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A holistic sustainability assessment of a zero-emission development in Norway

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Abstract. The decarbonisation of the construction sector is critical to meet national and international climate goals. Literature gives many examples of measures for the reduction of greenhouse gas (GHG) emissions from buildings. However, few studies investigate the trade-offs between potentially conflicting GHG emission reduction measures or the affordability of these measures. Ydalir is a Zero Emission Neighbourhood (ZEN) pilot area in the Norwegian research centre for Zero Emission Neighbourhoods in smart cities. One of the major challenges Ydalir faces is how to reduce GHG emissions from the neighbourhood towards a net zero emission building (nZEB). Additional challenges include retaining social, environmental, and economical sustainability for both the project developer and building owners and avoid suboptimal solutions. This paper investigates the trade-offs between energy efficiency and material use for two scenarios. The scenarios are a Norwegian building code scenario and a passive house scenario. The analysis ascertains total energy demand, whole life cycle GHG emissions, and cost assessment for two housing units within Ydalir Torg. The results show lower total GHG emissions and lower GHG emissions from operational energy use in the passive house scenario, and an increase in GHG emissions from the production phase due to thicker levels of insulation. The cost assessment shows increased investment costs for the project developer in the passive house scenario, despite lower operational costs for the building owner. Total GHG emission payback times for the passive house scenario are at 18 - 19 years. Cost payback time varies between 10 - 37 years. This paper is useful for practitioners that wish to balance GHG emission reduction requirements between operational energy use, material use and affordability.

1. Introduction

The decarbonisation of the construction sector is critical to meet national and international climate goals [1,2]. Construction typically accounts for 23 % of global greenhouse gas (GHG) emissions [3]. As energy infrastructure is decarbonised, and buildings become more energy efficient, GHG emissions from other parts of the building's life cycle (e.g., material production, transport and installation during the construction phase, use, maintenance, repair, replacement, and end-of-life) gain in significance [4–8]. For highly energy-efficient buildings these embedded emissions can account for up to 90 % of the building's total emissions [9]. At the same time, conflicts can arise between economic considerations and environmental ambitions, such as low energy consumption [10] or low-emission construction materials [11]. It is therefore paramount to use holistic sustainability assessments of buildings and neighbourhoods to consider energy, GHG emissions, and economic viability and thereby avoid problem-shifting, as well as enable decisionmakers to evaluate different design options and make informed choices.

Ydalir is a Zero Emission Neighbourhood (ZEN) pilot area in the Norwegian research centre for Zero Emission Neighbourhoods in smart cities (FME ZEN). One of the major challenges Ydalir faces is how to reduce GHG emissions from the neighbourhood towards net zero emission building (nZEB). Additional challenges include retaining social, environmental, and economical sustainability for both the project developer and building owners and avoiding suboptimal solutions. This paper aims to investigate the trade-offs between energy efficiency and material use for two scenarios. The scenarios are a Norwegian building code (TEK) scenario and a passive house (PH) scenario. The analysis ascertains total energy demand, whole life cycle GHG emissions, and cost assessment for two housing units within Ydalir Torg.

2. Background

Literature gives many examples of measures for the reduction of GHG emissions from buildings. However, few studies investigate the trade-offs between potentially conflicting GHG emission reduction measures or the affordability of these measures. There exists differing definitions of nearly/net zero emission/energy building (nZEB) [12–16]. In this article, we refer to the FME ZEB's definition of net zero emission building, whereby a range of ambition levels ranging from the lowest ambition level of ZEB-O to the highest ambition level of ZEB-COMPLETE are proposed [17–19]. Here, GHG emissions from the whole life cycle (WLC) of the building from the construction phase (C), operational energy use (O), material production and replacement (M), use, repair, and maintenance (PLE), operational transport use (T) and the end-of-life phase (E) are compensated for by renewable energy generation (D).

3. Method

Ydalir Torg consists of 13 timber-framed terraced housing units located in Ydalir, Hedmark, Norway [20–22]. Calculations are carried out for two of these two-storey housing units; building A which has 126 m^2 heated floor area and is a mid-terrace, and building B which has 107 m^2 heated floor area and is an end-terrace. The method comprises of three parts; operational energy use calculations in the energy modelling tool SIMIEN [23], GHG emission calculations in the carbon footprint calculation tool Reduzer [24], and cost assessments in MS Excel for four scenarios: 1. TEK with wood fibre insulation, 2. TEK with mineral wool insulation, 3. PH with wood fibre insulation, and 4. PH with mineral wool insulation.

Energy calculations are performed according to *NS/NSPEK 3031:2021 Building's energy performance – Calculation of energy need and energy supply* [25] for two scenarios, TEK and PH, according to requirements set in TEK [26], and *NS 3700:2013 Criteria for passive houses and low energy buildings – residential buildings* [27]. In the TEK scenario, outer walls have a U-value of 0.22 W/m^{2}K (corresponds to approx. 200 mm insulation), the roof has 0.09 W/m^{2}K (approx. 450 mm insulation), the floor has 0.15 W/m^{2}K (150 mm EPS insulation) and windows and doors 0.8 W/m^{2}K. The normalised thermal bridge for the whole building is 0.05 W/m^{2}K, whereby m^2 is the heated floor area, air leakage at 1.5 air changes per hour (ACH), and heat recovery temperature efficiency is 85%. In the PH scenario, outer walls have a U-value of 0.09 W/m^{2}K (approx. 500 mm insulation), the roof has 0.09 W/m^{2}K (approx. 450 mm insulation), the floor has 0.07 W/m^{2}K (450 mm EPS insulation) and windows and doors 0.7 W/m^{2}K. The normalised thermal bridge for the whole building is 0.03 W/m^{2}K, air leakage at 0.6 air changes per hour (ACH), and heat recovery temperature efficiency is 90%. Heating and hot water is supplied by district heating. There are 76.5 m^2 of photovoltaics producing around 10 kWh/m^2/yr, and the remaining energy demand is covered by grid electricity. These results are used to calculate GHG emissions from life cycle module "B6 – operational energy use" and the amount of exported energy in life cycle module "D – benefits and loads beyond the system boundary".

GHG emissions calculations are performed according to *NS 3720: 2018 Method for GHG emissions calculations in buildings* and the FutureBuilt ZERO (FBZ) method for all four scenarios [28,29].

FutureBuilt ZERO is based on NS 3720 but uses a dynamic LCA approach with time- and technology-weighting factors. The functional unit is 1 square meter of heated building over a 60-year reference study period. The system boundaries include life cycle modules A1-A3 production phase, A4-A5 construction phase, B1-B6 use phase, C1-C4 end-of-life phase, and D benefits and loads beyond the system boundary. Building parts are structured according to *NS 3451: 2022 Table of building elements* and include 21 groundworks and foundations, 22 load-bearing system, 23 outer walls, 24 inner walls, 25 slabs, 26 roofs, 28 stairs and balconies, and 47 local electricity production [30]. The material inventory is gathered from architectural drawings and has been quality assured by the property developer. GHG emission factors for materials are collected from environmental product declarations (EPDs) [31], and emission factors for electricity and district heating are 136 gCO_2e/kWh and 13 gCO_2e/kWh respectively. The emission factor for electricity considers exchange with the European consumption mix (EU28+NO), and the emission factor for district heating is calculated according to the local district heating company's energy mix of 99.6 % bioenergy wood chips and 0.4 % fossil oil [28,32]. Direct emissions from photovoltaics are set to zero, and the indirect emissions are accounted for in the building material inventory under "47 local electricity production". The export of PV energy uses the emission factor for electricity for compensation.

The cost assessment is carried out according to *NS 3453: 2013 Specification of costs in building projects* and *NS 3454: 2013 Life cycle costs for construction works – principles and classification*, and uses the same material inventory as the GHG emission calculations [33,34]. Only building materials that change between scenarios are included in the cost assessment (e.g., insulation, doors, and windows). Cost data is collected in 2022 from the Norwegian statistics office (SSB) for energy, the property developer, and the Norwegian price book [35–37]. The price for electricity is 1.88 kr/kWh, and the price for district heating is 0.92 kr/kWh. The property developer has agreed upon a sale price of 1.2 kr/kWh for surplus electricity from the photovoltaic system with the local energy company. Results are reported in Norwegian kroner (NOK), whereby 1 NOK corresponds to 0.09 Euro in December 2022 [38]. The cost assessment is limited to additional material investment costs for the property developer and operational energy costs for the homeowner. Costs exclude 25 % VAT. The analysis period is set to 60 years. These results are then used to calculate cost in NOK of GHG emissions saved.

4. Results

Operational energy use for the TEK scenario is 126 $kWh/m^2/yr$ for building A and 130 $kWh/m^2/yr$ for building B. Operational energy use in the PH scenario is 93 $kWh/m^2/yr$ for building A and 95 $kWh/m^2/yr$ for building B. Building B has slightly higher energy use than building A since it is an end-terrace. The PH scenario has 28 % lower energy use than the TEK scenario. Operational energy use emissions are 3.8 $kgCO_2e/m^2/yr$ in the TEK scenario and 3.2 $kgCO_2e/m^2/yr$ in the PH scenario. Electricity production from PV panels for building A is 9 713 kWh/yr and 11 817 kWh/yr for building B.

Figure 1 shows the GHG emissions results for the TEK and PH scenarios for building A and B with wood fibre and mineral wool insulation using the two methodologies NS 3720 and FBZ. The largest disparity in emissions arises from the type of calculation method used. The NS 3720 method shows 6.7 - 6.8 $kgCO_2e/m^2/yr$ in total GHG emissions in the TEK scenarios, and 6.8 - 7.2 $kgCO_2e/m^2/yr$ in the PH scenario. The FutureBuilt ZERO method shows 5.4 - 5.5 $kgCO_2e/m^2/yr$ in total GHG emissions in the TEK scenario, and 5.3 - 5.5 $kgCO_2e/m^2/yr$ in the PH scenario. The FutureBuilt ZERO method reports approximately 17 – 26 % less GHG emissions than the NS 3720 Norwegian standard. This is because FBZ uses discounting factors for technology and time weighting, and it allocates credits for biogenic carbon in B1. Embedded GHG emissions are lower in the TEK scenario than in the PH scenario. This is due to higher embodied GHG emissions from the increase in insulation thickness to reach PH energy requirements. The TEK scenario uses ca. three tonnes less material than the PH scenario.

Figure 2 shows the cost assessment results for the TEK and PH scenarios for buildings A and B for wood fibre insulation. The results show that the PH scenario breaks even with the TEK scenario after 9 years of operation for building A, and after 32 years of operation for building B. Building B has a longer payback time than building A since more electricity from PV is fed back to the grid. Hence, the difference in operational cost is smaller between the two energy standards leading to a longer payback time. The results also show that for both buildings A and B, the PH scenario has lower total costs over time than the TEK scenario.

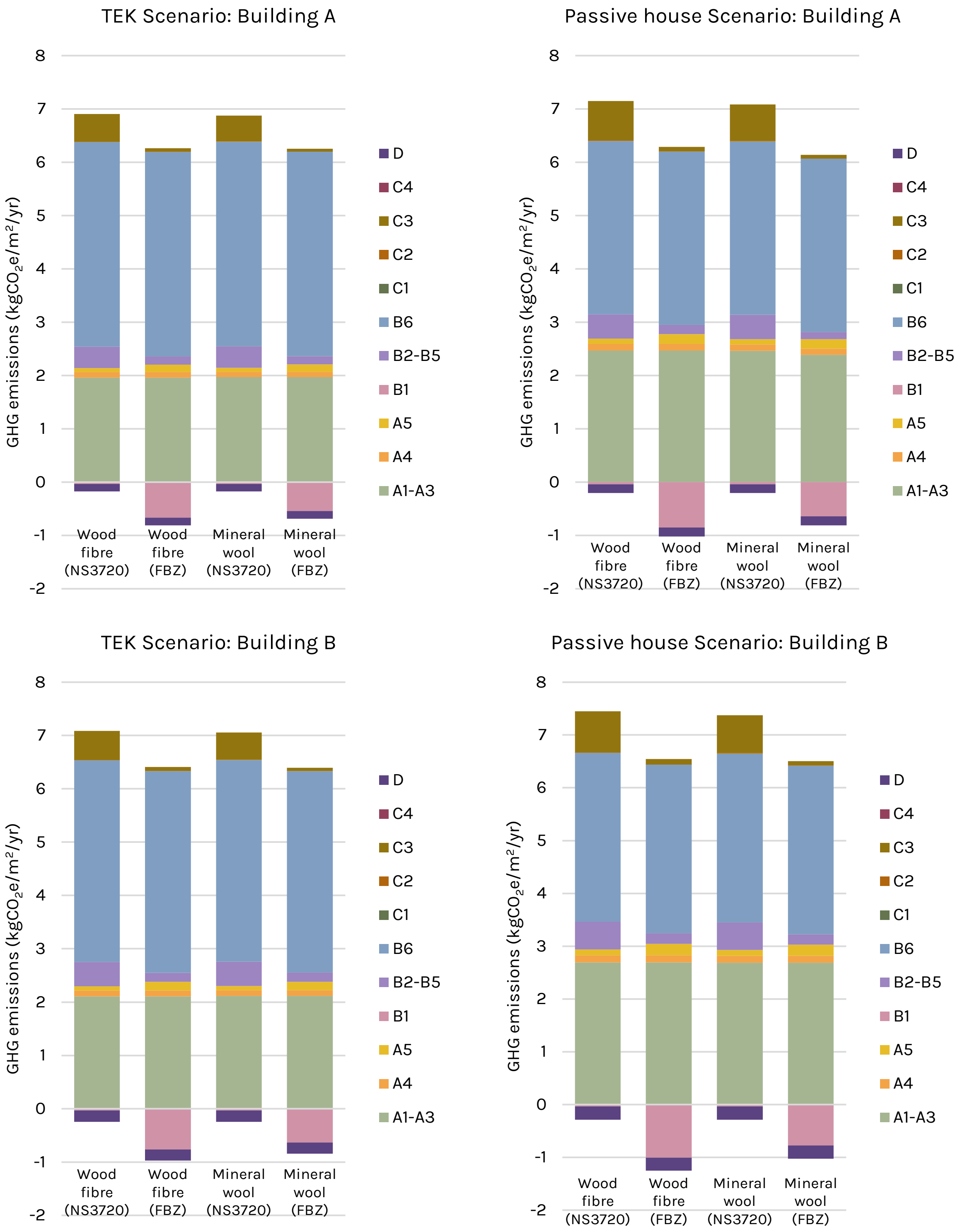

Figure 1. GHG emission results for the TEK and passive house (PH) scenarios, for buildings A and B, based on wood-fibre and mineral wool insulation and NS3720 and FutureBuilt ZERO (FBZ) methods.

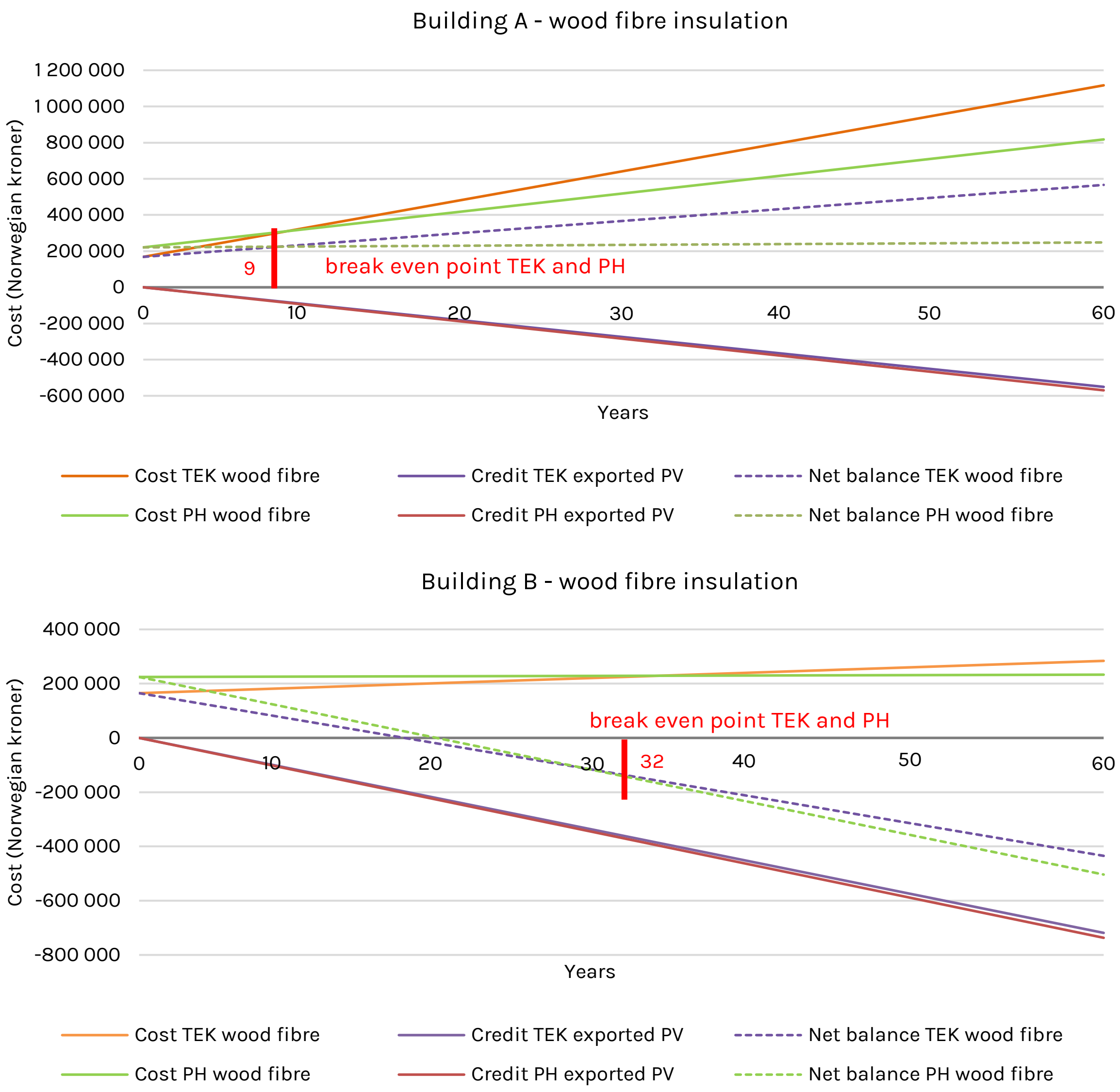

Figure 2. Cost assessment for the TEK and passive house (PH) scenarios for buildings A and B for wood fibre insulation.

Table 1 shows the cost of embedded GWP saved, cost of total GWP saved, embedded GWP payback time, and cost payback time (compared to a baseline scenario*)."MW" stands for mineral wool insulation and "wood" stands for wood fibre insulation. The results show only one scenario (FBZ TEK) for which investment in lower emission insulation (wood fibre) is required. Under NS 3720, the cheaper insulation (mineral wool) also has lower embedded emissions. However, increased capital investment in better insulation and windows in all PH scenarios pays off throughout the lifetime of the building and hence turns into a profit (negative costs) as well as lower lifetime emissions. Payback times for emissions (the year in which all additional embedded emissions are offset by emissions savings) vary from 14 to 19 years for the NS 3720 calculation method, and 3 to 10 years for the FBZ calculation method. Payback times for costs vary between 8 and 37 years.

Table 1. Cost of embedded GWP saved, cost of total GWP saved, embedded GWP payback time and cost payback time (compared to a baseline scenario*), whereby "MW" stands for mineral wool insulation and "wood" stands for wood fibre insulation

Method	**Building**	**Scenario**	**Cost of embedded GWP saved (kr/tCO$_2$e)**	**Cost of total GWP saved (kr/tCO$_2$e)**	**Embedded GWP payback time (years)**	**Cost payback time (years)**
NS 3720	A	**TEK MW**	*	*	*	*
		TEK wood	No savings	No savings	More emissions	More cost
		PH MW	No savings	- 46 019	14	8
		PH wood	No savings	- 46 789	18	10
	B	**TEK MW**	*	*	*	*
		TEK wood	No savings	No savings	More emissions	More cost
		PH MW	No savings	- 11 049	15	31
		PH wood	No savings	- 10 787	19	37
FBZ	A	**TEK MW**	*	*	*	*
		TEK wood	13 784	13 349	Less emissions	-
		PH MW	No savings	- 36 989	4	8
		PH wood	No savings	- 34 262	3	10
	B	**TEK MW**	*	*	*	*
		TEK wood	13 349	13 349	Less emissions	-
		PH MW	No savings	- 7 573	10	31
		PH wood	No savings	- 5 126	3	37

5. Discussion

One of the major challenges Ydalir faces is how to reduce GHG emissions from the neighbourhood towards a net zero emission building (nZEB). Additional challenges include retaining social, environmental, and economical sustainability for both the project developer and building owners and avoid suboptimal solutions.

The results show the importance of methodological choice, NS3720 versus FBZ, since the FBZ results have the lowest GHG emissions and the shortest GWP payback times. This is largely due to the time- and technology weighting factors used in FBZ.

One of the drawbacks of cost assessments is that they give only a snapshot of the costs at that point in time, whilst in reality prices are continuously fluctuating. Suggestions for further work involve carrying out a sensitivity analysis, and investigating the payback times when fluctuation in both energy and material prices is taken into consideration. Another scope for further work involves calculating the cost of GHG emissions saved for other energy and GHG emission reduction measures or strategies such as optimised floor plans, choosing locally sourced materials with long service lives, using reclaimed materials, or using alternative renewable energy production technologies such as heat pumps. Such assessments will give practitioners a better idea of the cost benefit of different GHG emission reduction strategies so that they can make more informed choices during the design phases of a building.

The simplified investigation on trade-offs between investment and emission savings shows that investments into operational energy savings pay off over time. This is true both for increased embedded emissions for a better energy standard, as well as increased capital investment for lower energy bills. However, payback times for increased costs and emissions differ between options. Increased amounts of energy fed back into the grid influence the length of pay-back time since exported energy is profitable for the building owner.

This paper is useful for Norwegian construction practitioners that wish to balance GHG emissions and costs between operational energy use and material use in buildings.

6. Conclusion

This article has compared the energy needs, GHG emissions, and cost of two residential buildings in terms of a range of parameters including energy standard (TEK or PH), type of insulation (mineral wool or wood fibre) and GHG emission calculation methodology (FutureBuilt Zero or NS 3720). This study shows lower total GHG emissions and lower GHG emissions from operational energy use in the PH scenario. It also shows an increase in GHG emissions from the production phase due to thicker levels of insulation in the PH scenario. The cost assessment shows increased investment costs for the project developer in the PH scenario, despite lower operational costs for the building owner. A key take-home message for practitioners is that it is important to holistically assess the whole life cycle of a building's environmental and economic profile in order to identify the best options in terms of GHG emission reductions and cost. For building A and B, the optimal solution is the PH mineral wool scenario using the FBZ method. This paper is useful for practitioners that wish to balance GHG emission reduction requirements between operational energy use, material use and affordability. Further research may include experimenting with other design choices such as optimised floor plans, choosing locally sourced materials, service lifetimes of materials, using reclaimed materials, or using alternative renewable energy production technologies such as heat pumps. Other parameters that may be investigated include sensitivity analysis of GHG emission factors or energy costs. The lessons learnt from this study may also be applicable to other countries and the comparison can be adapted to other national building codes.

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