BUILDINGS & CITIES

Evaluating past and future building operational emissions: improved method

METHODS PAPER

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ABSTRACT

A simple method is presented to improve the evaluation of past and/or future CO_2 emissions of heating and/or cooling a building. The degree-day—energy emission coefficient (DD-EEC) method relies on two established techniques. It starts with a building's known annual heating and/or cooling energy consumption. Degree-days are employed to estimate the consumption in other years, unveiling how climate warming influences the annual energy need for heating and/or cooling. The resulting emissions are then quantified by associating the energy need in each year with the emission factor for energy production that year. A case study demonstrates an application of the method: a 1950s' school building in Finland. Its past heating-related operational CO_2 emissions are reconstructed from its erection until today, and the future heating and cooling emissions are forecasted until 2100. The case demonstrates the impact of climate warming and projected energy decarbonisation on emissions, showcasing that the past may not be the best future predictor. In the 2010s, the emissions were estimated to be 57% of the 1960s' level. In the 2090s, they could be as little as 5% of the 2010s' level, even though the building's technical properties remain unchanged.

PRACTICE RELEVANCE

This new method is a straightforward technique that can be replicated and easily used by researchers and, most importantly, practitioners. The method is based on degree-days, which are widely used in building energy practice. The technique refines existing methodology, which does not yet consider the impact of a warmer climate and energy decarbonisation on a building's emission generation, at least not together. The availability of robust research-based data determines whether the method can be applied only retrospectively or also prospectively; such data are available in the European Union and other places. The practice relevance of this method is it can improve decision-making based on whole-life life cycle analysis (LCA), where the ratio between a building's embodied and operational emissions is a focal consideration in many kinds of decision-making situations. Too simple modelling of operational emissions risks getting this ratio wrong, potentially leading to decision-makers drawing incorrect conclusions with real-life adverse effects.

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1 INTRODUCTION

This paper explains a simple technique, the degree-day—energy emission coefficient (DD-EEC) method, for refining the estimation of a building's operational emissions as a part of the life cycle module B6 (*cf*. CEN 2011). Within B6, the introduced refinement targets emissions resulting from heating and/or cooling a building. The underlying motivation for introducing the technique stems from improving the life cycle assessment (LCA) of buildings, where operational emissions are often juxtaposed with embodied emissions in search of trade-offs and best whole-life performance. However, the DD-EEC method can also be used in energy assessments, without the whole-life emissions perspective. In addition to the 'intrinsic' heating and/or cooling energy consumption of a building stemming from the energy performance properties of its envelope and building services, the technique considers two external factors influencing the emissions generation: weather/climate and emission intensity of the energy used. As the name suggests, it is based on degree-days and emission coefficients for energy production. It can be used in a retrospective and/or prospective fashion, *i.e.* to estimate past and/or future emissions.

The DD method has traditionally been used in building energy research and practice as a simplified method (1) to monitor a building's heating energy use over a longer period, excluding the impact of weather, or (2) to compare technically similar buildings' heating energy needs in climatically different locations (Motiva 2023). This paper's technique draws from it in the first purpose, but shows how it can be used to specifically consider the influence of the changing climate. There are two types of DD: heating degree-days (HDD) depict the need for heating, while cooling degree-days (CDD) depict the need for cooling. HDD are generally available for the past, so they can be used to reconstruct a building's historic heating energy consumption. However, it is also possible to devise HDD and CDD for future climate scenarios. This way, DD can be used to forecast a building's heating and/or cooling energy consumption in a future climate. By combining the information on heating and/or cooling energy consumption, acquired with the help of the DD method, with past and forecasted future emission coefficients of energy production, a building's heating and/or cooling emissions can be evaluated over its whole life cycle.

Simultaneous to the preparation of the current paper, other researchers have presented studies using similar techniques (*e.g.* Institut für Immobilienökonomie 2023; Li & Tingley 2023; Walker *et al*. 2022), though they only consider the future and not the past. Therefore, the purpose of this 'method' paper is threefold. First, and most importantly, it gives step-by-step instructions on how to use the technique, easy to follow by researchers and practitioners alike, including where to find DD data (Section 2). Second, it demonstrates the use of the technique with the help of a case study located in Finland: a 1950s' school building in the city of Vantaa (Section 3). For clarity, the demonstrative case study is stripped from all other factors but those considered in the method. This is to highlight the impact of climate warming and energy decarbonisation, despite the fact that the DD-EEC method is primarily intended to improve the modelling of module B6 in whole-life LCA. Third, the paper discusses the different use cases of the method as well as its limitations (Section 4).

2 METHOD

2.1 PROCESS STEPS

The method consists of the following steps:

1. Acquire the target building's energy consumption data for one year and normalise the consumption.
2. Acquire retrospective and/or prospective HDD and/or CDD data pertaining to the building's location.
3. Apply the DD method to model the building's past and/or future energy consumption.
4. Associate the energy consumption with emission coefficients.
5. Visualise and report the results.

Steps 1–3 pertain to the DD method, which is elaborated on in Section 2.2. Steps 4–5 are a part of the emissions quantification, which is explained in Section 2.3.

2.2 DEGREE-DAY (DD) METHOD

The DD method was first applied in the building sector in the early 20th century to estimate domestic fuel consumption (Morgan 1928). It is a weather-based index that developed into a tool for building services engineers to evaluate buildings' heating and cooling energy needs (Vaughn 2005). While dynamic energy simulation is a newer alternative to modelling buildings' energy needs in a more refined and accurate manner, the DD technique remains widely in use thanks to its simplicity and easy data access. The method is based on the idea that when the outdoor temperature drops below a certain point, people on average start heating their homes, or when it rises above a given temperature, they typically switch on air-conditioning (Vaughn 2005). The exact threshold outdoor temperatures, as well as targeted indoor base temperatures, may vary for heating and cooling, and by country. Equations (1) and (2) give the principles for calculating daily HDD and CDD as the difference of the base temperature and daily mean outdoor temperature (adapted from Eurostat 2023):

$$\text{If } \overline{T}_i \leq T_{\text{threshold heating}}, \text{ then HDD} = \Sigma_i(T_{\text{base heating}} - \overline{T}_i). \text{ Else, HDD} = 0 \tag{1}$$

where $\overline{T}_i$ is the mean outdoor air temperature on each day i in the building's location, $T_{\text{threshold heating}}$ is the threshold outdoor temperature that triggers the heating need (which may differ for different seasons), $T_{\text{base heating}}$ is the base (indoor air) temperature that is targeted with heating, and Σ_i is the summation of daily HDD over a period of days, such as a month or a year.

$$\text{If } \overline{T}_i \geq T_{\text{threshold cooling}}, \text{ then CDD} = \Sigma_i(\overline{T}_i - T_{\text{base cooling}}). \text{ Else, CDD} = 0 \tag{2}$$

where $\overline{T}_i$ is the mean outdoor air temperature on each day i in the building's location, $T_{\text{threshold cooling}}$ is the threshold outdoor temperature that triggers the cooling need, $T_{\text{base cooling}}$ is the base (indoor air) temperature that is targeted with cooling, and Σ_i is the summation of daily CDD over a period of days, such as a month or a year.

To apply the DD method, two types of input data are needed. First, it is necessary to know the annual energy use of the building, which is discussed in Section 2.2.1. Second, the HDD and/or CDD for the period of interest are needed. Their acquisition and application on the case building is explained in Section 2.2.2.

2.2.1 Step 1: Acquire and normalise energy consumption

The starting point for applying the DD method is that the target building's annual energy consumption is known. For an existing building, this information can be read from previous energy bills. However, if domestic water is heated the same way, the energy used for its heating needs to be distinguished, because domestic hot water consumption does not depend on the weather. If the energy to heat the domestic water is not separately metered, there are ways to evaluate it based on the building type or metered water usage (Motiva 2023). Moreover, if the building has both heating and cooling, their energy uses should be distinguishable from one another for the DD method to work. Therefore, if an existing building's data are to be drawn from energy bills, heating and cooling should be on separate bills or otherwise separately monitored or evaluated. The realised heating energy use is calculated using equation (3) (adapted from Motiva 2023):

$$Q_{R\,\text{heating}} = Q_{\text{total}} - Q_{R\,\text{cooling}} - Q_{\text{domestic hot water}} \tag{3}$$

where $Q_{R\ \text{heating}}$ is the realised heating energy consumption, Q_{total} is the total heating energy consumption (*e.g.* from energy bills), $Q_{R\ \text{cooling}}$ is the realised cooling energy consumption, and $Q_{\text{domestic hot water}}$ is the energy consumption pertaining to heating domestic water.

To calculate realised cooling energy use, the places of $Q_{R\,\text{heating}}$ and $Q_{R\,\text{cooling}}$ are switched in equation (3). However, if realised energy consumptions are calculated for both heating and cooling, one should be careful not to subtract $Q_{\text{domestic hot water}}$ twice.

The realised heating energy consumption is then normalised, *i.e.* scaled to correspond to the building's average heating energy usage over a longer time (an officially defined reference period), such a few decades. Normalisation uses annual average HDD from the closest available reference location, calculated over the reference period. Equation (4) gives the normalised heating energy consumption (adapted from Motiva 2023):

$$Q_{N\,\text{heating}} = \frac{HDD_{N\,\text{location}}}{HDD_{R\,\text{location}}} \times Q_{R\,\text{heating}} \tag{4}$$

where $Q_{N\,\text{heating}}$ is the normalised energy consumption of heating the building, $Q_{R\,\text{heating}}$ is the realised heating energy consumption from equation (3), $HDD_{N\text{ location}}$ is the average annual HDD for the reference period in the reference location, and $HDD_{R\text{ location}}$ is the realised HDD at the reference location.

To normalise cooling energy use, $Q_{N/R\text{ heating}}$ are replaced by $Q_{N/R\text{ cooling}}$ and $HDD_{N/R\text{ location}}$ are replaced with $CDD_{N/R\text{ location}}$. The next section explains where the necessary DD data can be found.

If the target building is a new design or if the purpose is to evaluate a building's energy performance after energy renovation, the consumption must be calculated or simulated. It is assumed that the reader is familiar with these procedures, so they will not be elaborated on here. It may be possible to conduct the calculation or simulation directly for the 'normal year' weather and omitting domestic water heating, in which case equations (3) and (4) are not used.

2.2.2 Steps 2 and 3: Acquire and apply DD data

As equations (1) and (2) show, HDD and/or CDD can be calculated given that daily mean temperatures are available. In practice, though, statistical weather services publish ready-made HDD and CDD data. The data may be available in Open Access (OA) or purchased against a fee. HDD and CDD may come in a daily, monthly or annual formats. The monthly data are summed up from the daily data, and the annual data from the monthly data. The method introduced herein uses annual data. If the data are not in the annual format when acquired, they should be summated.

In Europe, Eurostat (2023) is a centralised source for European Union (EU) countries' HDD and CDD in OA. The data are presently available for the period 1979–2022 in both monthly and annual formats, and in two geographical granularities: the country level and a detailed regional level (*i.e.* level 3 in Eurostat's (n.d.) Nomenclature of Territorial Units for Statistics—NUTS, which represents 'small regions for specific diagnoses'). Future DD are, however, not provided. Prospective DD can be found until 2100 in the EU's (2022) Copernicus Climate Data Store.

In the US, historical DD data have been published by the National Weather Service, Climate Prediction Center (2009). Globally, retrospective data for an array of locations may be retrieved through the commercially maintained, though partially OA, service www.degreedays.net. The global prospective HDD and CDD in different climate scenarios (Gassert *et al.* 2021) are available through PREPdata.org and resourcewatch.org. Geographically more granulated and/or longer term data, including for the future, may also be available through national meteorological institutes or equivalent.

With the DD data, the target building's annual realised (or for the future, expected realising) heating energy consumption is calculated for each year using equation (5), which is a reversed version of equation (4). It (re-)inserts the effect of weather to the annual energy consumption, *i.e.* reverses the normalisation.

$$Q_{R\,\text{heating}} = \frac{HDD_{R\,\text{location}}}{HDD_{N\,\text{location}}} \times Q_{N\,\text{heating}} \tag{5}$$

To calculate annual realised cooling energy use, $Q_{N/R\,\text{heating}}$ are replaced by $Q_{N/R\,\text{cooling}}$ and $HDD_{N/R\,\text{location}}$ are replaced with $CDD_{N/R\,\text{location}}$.

2.3 EMISSIONS QUANTIFICATION

2.3.1 Step 4: Associate energy consumption with emission coefficients

In the emissions quantification, the past and/or future energy consumption of the building, modelled with the DD method, is simply associated with the emissions of interest (such as CO_2 or equivalent) of the past and/or future energy production. This takes place by multiplying each year's energy consumption by the emission coefficient for energy in the given year. Calculating the annual emissions does not require the use of a special software but can be conducted in a spreadsheet programme using:

$$\text{Emissions} = Q_{R\,\text{heating}} \times C_f \tag{6}$$

where $Q_{R\,\text{heating}}$ is the building's heating energy consumption in the given year from equation (5), and C_f is the energy production emission coefficient in the building's location in the same year.

Emission coefficients for CO_2 can be found, for example, in the OA database 'Our World in Data' (Ritchie *et al.* 2023), which has drawn and processed data from multiple sources to publish factors for the CO_2 intensity of energy (per kWh) for different locations over time. In addition to a 'general' factor, separate factors may be available for different fuel types. These can be employed for more accurate results if the fuel(s) used for heating and/or cooling the building in the past or the future are known.

2.3.2 Step 5: Visualise and interpret the results

Visualising and interpreting the results is a key part of the analysis. The type of visualisation chosen may influence how people interpret the results. Different visualisations may be appropriate for different research questions. However, since the introduced method purpose is to depict a dynamic phenomenon over time, a visualisation that conveys the dynamic nature is usually the most appropriate choice. Therefore, the use of a line graph is recommended.

3. CASE STUDY

The case study demonstrates the use of the method, focusing on past and future CO_2 emissions. The case study building, Korso school in the city of Vantaa, was built in 1959 and can be considered as a typical school building of the era. Interested readers can find a description of the building's structures and other properties in the supplemental data online, though these are not relevant for the purposes of demonstrating the use of the method (as any building or even a theoretical energy consumption figure could be used for this purpose). The current paper uses the building in its present condition, without any energy efficiency improvement measures. The building's fuel history is not known. The building is now considered to be heated with district heating, which is also assumed to be the heat source in the future. It is presently not equipped with cooling and is not in use in the warm summer months due to children's summer holidays. Overheating is, however, a concern in a warmer future climate, so cooling is also incorporated from the present day onwards for demonstration purposes. The introduction of cooling equipment would bring about embodied emissions, but in the interest of keeping the case study as 'pure' as possible, they are not included. This way, only the impact of using the method, *i.e.* the impact of energy decarbonisation and a warming climate, can be crystallised.

3.1 CASE STUDY METHODS AND DATA

3.1.1 Building energy consumption

The building is a part of a larger complex that also contains other buildings. Therefore, instead of using energy bills, the energy consumption was simulated in the IDA ICE dynamic energy modelling program. The simulation was conducted with a base (indoor air) temperature of 17°C, omitting internal gains from lighting, equipment and occupants. The simulation used Helsinki-Vantaa region reference weather data of the 'test reference year (TRY) 2012', drawn from Finnish Meteorological Institute (FMI) (n.d. a), which represents the current (1980–2009) climate. For the purposes of the case study, this is considered to correspond to the 'normal year' weather of the DD method, even though its reference period is currently 1991–2020. As a result on the simulation, $Q_{N\ \mathrm{heating}}$ is 530,202 kWh and $Q_{N\ \mathrm{cooling}}$ is 5892 kWh.

3.1.2 Degree-days (DD)

For the past, data were acquired from the online OA data service of the FMI. FMI (2024) provides ready-made HDD, both $HDD_{N\ \mathrm{location}}$ and $HDD_{R\ \mathrm{location}}$, for each Finnish municipality starting from 1991. The reference location for the building is the city of Vantaa. Thus, $HDD_{N\ \mathrm{Vantaa}}$ was acquired this way, but the range of $HDD_{R\ \mathrm{Vantaa}}$ was not sufficient to cover the building's early life. Therefore, mean daily outdoor temperatures (FMI n.d. b) were downloaded instead, as these started for the city of Vantaa in 1959. Then, annual $HDD_{R\ \mathrm{Vantaa}}$ were calculated using the principle demonstrated in equation (1). As per the Finnish DD method (Motiva 2023), in the case study $T_{\mathrm{threshold\ heating}}$ is 10°C in the spring and 12°C in the autumn, and $T_{\mathrm{base\ heating}}$ is 17°C.

Future DD were not available online but were requested from the FMI. Both HDD and CDD for the city of Vantaa were generated per order in two climate warming scenarios: the moderate scenario SSP2–4.5 and the high scenario SSP5–8.5 (for the scenarios, see Ruosteenoja & Jylhä 2021). The FMI derived the underlying data from five CMIP6 climate models, which it considers as representative (Reija Ruuhela, personal communication, 11 May 2023). The generated HDD and CDD start in 1991 and end in 2100. $CDD_{N\ \mathrm{location}}$ was not readily available from any source, so a 30-year average was calculated and used. Figure 1 visualises all the DD data in the case study.

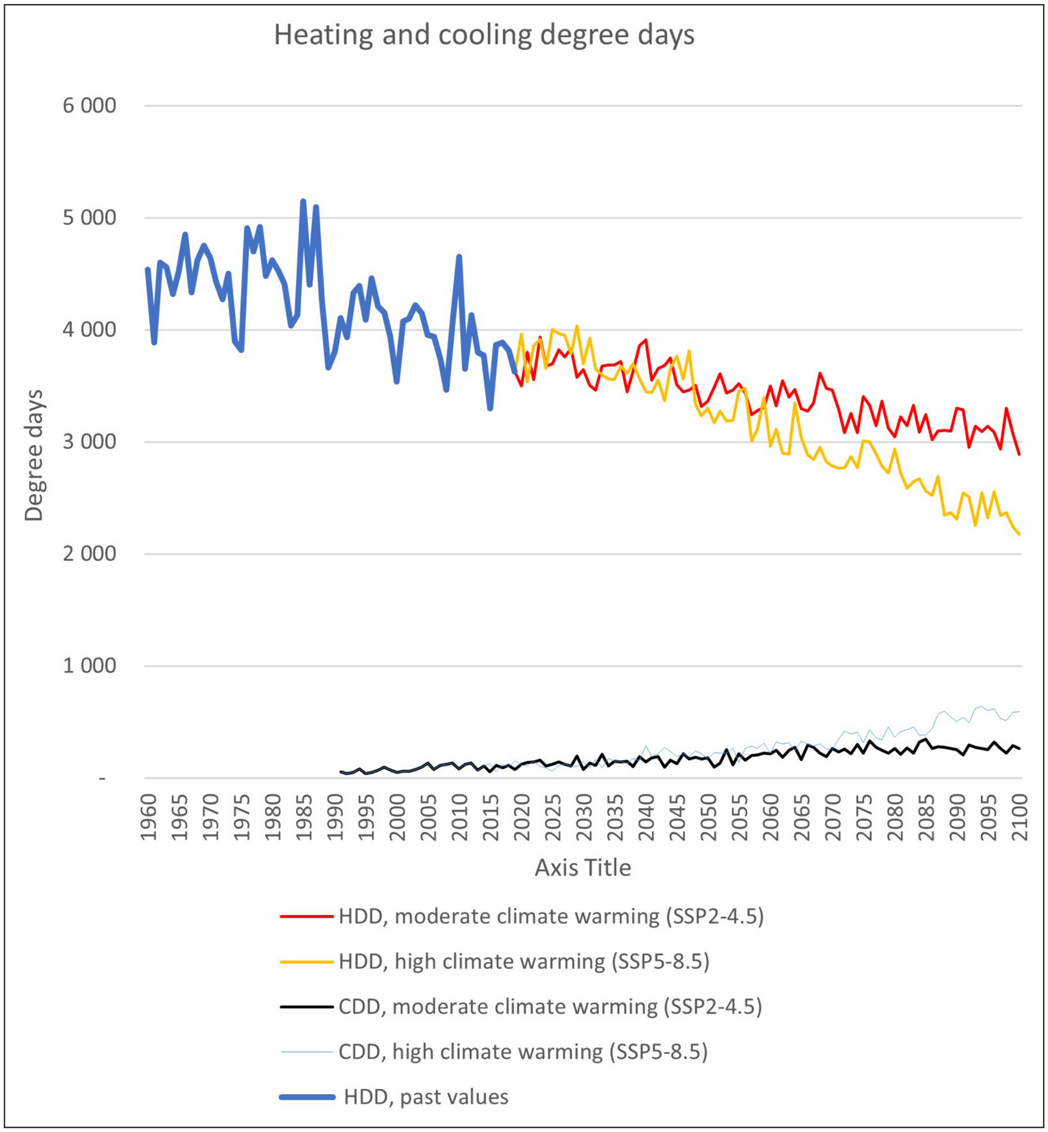

Figure 1: Past and future degree-day (DD) in the case study dataset.

Note: Heating degree-days (HDD) until 2019 were calculated using the Open Access (OA) data of Finnish Meteorological Institute (FMI) (n.d. b). HDD from 2020 onwards and all cooling degree-days (CDD) are modelled values, which are available from the FMI upon request.

3.1.3 Energy emission coefficients (EECs)

The emission coefficients for the past energy production in Finland were acquired from Our World in Data (Ritchie *et al.* 2020), which has generated OA the dataset by processing data from Andrew & Peters (2023), the Energy Institute (2023) and the US Energy Information Administration (EIA) (2023). Due to the lack of information on the building's fuel history, generic (*i.e.* non-fuel-specific) coefficients are used until 2019. The data start in 1965, so the coefficient of 1965 is also used for the period 1959–64.

From 2020 onwards, emission factors for district heating and district cooling are used. They were drawn from the OA Finnish national generic building-LCA database CO2data.fi, maintained by the Finnish Environment Institute (FEI). The database is used in conjunction with the Finnish national LCA method (Kuittinen 2019; see also Kuittinen & Häkkinen 2020) published by the Ministry of the Environment (MoE). A climate declaration made using the MoE method and CO2data.fi database will be legally mandated from new buildings and major renovations starting from 2026. The database gives forecasted emission coefficients for different means of future energy production (including district heating and cooling) at 10-year intervals from 2020 to 2120 with values for the years in between to be interpolated, though this study only uses the values until 2100. The provided factors (FEI 2023a, 2023b) reflect anticipated energy decarbonisation as per the policy commitments of the Finnish state, as explained in the background report by Soimakallio (2020). Figure 2 illustrates the emission coefficients, both past and present, used in the case study.

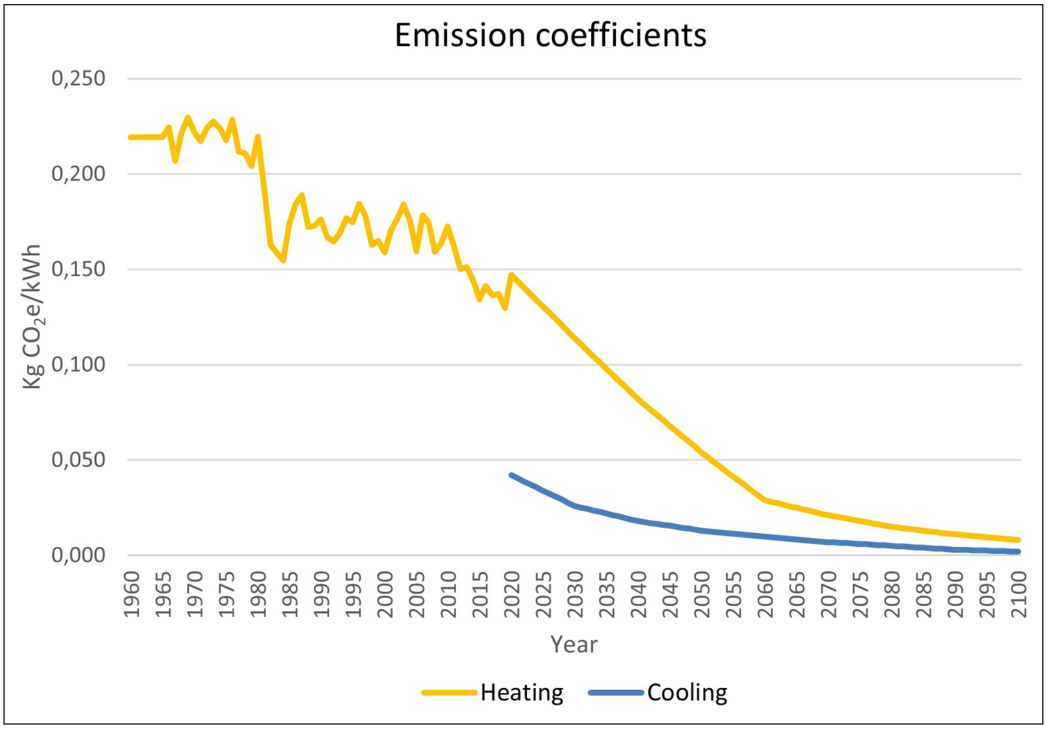

Figure 2: Energy emission coefficients (EECs) used in the case study.

Note: The period 1959–64 uses the coefficient of 1965.

Sources: 1965–2019: Ritchie *et al.* (2020); and 2020–2100: Finnish Environment Institute (FEI) (2023a [heating], 2023b [cooling]).

3.2 CASE STUDY RESULTS AND DISCUSSION

Figure 3 gives the case study's main result: the building's annual heating and cooling emissions on a timeline from 1959 to 2100 (cooling emissions from 2020 onwards). The emissions before 2020 are based on the observed HDD. Beyond 2020, the emissions are presented for two different climate scenarios. The decarbonisation of future energy production is considered.

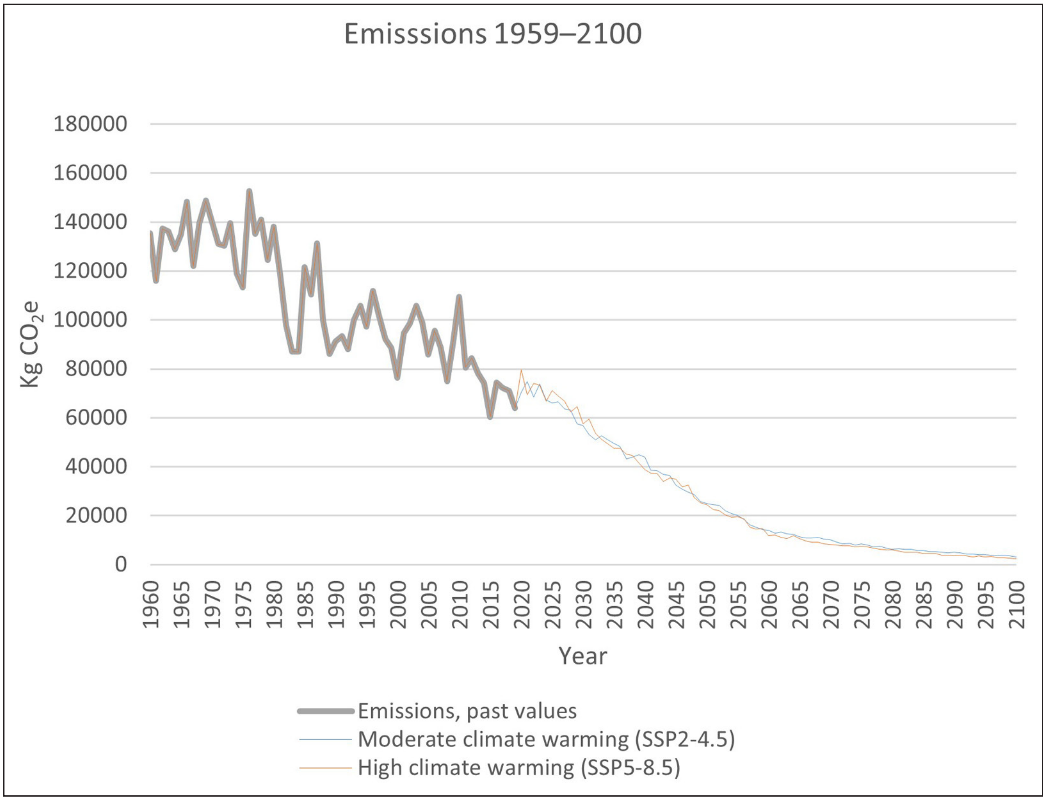

Figure 3: Case study building's heating emissions, 1959–2100, and cooling emissions, 2020 onwards.

Note: Projected energy decarbonisation is included.

Depending on the climate change scenario (moderate or high), the reconstructed CO_2 emissions of heating and cooling the case building for the first six decades (1959–2019) are 343–345% of the forecasted next six decades (2020–2080). If the actualising lifespan of the building were at midpoint by 2020, 77% of its lifespan heating and cooling emissions would already have been generated, with only 23% to be formed in the future. Most of the emissions reduction is associated with energy decarbonisation. Considering both climate warming and decarbonisation, by the 2090s the building's heating and cooling emissions are expected have decreased by 95–96% from the level of the 2010s and by 97–98% from the level of the 1960s (in the moderate and high warming scenarios, respectively).

For the sake of a sensitivity analysis, Figure 4 presents the results without the prospected future energy decarbonisation. It can be considered as a 'worst case' scenario from an energy decarbonisation viewpoint. If energy production fails to decarbonise, the impact of the warming climate will still remain. By the 2090s, the warming alone is expected to have reduced the combined heating and cooling related emissions of the case building by approximately 27–46% from the level of the 2010s, in the moderate and high warming scenarios, respectively.

Even though climate warming increases the cooling need, the heating energy need dominates in Finland. The cooling demand is currently about 1% of the building's heating demand. By 2100, the increased cooling need raises the modelled energy use by 4% in the moderate climate warming scenario and by circa 12% in the high scenario. Lower emission coefficients for cooling and energy decarbonisation considered, these figures translate into negligible increases (0.14–0.17%) in emissions.

If the demonstrated method is not used, the emission level of today is assumed to represent the building's heating and cooling emissions in the past and the future. In Finland, this leads to underestimation of past emissions and overestimation of future emissions. To specifically demonstrate this effect, the case study was intentionally limited to module B6 and within it, heating and cooling. When interpreting the results, note the limitation stemming from the exclusion of embodied emissions. These include not only the emissions from equipping the building with cooling but also those from necessary repairs to maintain the building in use over the long term. Even though a fully fledged whole-life LCA is not presented for the case study, one must be performed to draw robust conclusions for decision-making purposes.

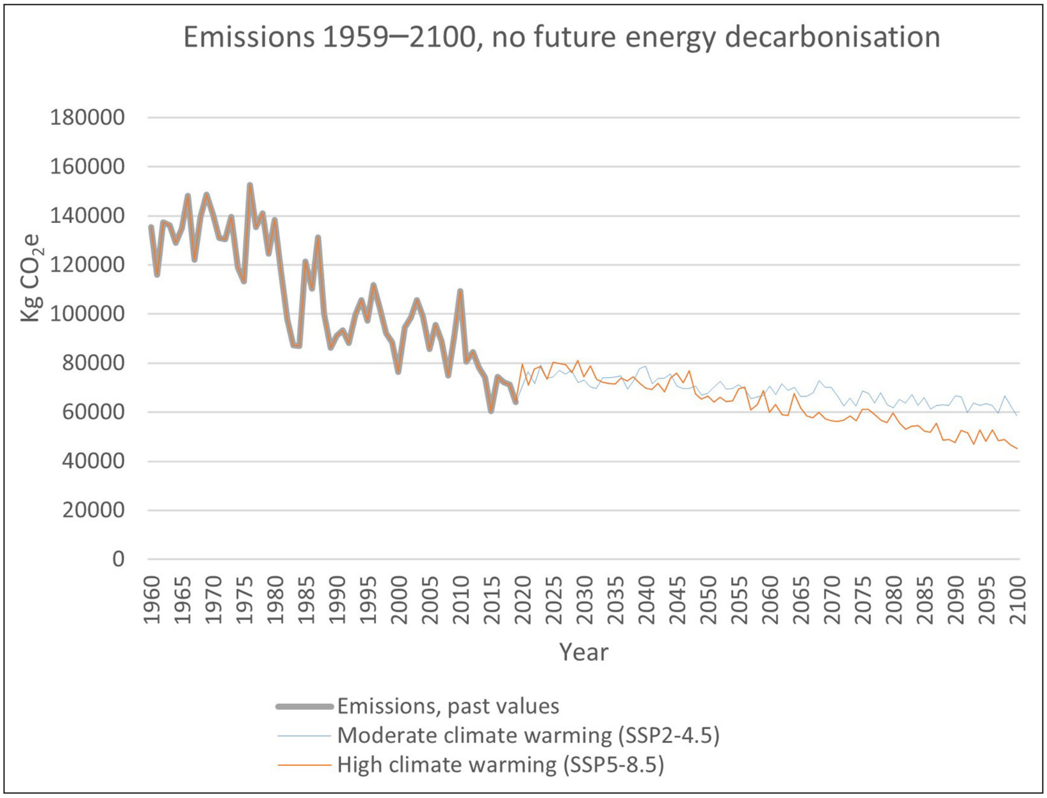

Figure 4: Case study building's heating emissions, 1959–2100, and cooling emissions, 2020 onwards.

Note: Projected energy decarbonisation is omitted. The period 2020–2100 uses the emission coefficients of 2020, thus illustrating the impact of climate warming only.

4 DISCUSSION AND CONCLUSIONS

This paper explained a simple method to estimate a building's past and/or future heating and/or cooling emissions based on the DD method and emission coefficients for energy production. The DD method is readily familiar to many building energy practitioners, so the covered technique should be easy to adopt. It is very straightforward to replicate: the only building-related input data are its annual energy consumption, and performing the calculation does not require any special software. It should be noted that the method pertains to a part of life cycle module B6 only, so it produces a partial picture of a building's whole-life emissions. However, the underlying motivation to introduce the method is to help refine how these emissions are modelled in whole-life LCA.

Researchers may have more elaborate modelling methods at their disposal, but the DD-EEC method is a low-threshold improvement to how heating and/or cooling-related emissions are handled in building energy and LCA practice. Policymakers, building owners and investors make impactful real-life decisions based on reports commissioned from consultants, rather than the scientific state-of-the-art. Therefore, the methods used by practitioners carry a lot of weight in the implementation of the sustainability transition. Too simple methods risk incorrect conclusions resulting potentially in decisions with large-scale adverse effects. Building energy practitioners, construction and real-estate sector decision-makers, and public policymakers must therefore understand that in times of change, the past or present may not be the best predictor of the future. Moreover, the method helps to distinguish the likely individual contributions of climate warming and energy decarbonisation to a building's operational emissions performance.

The most fruitful use cases of the demonstrated technique relate to decision-making situations where a building's (1) past or present and future operational emissions or costs are compared, (2) future embodied and operational emissions or costs are juxtaposed, or (3) both are done at the same time. The first decision-making situation taps into the emerging discussion whether 'fabric first', *i.e.* prioritising thermal improvement of building envelopes over low-carbon building services, is still the right approach for the existing building stock (*cf.* Eyre *et al.* 2023). It should be noted though that the DD-EEC method essentially introduces a coefficient by which a known energy consumption is multiplied. Therefore, if the performances of two or more buildings are compared, using the method will not change their mutual order, unless embodied emissions are also considered (as in the third decision-making situation).

In terms of the second situation, when new buildings or renovations are designed, trade-offs can occur between embodied and operational emissions (*i.e.* a decrease in one can denote an increase in the other). Decision-makers may want to balance these to achieve the best whole-life performance, which cannot be achieved if the modelling of the operational phase is biased. For example, Li & Tingley (2023) used the DD-EEC approach to determine the optimal insulation thickness to retrofit the English housing stock. The third situation occurs if a decision-maker deliberates the choice of premises (existing, renovated or new) or considers building replacement (*cf*. Huuhka *et al*. 2023). In such cases, not only the embodied and operational performances of one building or design are compared, but those of an existing building (or its renovation) are juxtaposed with those of a new building. In these situations, it is essential that the modelling of a key phase, such as the heating/cooling part of module B6, reflects a likely future. Otherwise, the results and conclusions drawn can be distorted.

The ratio between a building's embodied and operational emissions will depend on the length of the life cycle and on the location (climatic context and building culture). So will the percentage of heating and/or cooling emissions of the whole of operational emissions, and which one (heating or cooling) is more dominant. Therefore, the significance of the introduced methodological improvement will vary by context. In cold regions, such as Finland, whole-life emissions have so far been dominated by operational emissions, which are dominated by heating energy use. For example, heating accounts for 92%, domestic hot water for 7% and cooling for 1% of the case study building's present operational energy demand. Conducting more studies and in particular whole-life LCAs using the DD-EEC method for module B6 will help to uncover how important the introduced improvement is in different contexts. The naming and formalisation of the method enables to initiate the accumulation of this body of research.

The DD part of the method has applications in life cycle costing (LCC), too. The use of the DD-EEC approach by the Institut für Immobilienökonomie (2023) relates to this, as its purpose is to help real-estate investors to price risks pertaining to operational CO_2 emissions. In LCC, energy costs and interest rates are used as variables, but the energy consumption is usually assumed to be a constant. Forecasting future energy consumption with DDs can help to estimate operational energy costs in a way that is more reflective of possible and likely futures than a simple generalisation of the present state.

Of course, the method relies heavily on the DD values and emission coefficients for energy production. While past DD and emission coefficients are based on empirical data, deep uncertainty pertains to those for the future, which rely on predictive modelling. The availability of reliable data is a key consideration whether the DD-EEC method can be incorporated into public policy, such as buildings' climate declarations. National building LCA methods and databases, such as the Finnish ones used in the case study, may already include research-based energy decarbonisation trajectories. Climate modelling-based prospective DD have likewise been published by research institutions under the auspices of the EU, founded on Intergovernmental Panel on Climate Change (IPCC)-endorsed Representative Concentration Pathways. With such research-based datasets, the showcased technique helps to create a more nuanced and comprehensive understanding about likely futures than the current practice, despite the inherent uncertainties involved.

To improve how potential futures are modelled in module B6 even further, future iterations should look at possibilities to incorporate the influence of users. User behaviour can manifold a building's energy uptake (*e.g.* Vinha *et al*. 2009: 91–92; Sunikka-Blank & Galvin 2012). Thus, they can be a 'force of nature' not unlike climate change or energy decarbonisation that should not be underestimated.

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SH: conceptualisation, methodology, writing—original draft, writing—review and editing; supervision, project administration, funding acquisition; MM: investigation, visualisation, writing—original draft; MA: conceptualisation, data curation.

COMPETING INTERESTS

The authors declare no competing interests. SH is a member of the journal's editorial board; however, the authors confirm they were not involved in any of the editorial and decision-making processes with regard to this manuscript. The manuscript received no preferential treatment from the journal as a result of SH's position.

DATA ACCESSIBILITY

The past weather and degree-day (DD) data used in the article are available in Open Access (OA) from the Finnish Meteorological Institute (FMI) (2024, n.d. a, n.d. b). The future DD data used are available by request from the FMI climate service, climateservice@fmi.fi.

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SUPPLEMENTAL DATA

Supplemental data for this paper can be found at: https://doi.org/10.5334/bc.419.s1.

REFERENCES

Andrew, R. M., & **Peters, G. P.** (2023). *The Global Carbon Project's fossil CO_2 emissions dataset (2023v36)*. Zenodo. DOI: https://doi.org/10.5281/zenodo.10177738

CEN. (2011). *EN 15978: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method*. European Committee for Standardization.

Energy Institute. (2023). *Statistical review of world energy*. https://www.energyinst.org/statistical-review/

EU. (2022). *Heating and cooling degree days from 1979 to 2100*. European Union (EU). https://cds.climate.copernicus.eu/cdsapp#!/software/app-heating-cooling-degree-days?tab=overview

Eurostat. (2023). *Heating and cooling degree days—Statistics*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Heating_and_cooling_degree_days_-_statistics

Eurostat. (n.d.). *NUTS—Nomenclature of territorial units for statistics. Overview*. https://ec.europa.eu/eurostat/web/nuts/overview

Eyre, N., Fawcett, T., Topouzi, M., Killip, G., Oreszczyn, T., Jenkinson, K., & **Rosenow, J.** (2023). Fabric first: Is it still the right approach? *Buildings & Cities*, 4(1), 965–972. DOI: https://doi.org/10.5334/bc.388

FEI. (2023a). *Emissions database for construction. Energy, district heating*. Finnish Environment Institute (FEI). https://co2data.fi/rakentaminen/#fi_id7000000763

FEI. (2023b). *Emissions database for construction. Energy, district cooling*. Finnish Environment Institute (FEI). https://co2data.fi/rakentaminen/#fi_id7000000777

FMI. (2024). *Lämmitystarveluku eli astepäiväluku* [Degree-day]. Finnish Meteorological Institute (FMI). https://www.ilmatieteenlaitos.fi/lammitystarveluvut

FMI. (n.d. a). *Energianlaskennan testivuodet nykyilmastossa* [Test reference years for energy calculation in today's climate]. Finnish Meteorological Institute (FMI). https://www.ilmatieteenlaitos.fi/energialaskennan-testivuodet-nyky

FMI. (n.d. b). *Havaintojen lataus* [Observation data download]. Finnish Meteorological Institute (FMI). https://www.ilmatieteenlaitos.fi/havaintojen-lataus

Gassert, F., Cornejo, E., & **Nilson, E.** (2021). *Making climate data accessible: Methods for producing NEX-GDDP and LOCA downscaled climate indicators* (Technical Note). World Resources Institute. DOI: https://doi.org/10.46830/writn.19.00117

Huuhka, S., Moisio, M., Salmio, E., Köliö, A., & **Lahdensivu, J.** (2023). Renovate or replace? Consequential replacement LCA framework for buildings. *Buildings & Cities*, 4(1), 212–228. DOI: https://doi.org/10.5334/bc.309

Institut für Immobilienökonomie. (2023). *Carbon risk real estate monitor (CRREM). CRREM risk assessment reference guide: User manual for the CRREM Risk Assessment Tool V2*. https://www.crrem.eu/wp-content/uploads/2023/09/CRREM-Risk-Assessment-Reference-Guide-V2_11_09_2023-final.pdf

Kuittinen, M. (2019). *Method for the whole life carbon assessment of buildings*. MoE. https://julkaisut.valtioneuvosto.fi/handle/10024/161796

Kuittinen, M., & **Häkkinen, T.** (2020). Reduced carbon footprints of buildings: New Finnish standards and assessments. *Buildings & Cities*, 1(1): 182–197. DOI: https://doi.org/10.5334/bc.30

Li, X., & **Tingley, D. D.** (2023). A whole life, national approach to optimize the thickness of wall insulation. *Renewable and Sustainable Energy Reviews*, 174, 113137. DOI: https://doi.org/10.1016/j.rser.2022.113137

Morgan, A. B. (1928). Discussion (commentary on the paper 'The Degree-Day Method of Fuel-Consumption Analysis: Its Application to Fuel Deliveries for Domestic Oil Burners' by W. R. Abbott). *Transactions of the American Society of Mechanical Engineers*, 49–50(10), 105504. DOI: https://doi.org/10.1115/1.4058868

Motiva. (2023). *Kulutuksen normitus. Laskentakaavat ja ohjeet* [Normalization of consumption. Equations and instructions]. https://www.motiva.fi/files/20935/Motiva_Kulutuksennormitus_laskentakaavat-ja-ohjeet_01-2023.pdf

National Weather Service, Climate Prediction Center. (2009). *Degree days statistics*. https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/

Ritchie, H., Rosado, P., & **Roser, M.** (2023). CO_2 and greenhouse gas emissions. In *Our world in data*. https://ourworldindata.org/co2-and-greenhouse-gas-emissions

Ritchie, H., Roser, M., & **Rosado, P.** (2020). Finland: Carbon intensity: How much carbon does it emit per unit of energy? In *Our world in data*. https://ourworldindata.org/co2/country/finland#carbon-intensity-how-much-carbon-does-it-emit-per-unit-of-energy

Ruosteenoja, K., & **Jylhä, K.** (2021). Projected climate change in Finland during the 21st century calculated from CMIP6 model simulations. *Geophysica*, 56(1): 39–69. https://www.geophysica.fi/pdf/geophysica_2021_56_1_039_ruosteenoja_online_supplement.pdf

Soimakallio, S. (2020). *Specific emissions for district heat, district cooling and electricity used in buildings* (Background report to Finnish Environment Institute [2023]). https://co2data.fi/rakentaminen/reports/Energy%20service%20R01.00.pdf

Sunikka-Blank, M., & **Galvin, R.** (2012). Introducing the prebound effect: The gap between performance and actual energy consumption. *Building Research & Information*, 40(3), 260–273. DOI: https://doi.org/10.1080/09613218.2012.690952

US EIA. (2023). *International energy data*. US Energy Information Administration (US EIA). https://www.eia.gov/opendata/bulkfiles.php

Vaughn, D. M. (2005). Degree days. In Oliver, J. E. (Ed.), *Encyclopedia of world climatology*. Springer. DOI: https://doi.org/10.1007/1-4020-3266-8_64

Vinha, J., Korpi, M., Kalamees, T., Jokisalo, J., Eskola, L., Palonen, J., Kurnitski, J., Aho, H., Salminen, M., Salminen, K., & **Keto, M.** (2009). *Asuinrakennusten ilmanpitävyys, sisäilmasto ja energiatalous* [Air tightness, indoor climate and energy economy of detached houses and apartments] (Rakennustekniikan laitos. Rakennetekniikka. Tutkimusraportti 140) [Department of Civil Engineering. Structural Engineering. Research Report No. 140]. TTY. http://urn.fi/URN:NBN:fi:tty-2011122914971

Walker, L., Hischier, I., & **Schlueter, A.** (2022). Does context matter? Robust building retrofit decision-making for decarbonization across Europe. *Building and Environment*, 226, 109666. DOI: https://doi.org/10.1016/j.buildenv.2022.109666

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