, uncertainty is embedded in the energy and material emission intensities induced by the material aggregation level and emissions development over time. To reduce this uncertainty, a balance would have to be found between the level of data required to increase the accuracy of the emissions material layer and the amount of data required to apply a consistent resolution level across the various buildings in the building stock of the Knowledge axis.

Uncertainty was qualitatively assessed in the present study. To quantify uncertainty, a global sensitivity analysis technique, such as variance-based sensitivity analysis [55], can be employed. A possible option to assess each parameter of such a 'global sensitivity analysis' could involve using the pedigree matrix approach, as conducted by Ecoinvent [56]. Each parameter of the present study was then assigned a score for the following six characteristics: reliability, completeness, temporal correlation, geographic correlation, further technological correlation, and sample size.

4.3. Future work

Materials were assessed at an aggregated level through material GHG emissions intensities at the building level in units of $kgCO_2eq/m^2$, which fits well with the scope of this study. The next step

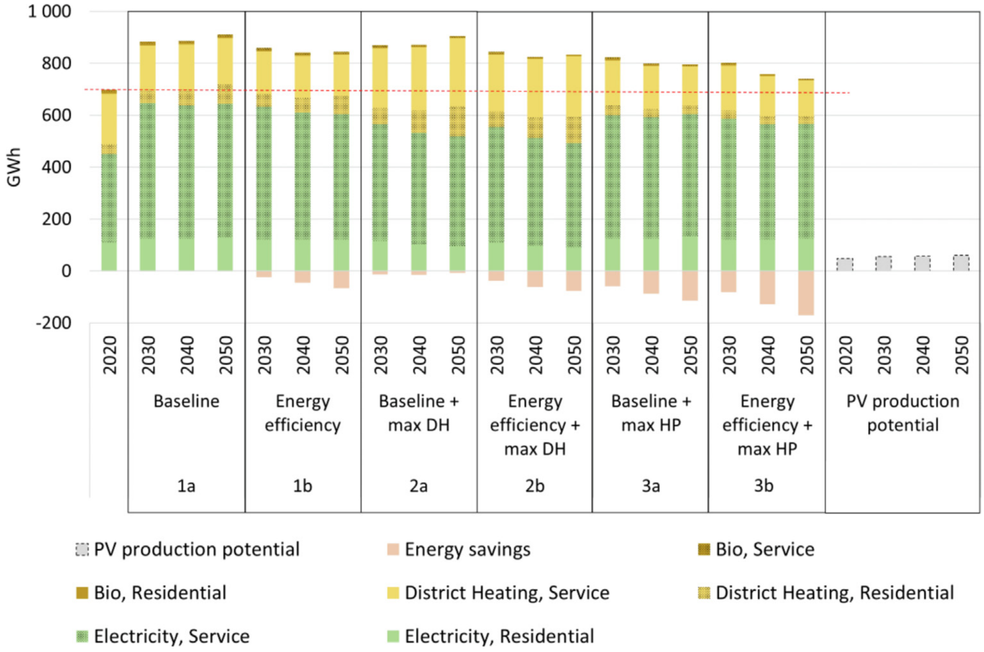

Fig. 4. Total energy use for each scenarios during 2020, 2030, 2040, and 2050.

involve the use of material inventories that are then multiplied with their respective and specific emission intensities. More material–specific strategies can be developed by increasing the resolution of the material layer. The inclusion of costs could further develop the assessment of the environmental and economic sustainability of the Knowledge Axis. By using geo-referenced building stock models, useful quantitative and regionalised insights can be obtained for the further development of the built environment of a region. However, a better understanding of the decisional mechanisms is required to ensure that these insights reach their full potential in decision-making process. Previous experiences have shown that the main barriers to achieving energy goals were not inadequate technological solutions, but the lack of synergy between sectors, lack of common standards and definitions, and lack of collaboration and commitment from the stakeholders involved [57,58].

Brattøra, Gløshaugen and Sluppen, the areas of the Knowledge axis predicted to experience the most growth (see Results section), are also planned to be PEDs, where the annual local energy use will be maintained below the amount of locally produced renewable energy. The inclusion of physical energy infrastructure in the GIS model will enable the assessment of the full potential of future PEDs. This will also include the charging capabilities for electric vehicles, local renewable energy sources, local storage, smart energy grids, demand response, energy management, user interaction, and involvement. In this context, the on-site electricity generated by the PV panels (used as indication in Fig. 4) will be integrated into the energy-use calculations.

Another way to further develop the model is to apply hourly energy profiles to factor in the capacity dimension. However, this results in uncertainty and challenges in the general data protection regulation when measuring data at the building level; the methodology should be developed by including this consideration to obtain more useful results at the local level. Such an approach can provide insights to avoid 'energy poverty' among certain social groups.

4.4. Policy implications

One of the challenges in developing policy frameworks for sustainable positive energy neighbourhoods at the neighbourhood or city scale is the adequate understanding and integration of the different fields involved: building construction and renovation, electricity network, electricity mobility, district heating and cooling, energy storage and flexibility, digitalisation, community engagement, urban development, etc. [59].

Local areal planning is typically a task that falls is governed by the local government, such as municipalities, as part of the Planning and Building Act published by the Norwegian Ministry of Environment [60]. However, municipalities have little influence on how grid companies and district heating companies choose to develop their energy systems, and on the requirements for energy performance beyond the national technical requirements for new construction. Municipalities can facilitate, recommend, and demand stricter energy levels, but this has not been observed so far.

For the Trondheim municipality, this study clearly shows that the goal stated in the energy and climate plan on stationary energy use after 2013 can be difficult to achieve without ambitious renovations and new constructions that follow low-energy-use standards. These measures decrease both the overall energy use and the peak loads. As peak loads are usually covered by fossil energy carriers in electricity and district heating generation, a decrease in their magnitude will have a secondary positive climate effect.

We also evaluated the allocation of GHG emissions arising from the waste incinerated with energy recovery that feeds the district heating system to either the waste or the energy producer. The allocation of these emissions to the waste producer can potentially promote circular economy initiatives that focus on reducing the total waste generated, along with increasing the reuse and recycling rates. However, a certain fraction of the generated waste will always be sent for incineration for different reasons. To allocate these GHG emissions to the waste producer, this heat is considered as waste heat, as stated by the Norwegian standard NS3720:2018 [61] and the Environmental Agency.

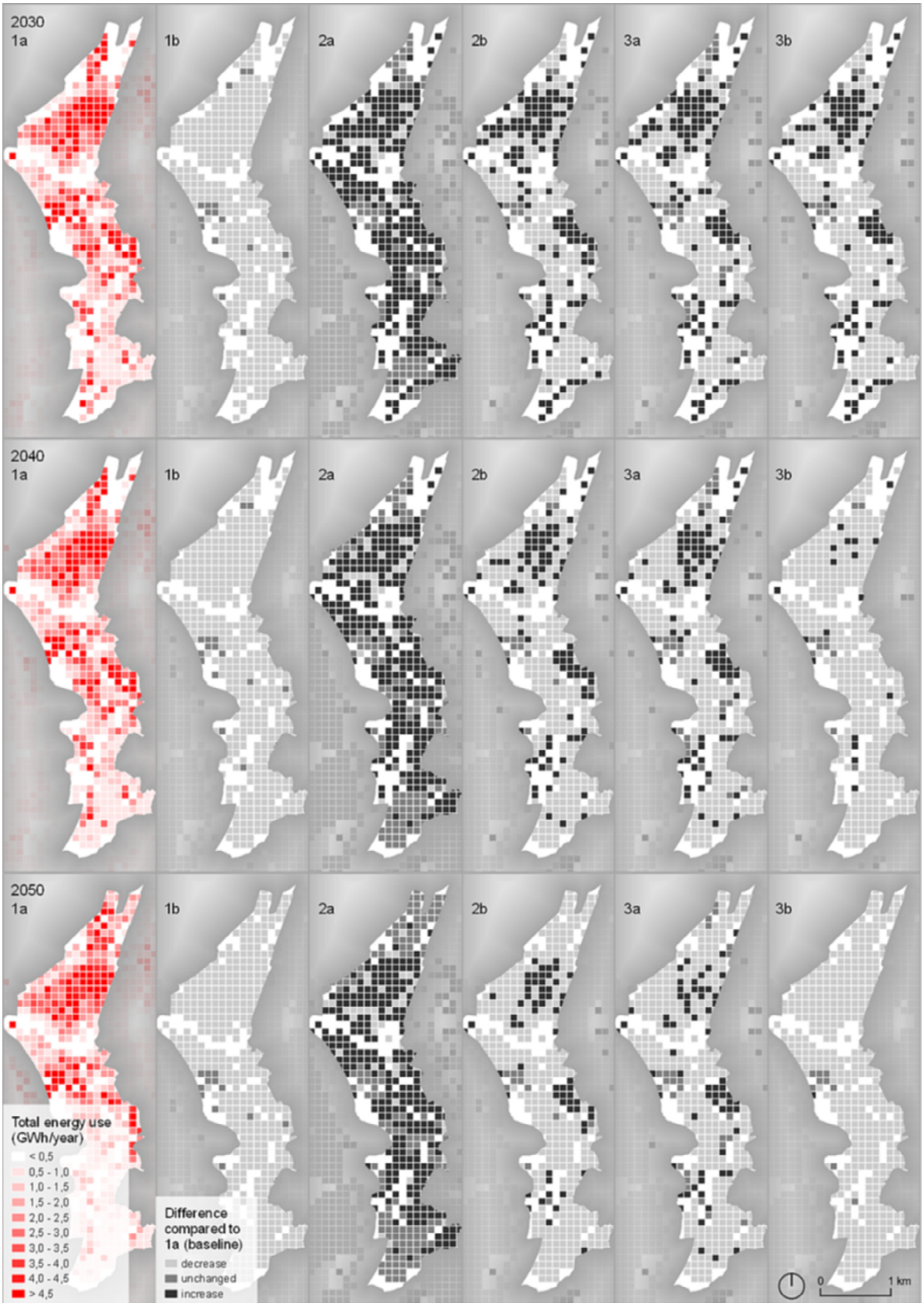

Fig. 5. Total energy use (GWh/year) for each scenario for the years 2030, 2040, and 2050. Maps of scenarioS 1b, 2a, 2b, 3a and 3b show the differences compared to scenario 1a for the same year. The grid resolution was 100x100 m.

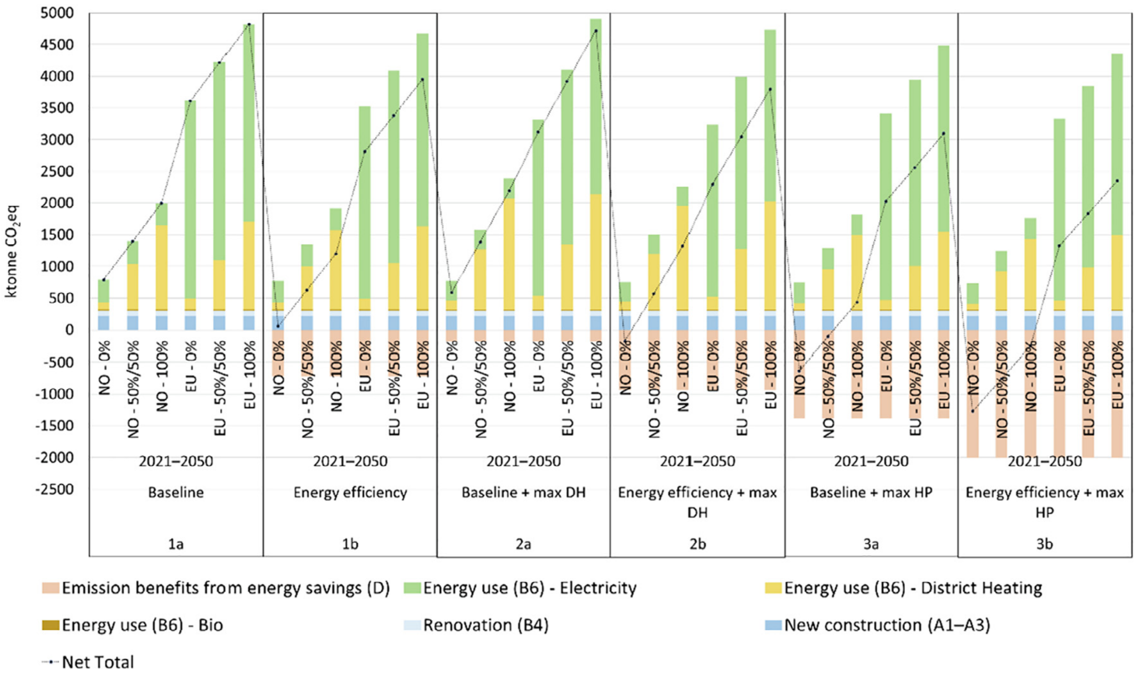

Fig. 6. Life-cycle of greenhouse (GHG) gas emissions for each scenario, cumulated over the period of assessment. The electricity mix of NO = Norwegian and EU = European are combined with three allocation variants for the GHG emissions resulting from the combustion of waste; 0 % to the energy producer, 50 %/50 % shared between the energy and waste producers, and 100 % to the energy producer.

5. Conclusion

The building stock is a large energy consumer and has the potential for significant energy efficiency improvements. Increased energy and electricity demand from the expected electrification of society at large implies a possible need for the expansion of the supply capacity and energy production in general. More energy-efficient building stocks can ensure the availability of electricity in other sectors and hence play an important role in alleviating the need for increased capacity. By applying a dynamic building stock model in a local context, we observed, compared to the baseline case, significant energy reduction potentials by introducing low energy-use standards to new construction and energy-efficient renovations of the existing building stock. Furthermore, the large-scale implementation of heat pumps has a significant effect on the total demand for delivered energy, even if this would be less realistic for the area under study, as it is part of a concession area for district heating.

A general trend observed across the different scenarios is that energy use will increase compared to the current level, even with significant improvements in the energy efficiency due to increasing population and the subsequent need for floor area. Furthermore, with the current renovation rates, the main part of the standing building stock in 2050 will not be subjected to renovation and energy upgraded during the assessment period. In the presented scenarios, we found possible energy reductions ranging from 2 to 9 % in 2030, 2–14 % in 2040, and 2–19 % in 2050.

For GHG emissions, the largest emissions were associated with the use phase (B6) and were heavily affected by the assumed electricity mix and allocation method applied to waste incineration in district heating. Under the assumption that energy reductions offset fossil fuel use, some scenarios achieved a net-zero GHG emission balance by 2050. The GHG results are sensitive to the assumptions for these key parameters and demonstrates the uncertainty associated with analyses of future development. However, the results from the underlying energy analysis are still robust with respect to the need for energy efficient improvements and the corresponding contribution to lower total energy and electricity demands.

Using GIS-generated maps to visualise the results can be valuable for local planners and policy decisions regarding different aspects of both area development and energy planning. It can be used to visualise potential bottle necks in energy supply systems for both the district heating and electricity transmission in the following decades. This can provide easily available inputs to planners regarding the need for increased electricity capacity, demand for extensions of the district heating network, possibilities for local energy production and local area planning with respect to the mix of building types and activities.

Data availability

Most of the data used is given in the Appendices.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: N. H. Sandberg reports financial support was provided by Research Council of Norway.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2022.112504.

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