Integrating climate change in life cycle assessment of buildings: literature review

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Abstract. The operational energy use and related greenhouse gas emissions of buildings are typically influenced by changes during the building service life such as climate change, technological evolution and energy mix evolution. Only few LCA studies consider these temporal variations. This paper investigates how climate change is currently considered in LCA studies. Three aspects related to the influence of climate change on the life cycle impact of buildings are focused on: (1) changes in operational energy use (heating and cooling) due to changes in the climatic context of the building, (2) changes in operational energy use due to technological evolution or climate regulations and (3) changes in energy mix due to climate regulations. All three influence the energy use and related environmental impact but the extent of the effect depends on the considered region, time step and environmental indicators. It is hence recommended to choose an appropriate time period when considering climate change in LCA and consider variations within a time period via dynamic building simulations or to include a static correction. A holistic set of impact categories should be focussed on to avoid burden shifting and the most influencing parameters should be checked via a sensitivity analysis.

1. Introduction
In 2017, buildings accounted for 36% of the final energy use worldwide and for nearly 40% of the CO₂-emissions [1]. Various studies identified that the operational energy use contributes most to the life cycle CO₂ emissions of a building [2–4]. This includes the energy needed for heating, hot water supply, air conditioning, ventilation, lighting and auxiliary energy used for pumps, control and automation [5]. Several parameters influence the operational energy use and related CO₂ emissions of buildings, such as energy equipment technology and characteristics, occupant behavior, climate conditions, energy mix and policy rules [6–10]. In addition, these parameters typically change over the life cycle of the building. Current environmental impact studies however typically do not consider these changes [11]. Operational energy use is for example often estimated based on a one-year dynamic calculation for a representative year [2,11] or a static calculation based on degree days [4,9,12,13] and standard Life Cycle Assessments (LCAs) assume a static (current) energy mix for the whole building service life.

This is confirmed by Collinge et al. [8], stating that current LCA approaches are mostly static assuming point values for flows (inputs and outputs), emissions and characterization factors. Time-related changes however do affect these variables considerably [7,8]. Dynamic LCA (DLCA) does take into account these temporal changes and is defined by Collinge et al. [8] as “an approach to LCA which explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems”. Only few LCA studies were found that indeed consider these temporal variations when assessing the life cycle impact of buildings.
In his paper Collinge distinguishes dynamic methods applied to the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA). Su et al. [7] follows this distinction and further divides them in four dynamics: technological progress, variation in occupancy behaviour, dynamic characterisation factors and dynamic weighting factors. The first two aspects are related to the building processes (inventory), while the last two are related to the impact assessment. Negishi et al. [6] defines three levels of which the first two (i.e. building technology level and end-user level) overlap with the first two dynamics defined by Su et al. His additional third level considers changes in the external system of the building, i.e. changes in energy production mix, climate conditions and climate regulations.

This paper focuses on one of these changes in the external system of the building, more specifically climate change. The aim is to investigate how climate change is currently taken into account in LCA studies and if any recommendations for improvement can be formulated. Three aspects related to the influence of climate change on the life cycle impact of buildings are focused on: (1) changes in operational energy use (heating and cooling) due to changes in the climatic context of the building during its service life, (2) changes in operational energy use due to technological evolution or climate regulations and (3) changes in energy mix (increase of renewable energy) due to climate regulations [14]. For example, the increased efficiency regulations lead to a shift towards electrical heat pumps being partly responsible for an increase in electricity use [14].

The next section presents the state of the art regarding the consideration of climate change in dynamic LCA considering the three aspects mentioned before based on a literature study. The influence on both the energy demand and related emissions are reviewed. The state of the art is discussed and recommendations for improvement are formulated in a final section.

2. State of the art

A state of the art is provided for each of the three aspects related to climate change and LCA as mentioned before (section 2.2 – 2.4). This is preceded by an overview of the state of the art of methods used in LCA to calculate the operational energy use (section 2.1).

2.1. Estimation of life cycle energy use and related environmental impacts

In current LCA practice, the operational energy use of buildings is calculated in different ways. A first method is based on heating and cooling degree days, applied amongst others in the research of Passer et al. [4], Isaac and Van Vuuren [9] and Roux et al. [15]. Heating or cooling is assumed to be needed from a certain external temperature onwards till a certain indoor temperature. The research of Trigaux et al. [16] defines dynamic equivalent heating degree days which consider internal heat gains and detailed solar gains. The yearly heating energy calculation includes in addition to these gains also the thermal losses through the building envelope (transmission and ventilation losses).

A second method is to use dynamic energy simulations. Komerska et al. [17] integrates thermal dynamic building simulations (i.e. DesignBuilder model) in their LCA study of office buildings in Poland to evaluate different façade solutions. A one-year simulation is used to estimate the energy consumption for the different solutions and kept constant during the building service life. Azari et al. [11] established an integrated framework by combining the Athena Impact Estimator for Buildings (LCA tool) and the eQuest energy analysis tool. The dynamic building energy simulation performed with eQuest is manually entered in the Athena framework. Similar as to Komerska et al. this is a point value in the sense that the input for Athena exists of the annual energy consumption for the different energy uses (i.e. lighting, space cooling, space heating and other).

The research of Allacker et al. [2] combines dynamic energy simulations with LCA on the building level to calculate the effect of micro-scale measures on the macro-scale and to compare different scenarios. In this study, climate datasets of three cities (Athens, Strasbourg and Helsinki) are used to represent three climatic zones across Europe. Different studies [9,18] have included multiple locations to get insights in the effect of regional climate. Again, these studies assume the climate unchanged over the building service life.
The research of Collinge et al. [8] used measured operational energy uses based on monitoring. Monthly data for energy uses and historical fuel mixes for the electricity grid and heating plant were available. The use of monitored data is of course only possible for constructed buildings and is not an option in the design phase. In his research, a dynamic mathematical model was developed considering at each moment in time the different energy uses and fuel mixes. The service life of the building is divided in two periods before and after renovation. Before renovation the detailed data is used, while for the period after renovation an estimation is made based on a model and kept constant for the remaining years. The model allows to keep constant values over the different time steps.

2.2. Changes in operational energy use due to climate change

Buildings are typically designed for certain environmental conditions but will have to deal with other conditions during their service life. The energy performance of a building will inherently be influenced by global warming. Worldwide, a reduction of the heating demand of 34% is expected by 2100 under a median climate change scenario, while an increase of the air-conditioning energy demand by 72% is expected [9]. It should be noted that part of these global changes is also caused by non-climatic drivers such as increasing income, population growth, and energy efficiency [9,19]. Globally the net effect on energy demand is expected to be relatively small compared with the total energy demand, however this highly depends on the climate change scenario (and related weather data) and assumptions made [9,18,20,21] as well as the region considered. For Europe, the IPCC report [22] states an increase of the cooling energy under a 3.7°C scenario to increase by 74% to 118% by 2100. A decrease of 0.7% per year is projected from 2010 onwards for heating energy.

In Europe, the share of cooling in the total building final energy use tripled since 1990 to 12% [19]. Most literature sources agree on the fact that raising temperatures are expected to decrease the heating demand of buildings and to increase the cooling demand [9,15,20,22–24]. However, there is more discussion about how big this effect will be depending on the region studied as well as the climate change scenario considered [19]. More specific, till 2050 a reduction is expected, followed by an increase in the second half of the century. For Europe, the reduction in heating demand is expected to outweigh the increase in cooling demand for the northern and central part at least till 2035 [9,25–27]. For the southern part, this is not the case and an increasing cooling demand will lead to a net increase. In addition to changes between heating and cooling loads, also seasonal patterns will be influenced by climate change having impacts on energy needs and mixes [9]. Winter peaks are expected to be less pronounced in future.

Looking to the related greenhouse gas (GHG) emissions, Isaac and van Vuuren [9] state a clear increase in the second half of the century on global level where India will be the most affected country. An increase of CO₂-emissions from 0.8 Gt C in 2000 to 2.2 Gt C in 2100 is projected which is about 12% of the total CO₂-emissions from energy use. Looking to heating and cooling separately, heating related emissions are stated to decrease with 36% by 2100 while the cooling related emissions are expected to increase with 72% by 2100 [9]. Heating is commonly foreseen with secondary energy sources while air conditioning in buildings is often anticipated by electricity likely leading to increased emissions and to outweigh the reduction of the heating related emissions [24,28]. Though this conclusion is very sensitive to the scenario used and the region studied [9,24]. In addition, several studies stressed the importance of the energy efficiency of the cooling system in buildings to reduce emissions [24,25,29].

The research of Williams et al. [24] presents a methodology for the early design stage which links the GHG emissions of heating and cooling energy with climate change, more specifically with changing external temperatures through a unique building fingerprint. The fingerprint is calibrated based on selection of weather years representing average, cold and warm years for a low, median and high emission scenario out of the 3000 years generated with the UKCP09 Weather Generator for different climate change scenarios. The fingerprint allows to calculate the GHG emissions for any weather year for that specific building and to consider the effect of climate change related uncertainties. Different
climate change scenarios were found to influence the total GHG emissions during the life cycle to an important extent.

The research of Colling et al. [8] used energy consumptions based on utility meters between 1979 and 2009. Changes in emission factors were found to have the biggest influence. Although, the electrical energy consumption increased over this period (due to an increased building footprint), it was outweighed by the decrease in GHG emissions from the energy supply. The latter was mainly caused by a decarbonisation of the district steam production (switch to 100% gas).

The research of Roux et al. [15] considers a variable energy use (and energy mix) for different time perspectives. The building service life is divided in three periods around 2020, 2030 and 2050 for which a certain energy use (and mix) are assumed to be constant. The energy use is estimated by projecting current degree-days with a high and low climate change scenario to the respective points in time.

The research of Negishi et al. [6] proposes a five-step framework which integrates the time dimension at different steps of the LCA. In the first step a dynamic energy simulation is performed with the COMETH software as it allows to consider long-term temporal changes such as a decrease in heating demand due to global warming. Similar as to the research of Roux et al. [15], the service life is gridded in different periods characterized by constant parameters for the processes involved. By contrast, depending on the building subsystem, these periods could be limited to one year and should not necessarily encounter multiple years.

2.3. Changes in operational energy use due to technological evolution due to climate regulations

The EU has set the goal to decrease GHG emissions by 80 to 98% by 2050 [30] which requires changes in the current energy systems and hence energy mix. To achieve this, amongst others, goals are set for further efficiency measures of equipment [14]. The strengthening of energy efficiency policies is expected to result in a trend towards electrification of the heating need (i.e. heat pumps) [14,30]. Though, electrification does not necessarily lead to lower environmental impacts. The research of Blom et al. [10] shows that even though a heat pump does not use fossil fuels, it could have higher environmental impacts than a gas-fired boiler depending on the coefficient of performance (CoP) caused by the higher environmental impact of electricity than natural gas in the Netherlands. Including the materials and refrigerants of the pump even increase the difference with a boiler. In contrast, further improvement of the efficiency rate will partly compensate this difference in future.

In the past decades, policy increased insulation values for building. By consequence, the thickness of insulation improved, glazing systems develop from single glazing to triple glazing systems with coatings. However, once a building is insulated, the effect of additional insulation is rather small on the total heating energy as shown in the research of Waddicor et al. [25]. It was even found to slightly increase the cooling load due to an improved air tightness and reduced thermal bridging. Improving window insulation has an important influence on the energy demands, however a good balance should be found between reducing solar gains in summer and increasing in winter. While a good insulating value is recommended for different regions, low g-values are only recommended in hotter arid locations and could lead to higher heating loads in cold locations. His study further highlights the increase of efficiency for the chiller as the most effective measure to reduce cooling energy as mentioned by other studies before [24,29].

2.4. Changes in energy mix due to climate regulations

In addition to increased efficiency measurements, also goals are set to reduce the use of fossil fuels and increase the use of renewables influencing the energy mix. By consequence, trends such as a shift from oil to gas and electrification of heating are expected [14]. Electricity is the fastest growing form of final energy use and multiple studies stress the importance of electricity in future. In Europe fossil sources are however still used for more than 50% of its production [27]. The energy mix evolution will have an influence on energy consumption related emissions of a building [10,12,15,24,31]. However, in most of the LCA studies an average energy mix is used and kept constant for the full building service life even though this mix is subjected to temporal variations from daily to decadal scale [15]. Multiple studies
were found to investigate a specific aspect of a changing energy mix (i.e. specific equipment component or mix evolution) but only few were found to study this in a building LCA.

In Europe, the increased share of renewables in the electricity mix is mainly driven by an increase of wind power [14]. The solar and biomass fraction both increase as well, but not as significantly as for wind. Multiple studies investigated the influence of climate change on the solar and wind power generation. For PV generation, it is unlikely that climate change will be a threat in Europe. Studies confirm possible decreases in the range of 15% and possible increase of some percent [32,33].

The research of Blom et al. [10] compares the use of gas and electricity consumption in Dutch apartment buildings. For the Dutch situation, the research shows a higher impact of the electricity consumption per MJ of energy than for gas caused by the low heating demand of the building. Gas is found to have a higher impact when considering the average consumption of all households in all dwelling types. Changing the sources for electricity generation influences the environmental impact, however, they should be chosen carefully as impacts could be shifted to other indicators. This shifting applies in general when reducing heat demand by increasing electric share or replacing gas by electricity consumption. A holistic approach is hence recommended to take well-founded decisions between multiple options.

The effect of the country specific electricity mix is highlighted in amongst others the research of Vuarnoz et al. [31]. For the year studied, the 17% of the electricity on the Swiss grid supplied by Germany was responsible for 70% of the GHG emission of this Swiss mix caused by the high share of fossil fuels used in the German electricity production.

Roux et al. [12,15] describe the importance of considering temporal variations in the electricity mix. In Roux et al. [15] a business as usual evolution and a scenario with the introduction of a carbon tax in France were used to predict future energy mix evolution. Further research of Roux [12] considers the hourly variation in the electricity mix. In this case, the environmental impact of the mix for that hour is multiplied by the consumed energy instead of using a yearly average environmental impact. It was found that the annual average mix leads to an important underestimation for Global Warming Potential (GWP) and Abiotic Depletion Potential mainly caused by higher shares of coal and gas power plants during winter. By using an hourly time step, differences in electricity production between on- and off-peak hours can be accounted for as well as on-site electricity production. Consistency between the energy simulation and electricity mix evaluation is hence recommended. The need for a representative hourly mix is stressed as real years could be subject to climatic or economic conditions and in consequence might not be representative for the years after. In further research [34], Roux stressed the importance of up-to-date data if electricity has an important share in the system as linked technologies and installed capacity change rapidly (e.g. increase in renewable power plant capacity).

3. Discussion
A literature review showed the relevant impact of climate change and climate regulations induced changes on the energy use and related GHG emissions. Based on the reviewed researches, LCA studies should be performed for an appropriate spatial context (e.g. full country or specific region or even city) as climate change impacts on buildings and climate policies could differ to a large extent from region to region. Further, three aspects are highlighted to be considered when performing a building LCA which are discussed in the following subsections: (1) considered time step; (2) holistic approach; and (3) uncertainties.

3.1. Time steps within service life of a building
As stated by Su et al. [7] ignoring time-varying influences decreases the accuracy of the assessment results. Time-varying influences can be defined on the short-, mid- and long-term perspective. When considering effects of climate change and long-term energy mix evolution, time steps of 20-25 years come forward as changes are mostly projected to future points in time (i.e. 2030, 2050 and 2100). Dividing the service life in two or three periods as proposed by Roux et al. with a certain energy use and energy mix for that period seems a good option to encounter these changes. Alternatively, linear
interpolation could be used between different scenarios in time. However, as both climate change and mix evolution do not change linearly, it would not necessary give an improved accuracy. For the energy mix defined, it was found that considering daily, weekly and seasonal variations are important. Instead of using an annual average mix, it is recommended to use per time period a yearly profile encountering these variations.

Technological changes rather evolve year by year. Replacement of elements will moreover intervene with these longer periods defined for climate change effects and energy mix. A shorter time step, as suggested by Negishi is more suited for the replacement of technical equipment.

Ideally changes in energy use due to climate change and technological evolutions are encountered by multi-year dynamic building simulations. If impossible or unworkable, the authors suggest to consider the change by technological improvement by applying a correction on the estimated energy use due to climate change (e.g. 5% reduction due to increased system efficiency of the heating system).

3.2. Holistic approach
A holistic approach is recommended to avoid burden shifting when considering changes between different end-energy uses, energy mixes and technologies. Other indicators than GWP should be focussed on such as acidification and terrestrial ecotoxicity. The shift towards more electricity use instead of fossil fuels has a significant negative impact on those indicators. Not considering those could lead to burden shifting.

3.3. Uncertainties
As all the studied changes will happen in future, it is important to consider the related uncertainties to come up with robust choices. Firstly, the influence of the climate change scenario chosen was highlighted multiple times in the reviewed literature. Considering multiple climate change scenarios as done by Williams et al. is recommended by the authors to get insights in the spread of energy use and related emissions. The multiple climate models available can be used to investigate the spread across different climate change scenarios. As this could be time intensive, a thorough study based on one scenario with a sensitivity study based on a worst case and best-case climate change scenario could already provide relevant information about the most sensitive components of the building LCA model.

Secondly, it is unsure when certain shifts (e.g. higher cooling than heating load or shift from gas to electricity) will happen and this might highly depend on the building characteristics and location. Multi-year dynamic simulations are recommended to get insights in these dynamics.

Lastly, evolutions in energy mixes and energy efficiencies are often driven by policy goals. It is however uncertain if these will evolve linearly towards those goals or not and whether they will be reached within the foreseen timeframe. If the goal of the LCA study is to get insights in the influence of changes, the authors recommend to assume linear trends. If the goal is to see which reductions in GHG emissions are needed by when to avoid further climate change, a sensitivity study on time steps is recommended to identify the necessary changes and their time steps.

4. Conclusion
This paper investigates changes in operational energy use and related emissions caused by climate change and how these are currently considered in building LCA studies. Three aspects are focused on during a literature review: (1) changes in operational energy use (heating and cooling) due to changes in the climatic context of the building during its service life, (2) changes in operational energy use due to technological evolution or climate regulations and (3) changes in energy mix (increase of renewable energy) due to climate regulations. All three were found to have an important influence on the energy use and related emissions, though the extent of influence depends on the considered region, time step and environmental indicators. The authors recommend to choose an appropriate time step for the investigated influences and to allow for changes within different time steps by means of dynamic building simulations (preferable multi-year simulation) or correction. Further a holistic approach is recommended to avoid burden shifting and to make well-founded decisions. Lastly, uncertainties are
inherently linked with future projections. Therefore, sensitivity analysis with at least best- and worst-case scenarios is recommended for the studied parameters to obtain robust design decisions.

Acknowledgements

This paper is part of an SBO PhD fellowship ‘Towards future-proof buildings in Flanders: Climate and Life Cycle modelling for resilient office buildings’ (1S97418N) funded by Research Foundation Flanders (FWO).

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