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Optimization of thermal insulation thickness pertaining to embodied and operational GHG emissions in cold climates – Future and present cases

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ABSTRACT

Determining the optimal insulation thickness is useful for designing zero-emission buildings (ZEB) to minimize the environmental impacts. The energy required to heat buildings in cold climates is relatively high. Substantial reductions in the total energy usage of a building can be achieved by reducing the U-value of the external surfaces. Increasing the insulation thickness reduces the operational CO_2 emissions, although simultaneously increases the embodied CO_2 emissions from materials. To mitigate climate change, Norway and Denmark are trending towards stricter regulations to limit energy use in buildings. However, these countries have no current regulations in the building codes for limit embodied CO_2 emissions from materials. This study analyzes the influence of the energy emission factor and future climate change (scenarios?) on the optimal insulation thickness. We used three independent models for case studies in Greenland and Norway. The differences between the case studies highlight the influence of model parameter choices, such as indoor climate, energy emission factor and material emissions, whereas the similarities may be used to analyze the problem from a broader perspective. The results show that optimal insulation thickness calculations are most valuable for case studies in which the energy emission factor is low. Considering energy emission factors above 25–30 g CO_2eq/kWh, operational emissions dominated the calculation results in all case studies.

1. Introduction

Globally, buildings are responsible for 40% of the total energy consumption and 25% of the greenhouse gas (GHG) emissions [1]. In Norway, one-third of the consumed energy is used for direct heating of buildings [2]. In cold climates, sufficient thermal insulation of buildings to reduce heat loss is important and this is reflected in both Norwegian and Danish building codes. Regulations for the energy performance of buildings have been tightened over the past decades in both Norway and Denmark [3]; Bygningsreglementet 2018), thereby reducing GHG emissions from buildings. Although the Greenlandic building codes have yet to be updated based on the Danish building codes of 2018. However, the environmental impacts of the materials used to insulate buildings have not yet been considered in the building codes. As the insulation layers become thicker, the embodied emissions increase, and operational emissions decrease. Earlier studies have found that the influence of operational emissions in buildings tend to outweigh the influence of embodied emissions in the Norwegian climate [4]. However, the results are sensitive to the energy emission factor of the heating source used to calculate operational emissions. The energy emission factor describes the GHG emissions resulting from power production to heat the building.

The past decade has yielded significant research findings relating to how future climate changes will impact energy use in buildings [5], and significant efforts have been made to reduce global emission rates. For example, the ongoing decarbonization of the European power sector has the ambitious aim of reducing GHG emissions by 90% between 2010 and 2050 [6], which will lower the energy emissions significantly. Temperature measurements of the climate in Norway conducted by the Norwegian Meteorological Institute (MET) since 1900 indicate a steady increase in average temperature starting from 1985 [7]. This trend is expected to continue, with the rate of increase dependent on future global emission rates [8]; 2022).

Most research concerning optimization of thermal insulation relates

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the issue to warmer climates, predominantly emphasizing energy use for cooling or moderate heating [9]. The building practice in warm regions (i.e. Turkey and Morocco) has traditionally neglected the need for thermal insulation, thus motivating research for lowering either cost or GHG-emissions through optimal insulation strategies [10–13]. These studies conclude that optimal insulation thicknesses are in the range of 5–20 cm, depending on the insulation material, climate and energy emission factors used [9].

It is becoming more important to address the issue in cold-climates as well, as changes in the climate are expected to occur more rapidly in arctic regions, compared to most other places on Earth [14]. Few studies have considered the consequences for the built environment in cold regions, or subsequently formulated appropriate adaptation measures [5]. High energy demands for heating and high energy emission factors in these regions, has led to an approach of "the more the better" within the practical range of insulation thicknesses [4]. This conclusion may change as the energy emission factors are likely to decrease in the future, due to the focus on green energy production in Europe [6].

This study analyzed how energy emission factors and future temperature changes affect the optimal strategies for limiting emissions from buildings in cold climates by examining three different models, each calculating four cases with varying climates and energy emission factors. The climates considered by the models were classified according to the Köppen climate classification [15] as subarctic continental (group Dfc) and arctic (group E). Subarctic continental climates are characterized by the coldest month averaging below 0 °C and 1–3 months averaging above 10 °C, whereas arctic climates are characterized by no month averaging above 10 °C. In addition to considering the Norwegian climate, this study also includes case studies of the Greenland climate. Greenland, being an island-based community, have challenges regarding centralized infrastructure. This leads to unique combinations of energy sources in each location, thus affecting the energy emission factors.

Future climate change and energy emission factors are highly complex subjects, as both depend on global socioeconomic developments, introducing high levels of uncertainty into the models. Due to the complexity, this study analyzed the problem using three independently constructed models for calculating the optimal insulation thicknesses. Models 1 and 2 were simplified to consider an insulated outer wall segment of 1 m^2. Thus, some of the complexities introduced by using a full-scale building model are omitted. Model 3 considers a full-scale building to verify the results from the first two models. The purpose of this study is to see how changes in climate and energy emission parameters influence the total emissions from energy and material use. The research questions explored are as follows.

1. How will future climate changes influence the optimal thermal insulation thickness in cold climates?
2. How will future changes in the energy emission factors used for heating influence the optimal insulation thickness?

A theoretical framework focused on climate modeling, energy performance, energy emission factors, and Life-Cycle Analysis (LCA) of building materials is presented in section 2. Three models were established for calculating operational and embodied emissions. The results of each model are presented in section 4, along with a sensitivity analysis that identifies the robustness of each method. A discussion of the impacts is presented in section 5. None of the models address the second-order benefits or disadvantages of a given insulation thickness (e.g., construction practicality, indoor comfort levels, or changes in floor area), as they are strictly focused on the emission intensities of different insulation thicknesses. Further, the models use input for material emissions using standard LCA methodology, documented through European Product Declarations (EPD). The impact of more holistic methods for determining the carbon footprints of materials emerging, such as the PEF method (EU 2013), are outside the scope of this paper. Because the models rely on pre-documented EPDs for determining the material emissions, the embodied emissions in materials are unchanged in the future scenarios considered.

2. Theoretical framework

2.1. Future climate scenarios

The climate is changing rapidly because of the increased concentration of GHGs in the atmosphere (IPCC 2022). This has consequences for the built environment and how buildings are designed [16]. An increase in GHGs in the atmosphere captures more thermal radiation, causing the global average temperature to rise. In the fifth assessment report from the International Panel on Climate Change (IPCC), different scenarios based on projections of emission rates were categorized by Representative Concentration Pathways (RCPs), which describe radiative forcing from GHG concentrations in the atmosphere. As defined in the IPCC report, the four RCPs used for climate modeling are RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5. The IPCC released a new assessment report in 2021/2022 with updated scenarios. As the case studies described in this study were conducted before the release of the sixth assessment report, future climate scenarios were used as outlined in the fifth assessment report.

The RCP 8.5 scenario, described as "business as usual" in the IPCC report and assuming negligible intervention to curtail GHG emissions, could lead to a global increase in average temperature of 2.6–4.8 °C by 2100. The emission curve in RCP 8.5 closely agrees with the historical total cumulative CO_2 emissions from 2005 to 2020 (within 1%), and is often used for near-to-mid-term assessments [17]. However, the RCP 8.5 scenario is not in agreement with the sub 2 °C goal outlined in the Paris Agreement [18]. Comparing the RCP 8.5 scenario with historical conditions is useful because these two scenarios may represent the outer boundaries of the optimal insulation strategy.

2.2. Energy performance

The U-value describes the amount of heat transported through the construction per unit area and per unit temperature difference and is defined in Equation (1).

$$U = \left(\sum_{0}^{i=n} R_i \right)^{-1} \quad \left[\mathrm{W} / \left(\mathrm{m}^2 \mathrm{K} \right) \right] \tag{1}$$

where R_i is the heat resistance of layer i (m^2K/W). The U-value does not decrease linearly with increasing insulation thickness because it is inversely related to the heat resistance, as illustrated in Fig. 1. Thus, increasing the insulation thickness to reduce operational emissions yields diminishing returns.

Neglecting solar irradiation and heating from internal loads, such as lighting and equipment, the conductive heat loss through a 1 m^2 outer wall can be balanced by considering the outdoor temperature at which occupants specifically use energy for heating the building [19]. proposed the use of $T_{out,\ crit} = 10$ °C because internal heating loads generated by occupants, hot water use, lighting, and equipment tend to match the heating demand above this temperature. Earlier studies have found that the variability of average indoor temperature for single-family homes was dominated by occupant behavior including comfort level, energy-saving behavior, and use of equipment [20,21]. The average indoor temperature measured by Ref. [20] was found to have a normal distribution with an average of 21.5 °C and a standard deviation of 1.3 °C.

2.3. Energy emission factor

To compare the embodied carbon emissions from the production of materials to the operational emissions from heating, the two categories

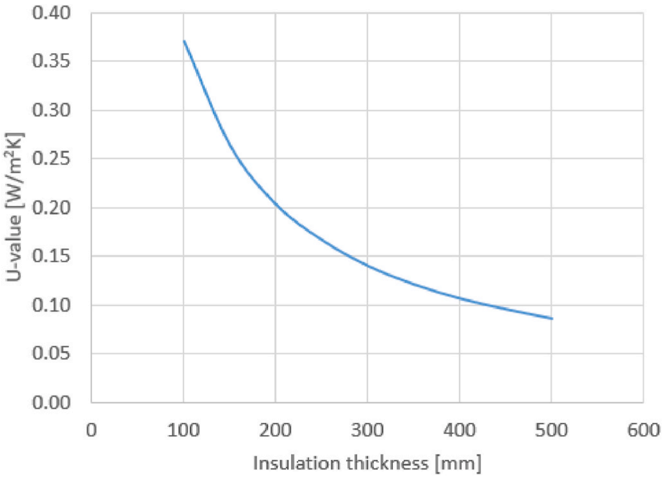


Fig. 1. U-value as a function of insulation thickness for a typical Norwegian wooden framework wall with ventilated outer cladding(36 mm thick wooden studs c/c 600 mm, wooden frame estimated to be 13% of total wall area, and. The insulation material heat conductivity is 0.034 W/(mK)).

must be converted into comparable functional units, i.e., the carbon footprint per functional unit. Emissions from energy use is described by the energy emission factor in units of gCO_2eq/kWh [22]. The Norwegian Standard NS 3720:2018 [23], which describes methods for GHG emission calculations for building designs, allows the use of two different scenarios related to the system boundaries. Firstly, the average emission rate from the Norwegian energy consumption mix over the last three years and secondly, the average emission rate from the European energy consumption mix over the last three years. Examining Norway in a closed system using the Norwegian energy mix is logical, e.g., Scenario 1; however, the global energy grid is interconnected between countries, and consuming an additional 1 kWh of electric energy in Norway may lead to either increased imports or decreased exports of 1 kWh of energy, both of which create a need to generate an additional 1 kWh outside of Norway. This is not the case in Greenland, as there are no imports or exports of energy. As there is no central grid connecting different cities in Greenland, each location is an isolated case with a clearly defined energy mix, giving high confidence to energy emission factor estimations. The various sources of energy used for heating buildings in different locations in Greenland include district heating from combustible sources, hydropower, and direct local heating from oil and gas [24].

The Norwegian energy mix is 95% hydropower [25] which is a very low-carbon intensity power source even by renewable energy standards [26]. The average emission factor for the Norwegian energy mix for the period 2015–2075 was set to 18 gCO_2/kWh in NS 3720:2018. The average European energy factor for the same period was set to 136 gCO_2/kWh, with 43% generated from combustible sources in 2015 [23]. The two major sources of hydropower emissions are activities related to the construction of dams and power stations, as well as methane emissions from the anaerobic decomposition of flooded organic matter. A meta-analysis by Ref. [26] comparing 12 studies on emission factors from hydropower reported calculated emission factors of 2–20 gCO_2/kWh. In comparison, the same study reported calculated emission factors for oil and natural gas in the range of 380–1000 gCO_2/kWh, and coal emission factors up to 1300 gCO_2/kWh [26]. A careful consideration of the energy mix used in the calculations is important as it affects calculated energy emission factors which are crucial in operational emission calculations.

Using a future scenario for the development of renewable energy sources in Europe, a Norwegian Research Center on Zero Emission Buildings (FME ZEB) proposed calculating emission factors by assuming a 90% reduction in GHG emissions in the power sector in 2050 compared to 2010, as per the European Union's (EU's) Roadmap Towards 2050 [6,27]. By first determining the service life of buildings in the LCA calculations, the average emission factor over the building lifetime can be calculated and used as a design value, as illustrated in Fig. 2.

The FME ZEB method considered an average European energy mix, which is substantially more carbon intensive than the Norwegian energy mix, and thus yields a higher emission rate per kWh. A study on energy emission factors proposed an energy emission factor of 132 g/kWh based on results from the FME ZEB [28]. However, this number is continuously changing as this method is based on the energy emission factor throughout the lifetime of a building. Assuming a building lifetime of 60 years, Fig. 2 shows the development of the design energy emission factor recommended by the FME ZEB depending on the year of construction. The energy emission factor for the year 2010 were estimated by the FME ZEBto be 361 gCO_2/kWh, with a linear decline towards 31 gCO_2/kWh in 2050 and reaching 0 by extrapolation in 2054 [27]. Therefore, this model is unrealistic for long-term energy emission factor estimations such as the future scenarios considered in this study (2071–2100).

In cooperation with Statistics Norway (SSB), the Norwegian Water Resources and Energy Directorate (NVE) calculated the emission factor to be 17 g CO_2eq/kWh for actual delivered electrical energy in Norway in 2019, based on hourly measurements of net import/export and energy consumption [29].

The NVE calculations only consider the direct emissions from the energy carrier used to generate energy and disregards the emissions from infrastructure (i.e., creating power plants and maintaining the power grid) and energy carrier harvest (i.e., procuring fossil and nuclear fuels). As import/export has a significant impact on the Norwegian energy mix, the energy emission factor for energy design in Norway must be carefully considered. An overview of the energy emission factors based on the sources discussed in this study is presented in Table 1.

3. Methods

3.1. Introduction to the case methodology

The estimated service life (ESL) was set to 60 years for all cases in accordance with the FME ZEB guidelines for life cycle assessments [30] assuming no need for maintenance or material exchange. When changing the insulation thickness in the models. Secondary effects, such as decreased floor area, are not considered. The analysis was performed using glass wool as a thermal insulation material. The global warming potential (GWP) for the insulation products considered in each model is presented in Table 2, along with the pertinent details required for the energy emission calculations. In all building models, the GWP included the production process from cradle-to-gate (A1-A3), transportation to the building site (A4), and transportation and the process of waste handling (C2–C3).

The geographical positions of the four locations studied in the three models are shown in Fig. 3. For each model, four calculation cases have been assessed, designated A-D. Cases designated A and B are calculated with the relevant low-end energy emission factor alternative for the location, with historic and future climate respectively. Cases C and D are equal to A and B in every respect, only calculated with the relevant high-end energy emission factor.

The total emissions over the service life time as a function of insulation thickness, $M_{tot}(t)$, are calculated for all models according to the definition given in Equation (2).

$$M_{tot}(t) = \sum_{60\ yr}\left(f_e \bullet E_{heat}(t)\right) + M_{mat}(t) \tag{2}$$

, where f_e is the energy emission factor, $E_{heat}(t)$ is the yearly energy use for heating as a function of insulation thickness and $M_{mat}(t)$ is the ma-

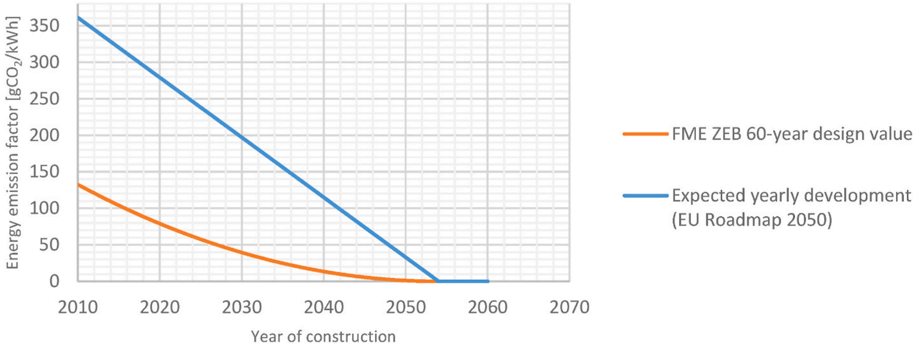


Fig. 2. Development of design energy emission factor for grid electricity [27], based on the development of energy emissions in the European energy market.

Table 1
Energy emission factors reported by the sources discussed in this chapter.

Source	Energy grid	Recommended energy emission factor [gCO$_2$/kWh]	Description
Norwegian Standard (NS3720:2018) [23]	Norway	18	Estimated average Norwegian energy mix in building lifetime (2015–2075)
Norwegian Standard (NS3720:2018) [23]	Norway	136	Estimated average European energy mix in building lifetime (2015–2075)
FME ZEB [28]	Norway	132	Estimated average European energy mix based on future development of renewable energies from 2010 to 2050 (reported in an article from 2014, based on construction year 2010)
FME ZEB [28]	Norway	74	Updated estimated average European energy mix based on the future development of renewable energies from 2010 to 2050 (calculated for construction year 2021)
Norwegian Water Resources and Energy Directorate [29]	Norway	17	Calculated actual average energy emission factor for delivered energy in Norway in 2019, including only direct emissions from energy carriers
Departement for Landbrug, Selvforsyning, Energi og Miljø [24]	Greenland	9	Electrical heating from 100% hydropower (location: Nuuk)
Departement for Landbrug, Selvforsyning, Energi og Miljø [24]	Greenland	207	Electrical heating from combustible energy sources (location: Aasiaat)

terial emissions as a function of insulation thickness.

3.2. *Case 1: subarctic continental climate (unit-level model, Norway)*

The first case study of a typical single-family home in the district of Ydalir, Elverum, Norway. Ydalir has been used as a pilot project in the FME ZEB research center, which emphasizes studying collective emissions for a neighborhood, both embodied and operational. Approximately 1000 residential living units with passive-house standards or higher will be developed in the district over the next 15–20 years [32].

The model for calculating operational and embodied emissions was restricted to 1 m^2 of a representative outer wall with insulation thicknesses of 100–500 mm. Based on historical conditions and a future climate scenario (RCP 8.5), the energy performance and resulting emissions were calculated for the case study.

The U-value is calculated based on a typical Norwegian wooden framework wall. The wall is composed of glass wool insulation with heat conductivity equal to 0.034 W/(mK) placed in a wooden framework with an inner cladding of 12.5 mm gypsum board, and ventilated wooden outer cladding with a 9 mm gypsum board wind barrier. Assuming a stud width of 36 mm and c/c 600 mm studding in a single-family home with a ceiling height of 2.4 m the wood-to-insulation ratio per area is 13%, in accordance with the tables provided by SINTEF in Byggforskserien 471.401 [33].

The model compares operational emissions in two different climates: one based on historical weather data and the other based on a future climate scenario. MET has weather stations throughout the country that continually register weather data. Weather data from Rena, 35 km north of Elverum, were used to create weather files with hourly temperature data. The basis for the historical reference year is temperature measurements in the period 1961–1990, and the future scenario (2071–2100) is a downscaling of a regional climate model based on the RCP 8.5.

Weather files were generated by MET and median, maximum, and minimum temperatures, as well as standard deviations for each month were recorded for each period. A 366-day year series, with maximum and minimum temperature values, was generated by random drawing with a normal distribution over each month as a constraint. Three repetitive years were generated, and the hourly values generated by spline interpolation before the first and last years were removed to eliminate noise from the series. Energy calculations for ten runs of both historical and future scenarios were performed, and the results are shown as the average of the ten runs.

The heating strategy assumed in Model 1 was based on the critical outdoor temperature. The critical outdoor temperature, below which energy is used specifically for heating, is set to 10 $^\circ$C in accordance with the recommendations of [19]. The indoor temperature was set to 21 $^\circ$C in close agreement with the average measured indoor dwelling temperature in a comprehensive survey by Refs. [19,20]. The yearly energy use for heating, $E_{heat}(t)$, in Model 1 is calculated according to Equation (3).

$$E_{heat}(t) = U(t) \bullet \sum_{n=1}^{8760}((T_{in} - T_{out}(n)) \bullet 1hr \Bigg) \tag{3}$$

Table 2
Parameters and ID of each model.

Case	Model type[a]	ID	Location	Climate	Indoor temp [C°]	Average HDD[b] [(K • d)/a]	Energy emission factor [kg CO_2eq/kWh]	Insulation material GWP [kg CO_2eq/(m^{2}K/W)m^2]
Model 1	Local	1.A	Elverum (NO)	1961–1990	21.5	6637	0.017	0.8
		1.B	Elverum (NO)	2071-2100 (RCP 8.5)	21.5	4995	0.017	0.8
		1.C	Elverum (NO)	1961–1990	21.5	6637	0.132	0.8
		1.D	Elverum (NO)	2071-2100 (RCP 8.5)	21.5	4995	0.132	0.8
Model2	Local	2.A	Nuuk (GL)	1996–2000	19	7200	0.009	1.0
		2.B	Nuuk (GL)	2021–2040 (RCP 8.5)	19	6950	0.009	1.0
		2.C	Aasiaat (GL)	1996–2000	19	8150	0.207	1.0
		2.D	Aasiaat (GL)	2021–2040 (RCP 8.5)	19	7900	0.207	1.0
Model 3	BES	3.A	Oslo (NO)	1961–1990	19	4088	0.017	0.5
		3.B	Oslo (NO)	2071-2100 (RCP 8.5)	19	3016	0.017	0.5
		3.C	Oslo (NO)	1961–1990	19	4088	0.132	0.5
		3.D	Oslo (NO)	2071-2100 (RCP 8.5)	19	3016	0.132	0.5

[a] Local model: values calculated for 1 m^2 wall, BES model: values calculated on a building level.

[b] HDD = Heating Degree Days. The HDD for Models 1 and 3 are calculated for comparison purposes only, as neither model uses HDD as an explicit input value.

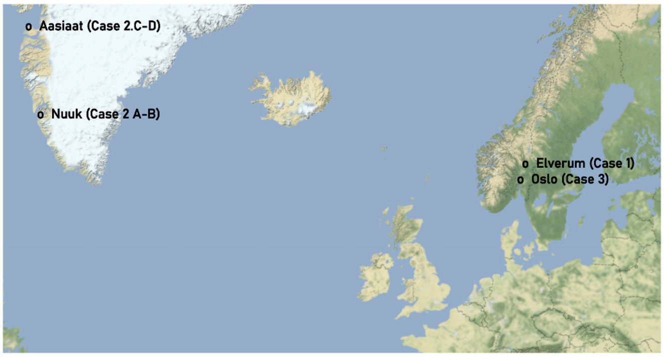


Fig. 3. Geographical locations included in the study [31].

, where $U(t)$ is the U-value of the wall with insulation thickness t in W/(m^{2}K), T_{in} is the indoor temperature (21 °C) and $T_{out}(n)$ is the outdoor temperature in hour n. All hourly values where $T_{out} > 10^\circ C$ were omitted.

The resulting operational emissions were calculated according to Equation (2) using energy emission factors of 17 gCO_2eq/kWh for the measured Norwegian energy consumption mix in 2019 [29] and 132 gCO_2eq/kWh for the European mix for construction year 2010 according to the method proposed by the research center FME ZEB [27].

Based on the environmental impacts of glass wool insulation reported in the European Product Declarations (EPD) review by Ref. [34] and a control comparison against 5 EPDs found in the database provided by EPD Norway, the median value is used (0.8 kg CO_2eq/(m^{2}K/W)m^2). For wood materials, the average environmental impact from the four studied EPDs found in the EPD-Norway database (EPD-Norway 2022) was used (106 kg CO_{2eq}/m^3). As proposed by NS 3720:2018, the biogenic carbon storage of wood was set to zero [23]. The calculations included emissions from the production, transport, construction, maintenance, and demolition stages. Benefits beyond the system boundaries, such as the reusing of materials, were not considered. Furthermore, changes in future energy emission factors were not considered in the calculation of material emissions.

3.3. *Case 2: arctic climates (Greenland, unit-level model)*

The model for the Greenland case is based on the insulation thickness optimizer tool ITO, which was described and analyzed in an earlier study [35]. Considering the optimal insulation thickness in Greenland, the conditions varied for each town. The model for calculating operational and embodied emissions was restricted to a 1 m^2 wall. The wall consisted of 150 mm of concrete, insulation, a ventilated air cavity, and cladding. Construction represents a typical wall for residential buildings in Greenland. Without insulation, the wall exhibited an R-value of 0.331 m^{2}K/W.

The calculations for ITO were based on heating degree days (HDD). The HDD for the historical climate dataset is based on five-year-average data from 1996 to 2000, provided by the Danish public institution Statistikbanken (2022). According to Ref. [36]; following the RCP 8.5 pathway is equal to a future change in HDD of −400 K°d over the next 40 years in Greenland, leading to an average temperature decrease of 10 HDD/year. The tool distributes the temperature change evenly over the ESL of the building, which is a simplification as research shows that changes occur more rapidly over time.

The analysis was conducted at two locations, Nuuk and Aasiaat. Nuuk is the largest city in Greenland, with approximately 19,000 inhabitants, and has a very low emission factor of only 9 g/kWh owing to the availability of local hydropower [24]. Additionally, Nuuk is located south of the polar circle, making the climate less extreme than that in many other parts of Greenland. There is no central electrical grid in Greenland between different urban areas, making the energy emission factors of the different areas independent. Aasiaat is a much smaller town with approximately 3000 inhabitants, and the emission factor of heating energy was calculated to be 207 g/kWh, as the energy mix in Aasiaat is based on combustible energy sources [24]. Aasiaat is located north of the polar circle, thereby causing a higher heating demand (see Table 2).

The analysis was based on the EPD from the LCAbyg database (LCAbyg 2022). The EPD for glass wool is suitable for façade construction (Ökobaudat 2022) and is given as 1.0 kg CO_2eq/(m^{2}K/W)m^2. The density was 46.25 kg/m^3 and the lambda value was 0.034 W/(mK). The EPD contributes to stages, A1-3, C3, and C4, while transportation is based on distances from the production country to the respective location of the building.

3.4. *Case 3: subarctic continental climate (Norway, global model)*

The boundary of the model in Case 3 is expanded to encompass the entire building, using a building energy simulation model (BES). For Cases 1 and 2, the model calculates changes in operational and embodied emissions as a function of the thermal insulation thickness of the wall but is summed up at the building level. As Case 3 is a full-scale model of a building, the energy calculations consider excess heat from electrical equipment and heat loss through ventilation when calculating the energy demand for heating, and is therefore valuable as a validation for the necessary assumptions of heating strategies in the unit-level models for Cases 1 and 2. To ensure that the embodied emissions of materials outside the wall boundaries are fixed for varying wall thicknesses, the model assumes that the outer dimensions of the building are fixed rather than the inner floor area.

The building in the model is a prefabricated detached single-family house designed by Norgeshus, called Trend 2 (see Fig. 4), which is representative of a typical Norwegian single-family dwelling and satisfies the Norwegian Building Code. The full set of schematics, including a full list of materials and quantities, were made available to the authors by the contractor. The total heated floor area is 129.4 m^2 over two stories. For a full set of details on the building in this case study, see Totland [4] and Andenæs, Kvande, and Bohne [37]. To calculate the energy demand, SIMIEN, which is a commercial Norwegian simulation program for calculating energy consumption and power requirements in buildings, was used. SIMIEN simulates energy need based on the Norwegian Standard NS 3130: Calculation of energy performance of buildings (Standard-Norge 2014). Standard input values from NS 3130 were used in all instances except where data specific to Trend 2 was obtained. The central parameters of the BES are listed in Table 3.

The embodied emissions from the materials used were calculated using OneClick-LCA software, and the standard values of environmental impacts proposed by the program were used for all materials except thermal insulation. The materials in the considered wall includes ventilated outer wooden cladding, wooden fiber wind barrier, thermal insulation in a wooden framework, PE vapor barrier and wooden fiber inner cladding. The environmental impact of the thermal insulation is chosen based on an EPD of a specific type of Norwegian-produced soft glass wool, Glava Proff 34, with a lambda value of 0.034 W/(mK, and an environmental impact calculated to 0.5 kg CO_2eq/(m^{2}K/W)m^2 (EPD-Norway 2022).

Operational emissions for two climate scenarios were compared: one based on 30-year average historical measurements (normal period 1961–1990) and the other based on future climate projections using RCP 8.5. Climate data was provided by the MET using the same methods as in Case 1 to generate the weather data. The chosen geographical location for Case 3 was Oslo, Norway, which has a normal inland Norwegian climate.

Fig. 4. Architectural rendition of the prefabricated detached single-family house used for the energy calculations in Case 3 (Illustration used with permission by Norgeshus).

Table 3
Central parameters of the building energy simulation model used in Case 3.

Parameter	Value
U-value external wall	0,086–0371 W/(m^{2}K)
U-value ground floor	0,09 W/(m^{2}K)
U-value roof	0,14 W/(m^{2}K)
U-value windows	0,81 W/(m^{2}K)
Airtightness, n50	0,9 h^{-1}
Normalized thermal bridge value	0,05 W/(m^{2}K)
Normalized internal heat capacity	51 Wh/(m^{2}K)
Set-point temperature, heating	19 °C
Ventilation heat recovery efficiency	85%
Specific fan power, SFP	1,10 kw/(m^3/s)
Ventilation	1,20 m^3/(m^{2}h)
Excess heat from lighting, equipment, occupants	5,25 W/m^2
Solar factor, windows, SF	0,33
Installed effect, heating	80 W/m^2
Operational schedule, ventilation	24 h
Operational schedule, heating	16 h

4. Results

This section presents the results from the three cases as well as a sensitivity analysis for unit-level Models 1 and 2. A sensitivity analysis was performed by changing the input parameters to ±10% and evaluating the changes in the model outputs.

4.1. *Case 1: subarctic continental climate (Norway, unit-level model)*

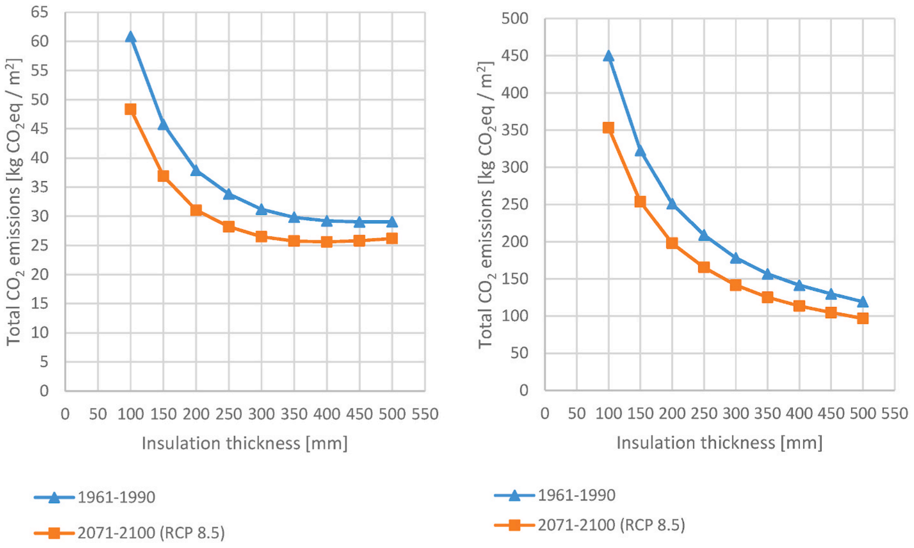
4.1.1. *Model results*

The energy performance calculations estimated a 22% reduction in the energy needed for heating in the RCP 8.5 future scenario (2071–2100) compared to the historical scenario (1961–1990). Operational emissions from the heat loss through a 1 m^2 wall were calculated based on the emission factors for the Norwegian energy mix in isolation in 2017 (17 g CO_2eq/kwh) and the energy mix for the interconnected power grid with import/export to Europe, proposed by the FME ZEB in 2010 (132 g CO_2eq/kwh). The embodied emissions for each insulation thickness and the corresponding operational emissions were added and presented as a function of insulation thickness. The results for Case 1.A – 1.D, are shown in Fig. 5.

According to this model, the optimal insulation thickness for the RCP 8.5 future scenario was reduced by 75 mm compared to the historical scenario (from approximately 475 mm to approximately 400 mm), assuming an energy emission factor of 17 g CO_2eq/kWh. As the chosen insulation thickness approached the optimum value, the impact of the change on total emissions was reduced. Increasing or reducing the insulation thickness by 100 mm from the optimum value resulted in a 3.5% increase in the total CO_2 emissions. The total emissions were more sensitive to changes in insulation thickness on the left side of the optimum, owing to the nonlinear nature of the U-value as a function of insulation thickness, as illustrated in Fig. 1.

4.1.2. *Sensitivity analysis*

To determine how the changes in each parameter influenced the model results, a sensitivity analysis was performed. The analyzed parameters were the insulation lambda-value, HDD, energy emissions, and material emissions, as these were the most critical parameters. The HDD expresses the difference between the outdoor and indoor climates used in the model, which was separated into two different input parameters in



a) Emission factor = 17 g CO_2eq/kWh (Case 1.A and 1.B) b) Emission factor = 132 g CO_2eq/kWh (Case 1.C and 1.D)

Fig. 5. Comparison of calculated future and historical CO_2 emissions for Case 1, using 17 g CO_2eq/kWh (a) and 132 g CO_2eq/kWh (b) as energy emission factors. Note the different scales on the y-axes.

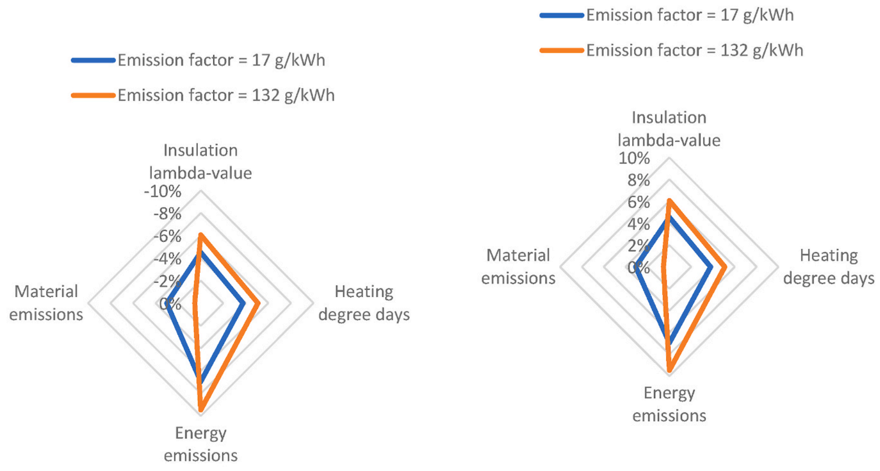
the model of Case 1. Hence, the HDD is calculated for the sensitivity analysis only. This was a critical parameter because of the uncertainty in future climate change and occupant behavior. Energy emissions also had high uncertainty, owing to both future developments in energy generation and the calculation of the energy emission factor. The latter was especially true in the Norwegian context because the locally produced energy mix had a significantly lower emission factor than the interconnected energy mix of Europe. The results of the sensitivity analysis are shown in Fig. 6.

The parameter with the highest influence on the model in each of the four cases was the energy emissions. This was also the parameter with the highest variability, as the energy emissions for different cases could vary by a factor of 10, based on the building source of heating energy. The high impact of this parameter was also expressed by the effect of material emissions on the results for different energy emission factors. For an energy emission factor of 17 g CO_2/kWh, a 10% change in material emissions yielded a 3% change in model outputs (total emissions), whereas for an energy emission factor of 132 g CO_2/kWh, the same change in material emissions yielded almost no change. This was because the absolute material emissions were much lower than the absolute operational emissions for the high-energy emission factors. A 10% reduction in parameter values yielded approximately the same result as a 10% increase because the parameters were either linearly connected to the model result or approximately.

4.2. *Case 2: arctic climates (Greenland, unit-level model)*

4.2.1. *Model results*

The future and historic climates in Case 2 were closer to each other than for Cases 1 and 3, as the historical climate was based on measurements from 1981 to 2000, and the future climate was based on a climate model for 2021–2040. The chosen climate scenario had a very low influence on the model results compared to the Norwegian cases where the climates are 110 years apart. However, the energy emission factor was more pronounced in the Greenlandic cases, as the energy emission factor for Nuuk was based on 100% locally produced



a) 10% reduction of parameter value b) 10% increase of parameter value

Fig. 6. Sensitivity analysis for the model used in Case 1, using wall insulation thickness d = 300 mm. Each parameter is changed by 10% with all other parameters fixed, and the change in model outputs is expressed as a percentage of change from the base case.

hydropower, and the energy emission factor for Aasiaat was based on district heating from combustible energy sources. The results of the Greenland model are shown in Fig. 7.

Climate change factors caused larger absolute changes in Aasiaat than in Nuuk; however, the percentage of change was the opposite. The low-emitting energy mix in Nuuk made the impact of reduced HDD very small, and the nearness in the two climate cases (1996–2000 and 2021–2040) resulted in climate parameters having a very low impact on the overall results. The optimal insulation thickness for Nuuk was 250 mm, whereas that of Aasiaat was outside the calculated area. This illustrated the high impact of energy emission factors on such calculations and underlines the importance of carefully considering this parameter.

4.2.2. *Sensitivity analysis*

The sensitivity analysis in Fig. 8 shows that the model for Aasiaat was more sensitive to positive changes than to negative changes. In both diagrams, the model for Aasiaat had low sensitivity to changes in emissions related to the production of insulation material. For Nuuk, the model showed approximately equal sensitivity to all parameters, although it was slightly more sensitive to negative changes than to positive changes, which is the opposite of Aasiaat.

Owing to the equation for calculating the heat loss through construction, a sensitivity analysis for the estimated service life was equivalent to the analysis of the HDD. Multiplying the HDD with a given factor yielded the same result in the model output as multiplying the estimated service life with the same factor. Therefore, the sensitivity analysis of the estimated service life was omitted.

An identical analysis was conducted for 30% changes, which led to similar trends but with greater sensitivity. This analysis was performed for an insulation layer of 300 mm which is beyond the optimal insulation thickness for Nuuk and may be responsible for its generally low sensitivity. The Nuuk case study is more sensitive to changes in the energy emission factor than the Aasiaat case study. Lower operational emissions make the contribution from embodied emissions more significant. For the other three parameters, the Aasiaat case study was more sensitive than the Nuuk case study, which was caused by the significance of the energy emission factor. When the energy emission factor was high, the operational emissions were more dependent on the climate and insulation quality.

4.3. *Case 3: subarctic continental climate (Norway, global model)*

4.3.1. *Model results*

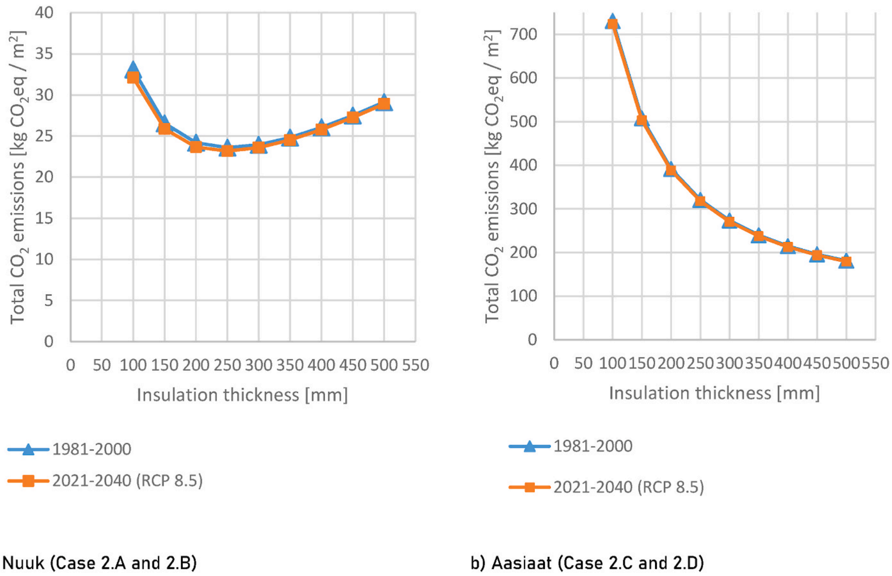
The energy emission factors for Case 3 were the same as those for Case 1, as both case studies were situated in Norway, and both assumed the building was heated with 100% electrical energy and no locally-produced energy. The method of determining future climate conditions was also similar; however, Case 3 was based on the Oslo climate, whereas Case 1 was based on the Elverum climate, with the latter being slightly colder on average (see Table 2). The model results for Case 3 are shown in Fig. 9.

The model outputs from the global model in Case 3 displayed similar behavior to the model outputs in Case 1, but with less pronounced effects of changing insulation thicknesses. This is because the Case 3 models considers more effects, such as ventilation systems and passive heating through electrical equipment. In addition, the material emissions of the wall in Case 3 included outer and inner claddings. For an energy emission factor of 17 g CO_2/kWh, the optimal insulation thickness in Case 3 was calculated to be approximately 350 mm for the future case and approximately 300 mm for the historical case, in agreement with the results from the unit-level model in Case 1. For both Cases 1 and 2, when the energy emission factor was high, the optimal insulation thickness was outside the thickness range calculated by the model.

4.4. *Summary of results*

Table 4 summarizes the results from all calculated cases. The results for each case have been normalized for comparison purposes, by calculating the ratio of embodied and operational emissions of each insulation thickness relative to the embodied and operational emissions of insulation thickness 300 mm.

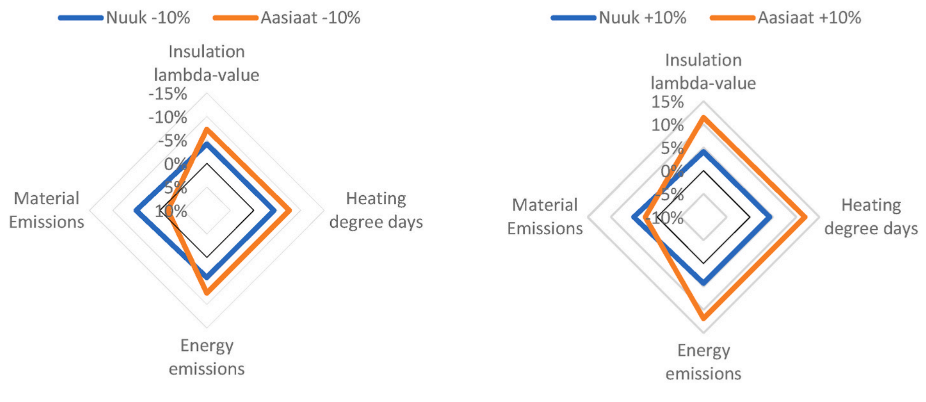
Models 1 and 2 are unit-level studies of the emission balance of a 1 m^2 wall. The internal energy loads from lighting and equipment and other effects must be estimated for the energy calculations. Therefore, a comparison of the findings from Models 1 and 2 to those of a similar study using a BES model (Model 3) should be performed to verify the validity of the assumptions. The climate scenarios and energy emission factors of Models 1 and 3 were the most similar and the results show similar trends for the optimal insulation thicknesses. Both show an optimum thickness of approximately 300–400 mm for the historic climate scenario with an energy emission factor 17 gCO_2eq/kWh, and both show



a) Nuuk (Case 2.A and 2.B)

b) Aasiaat (Case 2.C and 2.D)

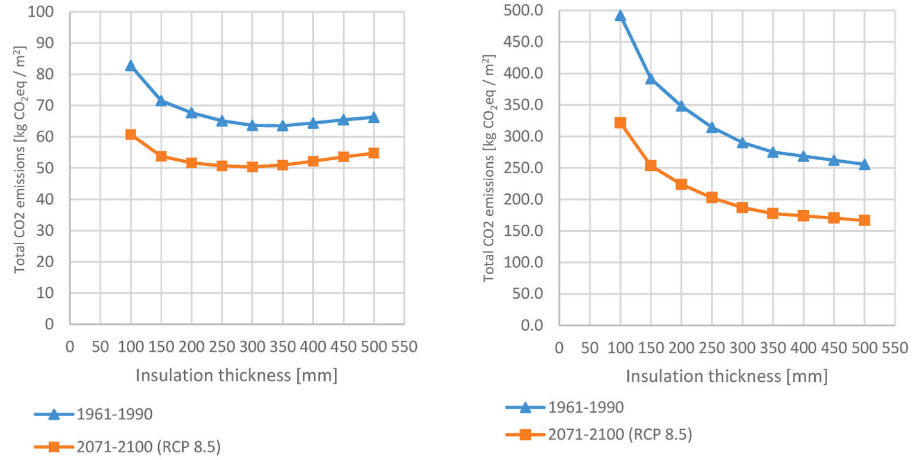
Fig. 7. Comparison of calculated future and historic CO_2 emissions for the two locations in Case 2. Nuuk's energy emission factor is 9 g CO_2eq/kWh (a) and Aasiaat's 207 g CO_2eq/kWh (b). Note the different scales on the y-axes.



a) 10% reduction of parameter value

b) 10% increase of parameter value

Fig. 8. Sensitivity analysis for the model used in Case 2, using wall insulation thickness d = 300 mm.



a) Emission factor = 17 g CO_2eq/kWh (Case 3.A and 3.B)

b) Emission factor = 132 g CO_2eq/kWh (Case 3.C and 3.D)

Fig. 9. Comparison of calculated future and historic CO_2 emissions for Case 3, using 17 g CO_2eq/kWh (a) and 132 g CO_2eq/kWh (b) as energy emission factors. Note the different scales on the y-axes.

Table 4
Calculated ratio of embodied and operational emissions over 60 years for insulation thicknesses 100–500 mm for all cases, relative to t = 300.

T [mm]	The ratio of total emissions for a wall construction with insulation thickness t, relative to t = 300 mm											
	1.A	1.B	1.C	1.D	2.A	2.B	2.C	2.D	3.A	3.B	3.C	3.D
100	1.95	1.82	2.53	2.50	1.38	1.36	2.67	2.67	1.30	1.21	1.70	1.72
150	1.47	1.39	1.81	1.79	1.11	1.10	1.86	1.86	1.12	1.07	1.35	1.35
200	1.21	1.17	1.41	1.40	1.01	1.00	1.43	1.43	1.06	1.03	1.20	1.20
250	1.08	1.06	1.17	1.17	0.99	0.98	1.17	1.17	1.02	1.01	1.08	1.08
300	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
350	0.96	0.97	0.88	0.88	1.04	1.04	0.88	0.88	1.00	1.01	0.95	0.95
400	0.94	0.97	0.79	0.80	1.09	1.09	0.79	0.79	1.01	1.04	0.93	0.93
450	0.93	0.97	0.73	0.74	1.15	1.16	0.72	0.72	1.02	1.06	0.90	0.91
500	0.93	0.99	0.67	0.68	1.22	1.23	0.66	0.66	1.04	1.09	0.88	0.89

a reduction in the optimum thickness of approximately 75–100 mm for the future climate scenario. Furthermore, the models displayed similar behavior regarding the impacts of both climate and emission parameters. Note that the absolute values calculated by the two models are on different scales: Model 1 reports emissions per m^2 wall, and Model 3 reports emissions for the total wall area.

The most significant difference between Models 1 and 2, the two unit-level models, is the choice of the future climate scenario. Model 2 imposes gradually developing climate change for the future scenario, and Model 1 assumes a static climate. The comparably lower impact of climate change in Model 2 illustrates the sensitivity of these models to methodological choices.

5. Discussion

5.1. Assessment of optimal insulation thickness

Calculations of optimal insulation thicknesses in cold climates are most useful for low energy emission factors, as the combination of high energy emission factor and cold climate results in high operational emissions. For energy emission factors above 25–30 gCO_2eq/kWh, more insulation will always yield lower total emissions over the building lifespan within the practical range of insulation thicknesses assessed in this study (100–500 mm). A comparable study by Raimundo et al. [38] reached the same conclusion for cold climates and high energy emission factors. Raimundo et al. calculated and compared results from 5 different climate zones using a similar methodology as this study and concluded that for the climate of Reykjavik (HDD = 5670 Kd/a) an energy emission factor of 144 gCO_2eq/kWh yielded insulation thicknesses above 400 mm even when using EPS as insulation material, which has a lower environmental impact than the glass wools used in this study. When using high energy emission factors, even studies of milder climates such as Ireland, with HDD in the range of 2–3000 Kd/a and energy emission factors 205–437 gCO_2eq/kWh, yields insulation thicknesses higher than the highest calculated insulation thickness (>250 mm) when optimizing for environmental impact [39]. The total emissions will be lower for a decreasing energy emission factor, but the sensitivity of the total emissions to deviations from the optimum value will increase. Therefore, building projects with emission reduction ambitions should not neglect calculating the optimal insulation thickness if the energy source for heating the building has a low emission factor.

5.2. Influence of climate parameters on the model results

An assessment of how future climate change influences the optimal insulation thickness can only be made after defining the energy emission factor, as this parameter will change the model's response to climate change. The results from Cases 1 and 3 are discussed using the energy emission factor suggested by the NVE (17 g CO_2eq/kWh). Greenland is self-sufficient on a national scale and also on a local scale, as the infrastructure in Greenland does not allow for an intercity exchange of energy. Nuuk is currently self-sufficient, with 100% of the electrical energy generated by hydropower, whereas Aasiaat relies on locally generated power from fossil fuel sources [24]. To compare the high and low emission factors in the discussion of how climate parameters impact the results, these are assumed to remain unchanged in future climate change scenarios.

RCP 8.5 is used as the future scenario in all three cases. When conducting studies comparing a historical scenario to only one future scenario, the worst-case scenario provides valuable insights, as the two curves comprise the outer limits of the probable outcome space. The temporal spacing of the two scenarios was approximately 100 years for Cases 1 and 3 (1961–1990 and 2071–2100). For assumed emission rates equal to or lower than the assumptions in scenario RCP 8.5, the total emissions over 60 years for a given insulation thickness will therefore be somewhere between the two curves according to these models.

The future scenario used for Greenland has a relatively small impact on total emissions compared to the future scenario used for Norway. This is partly because the future scenario in Case 2 is calculated over a shorter period (40 years) and because the model for future development in Case 2 is different from Cases 1 and 3. Cases 1 and 3 were calculated for (a) a static historical climate and (b) a static future climate, while Case 2 was calculated for (a) a static historical climate and (b) gradually changing future climate. Consequently, the Norwegian cases are based on climates 110 years apart, whereas the Greenlandic cases operates only 40 years apart. The effect can be observed by comparing the HDD for the different cases in Table 2, where the calculated HDD for both Norwegian case studies decreased by approximately 25% in the climate change scenario, and the same number was 3–4% in the Greenland climate change scenarios. The difference between the methods in the Greenland and Norwegian cases highlights an important fact: Choosing the appropriate model for the future scenario considering its intended use is vital, as there is a significant difference in the impact of climate change on a building built in 2071 compared to the impact on a building built today.

The difference between the indoor and outdoor temperatures is the deciding factor for the heating demand, as there is no principal difference between increasing outdoor temperature through climate change and decreasing indoor temperature through occupant behavior. Assessing how these two thermal conditions develop in relation to each other, and how much uncertainty is connected to the prediction of both becomes important. Case 1 assumes an indoor temperature of 21.5 °C and Cases 2 and 3 assume an indoor temperature of 19 °C. Both are viable options within the normal indoor temperature range during the heating season. However, there is still a 2.5 °difference between them, analogous to changes in the outdoor temperature resulting from decades of climate change in the RCP 8.5 scenario. The uncertainty of indoor temperatures due to occupant behavior is frequently highlighted as a critical parameter, by i.e. Galimshina et al., who in an earlier study evaluated the method-related and future-related uncertainties in calculations of LCA-optimized building renovation [40]. Occupant heating strategy preferences may change over time because of increased environmental awareness or an increased focus on thermal comfort. Both future climate and occupant behavior changes will affect future heating demand. The development of these two important input parameters has both a high uncertainty and a high impact on the results. Total emissions from heating energy use and insulation material production should be carefully considered and include multiplecombinations of indoor and outdoor climates to highlight the range of possible outcomes. This conclusion is also reached by Ylmen et al. [41], who developed a method for optimal insulation thickness calculation through the use of parametric analysis. Ylmen et al. showed that by considering parametric uncertainties, fewer design solutions are rejected in comparison with using point estimates. Calculating a range of values for critical parameters mitigates the problem of rejecting promising solutions based on low quality data. Further, it provides a means of addressing and evaluating subjective choices present in life cycle studies of building design [41].

5.3. Influence of the energy emission factor on model results

Fig. 10 shows the annual development of the calculated total CO_2 emissions for Case 1 with insulation thicknesses of 200, 300, and 400 mm based on the energy emission factor recommended by FME ZEB [27]. Future climate change was assumed to be a linear development from a historical climate (1990) to a future climate (2071). The estimated lifetime of the building used in the calculations was 60 years, and the energy emission factor was a function of the construction year, assuming the development illustrated in Fig. 2.

The total CO_2 emissions are highly dependent on the chosen emission factor for the energy mix, which is consistent with the results of similar studies [42,43]. Using the factor proposed by the FME ZEB, which declines linearly towards zero in 2054, the insulation thickness with respect to CO_2 emissions becomes arbitrary by approximately 2040 for the model in Case 1 (Fig. 10). After 2040, the results will be dominated by embodied emissions from the materials, and an increase in insulation thickness will yield an increase in total CO_2 emissions. A study on retrofitting building stock in England conducted by Li and Densley Tingley [44] found that adding insulation to walls with relatively low pre-retrofit U-valueled to an increase in total CO_2 emissions over the building life-time when considering an energy emission factor declining towards near-zero in 2050. It is however important to note the distinct differences in the studied climates, as the study by Li and Densley Tingley was conducted using English climate, using HDD = 2183 Kd/a in 2023 with a linear decline towards 1419 Kd/a in 2050. The heating demand in the climates investigated in this study are considerably higher, thus giving higher influence to operational emissions for the considered range of insulation thickness (100–500 mm).The rapid decline of the energy emission factor towards zero in 2050 may underestimate future operational emissions, as even renewable sources of

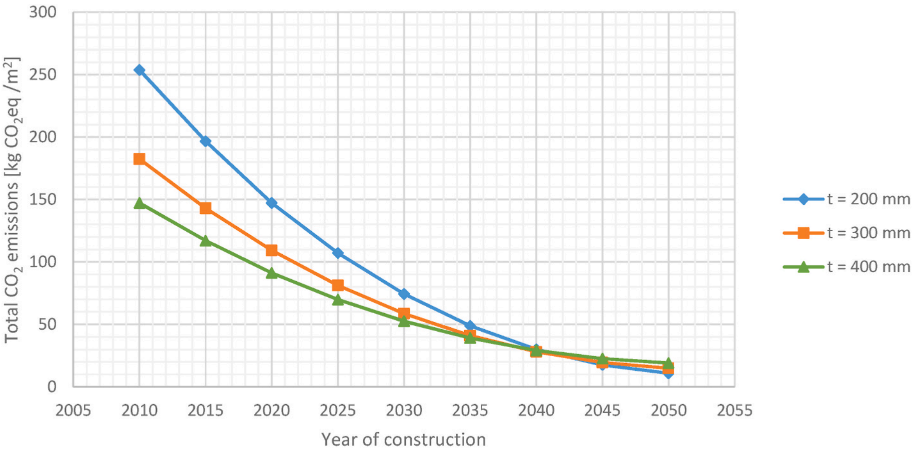


Fig. 10. Development of total CO_2 emissions for construction years between 2010 and 2050 using the model from Case 1 and using FME ZEB energy emission factor updated year by year.

energy will produce emissions because of infrastructure development [26]. This method of calculating the energy emission factor is not suitable to assess the development of future conditions in 2071–2100 as it assumes zero operational emissions. But it illustrates the high-impact energy emission factors have in studies such as this, and further highlights the need for considering multiple calculation cases due to future uncertainties, as confirmed by similar studies [39,41,45]When the considerations by the FME ZEB were performed in 2010–2012 the energy mix in Europe was dominated by emissions from the burning of oil, coal, and gas [28]. However, this will not be the case in the future if the EU goal of a 90% reduction in GHG emissions in the power sector by 2050 are realized. Future emissions from the power sector in Europe in 20–30 years are more likely to be comparable to the emissions of the Norwegian power sector today, as proposed by Ref. [46] when describing a method for the temporal development of emission intensities in LCA analysis [26]. found that sector-specific emission rates from renewable sources still exceed zero, but are highly variable when considering infrastructure and secondary effects. When the EU grid is dominated by renewable sources, infrastructure and secondary effects become more prevalent in the estimation of energy emission factors.

To assess the influence of the energy emission factor, the optimal insulation thickness as a function of the energy-emission factor was calculated for all cases, as shown in Fig. 11. When using energy emission factors exceeding 25–30 $kgCO_2eq/kWh$, the total emissions are dominated by operational emissions, resulting in an increasing gradient of the curves for higher insulation thicknesses. Because the calculation points are based on the optimum thicknesses the curves displayed in Fig. 11 do not express the consequences of deviating from the optimum thickness. Small deviations from the optimum will not yield significant changes in total emissions. Together with the inherent uncertainties involved in the parameters of such models (i.e., future energy emission factors, future climate, occupant heating behaviors, and material emissions), such calculations should not be performed to find a precise optimum, but rather to see the general development of optimal insulation thickness within a value range of energy emission factors.

As more green energy becomes available, the energy emission factor is expected to decrease [6]. However, the rate of development is difficult to predict in the short term, and increasingly complex in the long term. For interconnected grids, such as in Cases 1 and 3, the rate of development depends on socio-economic development and policy-making on an international scale. The evaluation of a single deterministic value will conceal high levels of uncertainty in the results. However, the uncertainty of this factor decreases dramatically if the energy for heating is dominated by locally produced renewable heat and energy sources, such

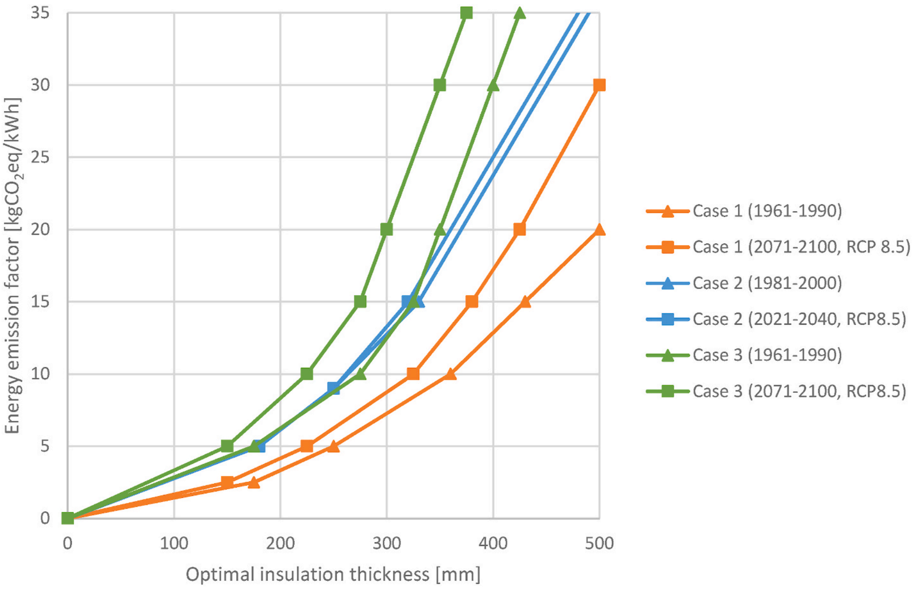


Fig. 11. Comparison of calculated future and historic optimal insulation thickness for all cases, as a function of the energy emission factor.

as in Cases 2A and 2B.

For the lower energy emission factor scenarios considered in Cases 1 and 3, the shift from the future to the historical scenario in the minima was approximately 50–75 mm. However, missing the optimum by ± 100 mm will have a limited impact on total CO_2 emissions. For Case 1, by increasing or decreasing the insulation thickness by 100 mm from the optimum value, the total emissions increased by less than 5%. The Greenlandic case of Nuuk, with an even lower energy emission factor, is more sensitive around the optimum value, and choosing an optimal insulation thickness outside the range of ±50 mm from the optimum value will have a significant impact on the total emissions. While this result indicates that the precision of the calculations is more important for lower-energy emission factors, low-energy emission factors also lead to low total emissions. This indicates that the absolute difference in total emissions will not be as dramatic in the lower range of emission factors.

The evaluation of reduced grid emission factors due to future development is more complex than evaluating emission factors from locally produced green energy, as material emissions also rely on the development of the grid energy emission factor. Embodied emissions are influenced by the types of energy sources available owing to the production and transportation of materials requiring energy. Further complicating the relationship between embodied and operational emissions, reduced emissions in the construction phase (from embodied emissions) have a greater impact on future climate change than an equal reduction in emissions over a 60-year lifespan (from operational emissions). Assessing the value relationship between these two parameters is outside the scope of this study; however, further study of this relationship should be made considering the total emissions from the heating demand of buildings.

6. Conclusions

This study assessed how future climate and energy emission factor changes in cold climates influence the selection of optimal insulation thickness of walls. A comparison of the three case study models for such calculations yielded the following conclusions.

Climate change will reduce the optimal insulation thickness for Norwegian inland climates by 75–100 mm towards 2071–2100, compared to the situation in 1961–1990 considering scenario RCP 8.5, an energy emission factor of 17 g CO_2eq/kWh, and glass-wool insulation. However, occupant behavior has a significant impact on the calculations as this determines the indoor climate. Multiple combinations of indoor and outdoor climates should be considered by calculating a range of optimal insulation thicknesses before finalizing the insulation thickness. These factors have both high impact and high uncertainty.

In cold climates, optimal insulation thickness calculations are most valuable for cases with low energy emission factors. When considering energy emission factors above 25–30 g CO_2eq/kWh, the total emissions from insulation and heating energy use were dominated by operational emissions for all the considered cases due to the high energy demand for heating. Furthermore, the energy emission factor significantly impacts the calculated optimal insulation thickness and should be carefully chosen. Case 1 demonstrated that, given an energy conversion factor of 17 g CO_2eq/kWh, insulation thicknesses within 100 mm from the optimum thickness increased the total CO_2 emissions by less than 5%. Given an energy emission factor under 10 g CO_2eq/kWh, deviation from the optimum will have a more significant impact on the total emissions.

The results from all three cases highlight the energy emission factor as the dominant influencing factor in climates with high energy demands for heating. Considering the applicability of the results to other Nordic countries, the relative difference in climate seems not to be the determining factor. If the building is self-sufficient in locally produced energy from i.e. solar panels, calculations of optimal insulation thickness may prove valuable regardless of location in the arctic and sub-arctic climate zones. If however, the building relies on grid electricity for heating with an energy emission factor above 25–30 g CO_2eq/kWh, the conclusion found by previous studies remains: “The more insulation the better”.

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CRediT authorship contribution statement

Jørn Emil Gaarder: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Naja Kastrup Friis:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Ingrid Sølverud Larsen:** Visualization, Methodology, Formal analysis. **Berit Time:** Writing – review & editing, Supervision, Funding acquisition. **Eva B. Møller:** Writing – review & editing, Supervision, Funding acquisition. **Tore Kvande:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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