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Comparative environmental assessment of heat pumps and gas boilers under evolving electricity mixes and climate change: A Case Study of a Residential Building in London

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Abstract

This study compares the environmental performance of 18 impacts of a timber structured residential building in London, when heating and DHW are either provided by a heat pump or a condensing gas boiler by considering the dynamic effects of climate change and electricity mix evolution. A Life Cycle Assessment (LCA) approach was followed. To accurately describe future electricity mixes relevant for embodied and operational modules, the Life Cycle Inventory (LCI) was modified reflecting future projections for the UK, EU and China. The influence of climate change was considered through dynamic thermal simulations using London's future climatic projections. Results show a general reducing trend in the building's heating demand driving the overall energy needs of module B6 of EN15978 down. Switching to a heat pump makes the building perform significantly better in terms of lifecycle carbon, land transformation and fossil depletion benefiting from grid decarbonisation. However, the pressure on several beyond carbon impacts such as ozone depletion, ecotoxicity, eutrophication and metal depletion intensifies. This highlights the need for a holistic approach when switching technologies towards Net Zero to avoid trade-offs. As most beyond carbon impacts that expect intensified pressure are geographically specific, future research is needed to examine whether more granular data will corroborate this study's trends. This is to help assess whether the pressure on beyond carbon impacts is of concerning magnitude. Finally, although the installation of active cooling devices was not considered for comparability consistency, results show cooling demand might become important in future.

1. Introduction

Buildings account for 42 per cent of EU's annual energy consumption, a third of all materials consumed and 4 per cent of European land use [1]. In 2008, the UK has enacted the Climate Change Act requiring Net Zero carbon in 2050 [2]. Similarly, the EU aims at climate neutrality by 2050 and a 55 per cent reduction below 1990 levels by 2030 [3]. Meeting these ambitious targets relies significantly on buildings that contribute to environmental burdens, from raw material extraction to decommissioning.

Efforts to reduce building related Green House Gas (GHG) emissions focus on optimising thermal envelopes and electrification of services that can benefit from renewable energy [3]. These led to a surging interest in eco-friendly materials and technologies. Although covering only 10 per cent of global building heating needs [4], heat pumps are considered a low carbon alternative to gas boilers due to their higher efficiency which minimises operational carbon in the case of decarbonised grids [5]. Despite heat pumps lowering significantly the operational carbon there are side-effects on beyond carbon impacts, such as Ozone Depletion (OD) [6,7].

Strict regulations, like UK's Approved Document part L [8], drive demand for low-carbon structural materials. Timber structured buildings are becoming popular due to biomass acting as a temporary carbon storage [9]. Individual studies support that timber structured buildings have lower embodied carbon than concrete and steel ones [10]. However, if timber structured buildings become the norm the pressure on land use - a beyond carbon impact of EN15804 - might intensify [11].

Life Cycle Assessment, governed by EN ISO 14040:2006+A1:2020 [12], assesses the environmental impacts across a product's lifecycle. It is appropriated for the built environment by EN ISO 15978:2011+A2:2019 and EN ISO 15804:2012+A2:2019 [13,14] and cover carbon (CO_{2e}) and beyond carbon environmental impacts (i.e. all remaining impacts such as land use, ozone depletion, water depletion, ecotoxicity etc.). Although ISO 15392:2019 advises equal consideration of all impacts, building LCA literature is still carbon focused [15]. Transitioning to 2050 will see grids decarbonise and climate change evolving. Climate change will alter the heating and cooling demand of buildings [16] and decarbonised mixes will affect the manufacturing of building materials and their associated impacts. Although dynamic LCA (an LCA procedure which accounts for those dynamic processes) has emerged, practitioners still work with current-day climate and electricity data [17].

Evaluating mostly carbon through a static approach, risks optimising one impact at the expense of others and creates a knowledge gap. Considering this, research is warranted to investigate how carbon and beyond carbon impacts of low carbon buildings are affected by climate change and grid decarbonisation.

The innovative aspect of this paper, building on [18], is twofold; (a) to compare the carbon and beyond carbon impacts of a timber structured residential building case study using a heat pump versus a condensing gas boiler, by (b) considering the dynamic effects of climate change and evolving electricity mixes.

2. Methodology

To explore the influence of climate change and grid decarbonisation on the building's environmental impacts, 15 scenarios were designed (Figure 1).

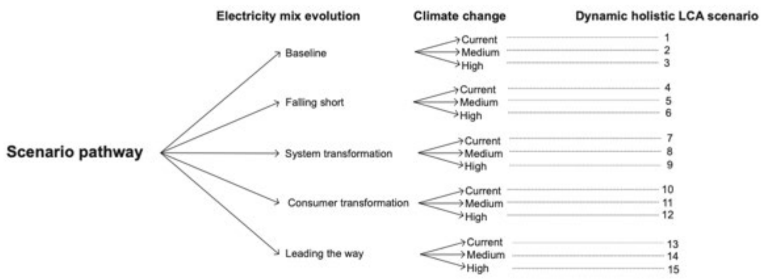

Figure 1. Simulated scenarios

SimaPro 8.03 [20] and IESve [21] have been used for modelling purposes. The Ecoinvent 3.01 [22] Life Cycle Inventory (LCI) was modified on SimaPro to reflect the electricity mix evolution pathways in the UK, the EU and China. Electricity mixes were sourced from [23–25]. For materials manufactured in the UK the Falling Short (FS), Consumer Transformation (CT), System Transformation (ST) and Leading the Way (LW) annual mixes were used by [23]. For materials manufactured in the EU the current and future average EU electricity mixes derived from [24]. For China, current and future electricity mixes derive from [25]. Hydrogen-fuelled electricity and Bioenergy with Carbon Capture and Storage (BECCS) have not been considered as hydrogen has a minimal contribution (less than 1.5 per cent) and BECCS is not yet on track for deployment [26]. To account for UK's net imports from EU, [27] had been followed. Net exports were ignored as they are not part of UK's consumption [27]. For beyond 2050 years, 2050 mixes were assumed to prevail.

IESve [21] helped obtain the module B6 energy needs at an annual level through dynamic thermal simulation for the case study building under current and future weather. To do so, hourly weather files containing projections for climate change by CIBSE were implemented [28]. CIBSE provides weather data relevant for 30-year periods (i.e. 2020s, 2050s, 2080s etc.). The 90th percentile Test Reference Years (TRY) files were used as they give an indication of the extent of likely future warming. RCP 2.6 has been evaluated as unlike [29] and thus, CIBSE medium and high emissions weather files were used. Despite that CIBSE (2021) does not give medium emissions weather files for the 2020-2050 period, this study averaged the 2050s medium and current weather results to obtain an indication of the potential energy consumption for 2020s medium climate. Heating and cooling patterns, temperature setpoints and equipment loads were sourced from UK SAP 10.2 [30] whilst occupancy and lighting loads from CIBSE TM 59 [31]. All elements' thermal properties meet the latest building regulations [8].

The building's LCA was based on the modified Ecoinvent 3.01 [22] using the Characterisation Factors (CF) of ReCiPe [19] in SimaPro [20]. This means that the LCA protocol has not been challenged in any way except for the consideration of climate change and varying electricity mixes.

2.1. Study assumptions

The lifespan of the case building was taken at 60 years [32]. Any building elements with shorter lifespans were replaced based on their expected lifespan [32]. The electricity involved in material manufacturing processes corresponds to the year each process takes place. For example, upfront impacts A1-A5 make use of 2024 UK baseline mix whilst materials replaced in future use the mix of the respective point in time.

Transportation of products is set at tkm with distances taken from [32]. For non-baseline electricity scenarios (Figure 1) diesel fuelled trucks were electrified using a consumption of 0.926 kWh per km [33]. No changes in the fuel was assumed for sea transport. For UK manufactured elements the electricity used is either FS, CT, ST or LW whereas for EU manufactured ones electricity reflects the average EU mix.

The End of Life (EoL) rates were sourced from [32]. In case recycling is forecasted, this is calculated in module D, meaning that no recycling rate had been considered in modules A. This highlights the importance of reducing upfront material consumption.

The material inventories for the heat pumps and the gas boilers are sourced from [7] and are modelled on a per functional unit basis. An annual 6 per cent R134a refrigerant leakage to be replaced on top of the upfront 4.9 kg was assumed. The heat pump's COP was set at 3.5 whilst the boiler's efficiency at 89.5 per cent. Photovoltaics were modelled based on the inventory of [34] assuming a total 12.51 kg/m^2 with 11 kg of unframed weight and 1.51 kg of frame [35]. Their mounting system requires 5.04 kg of aluminium, and 5.01×10^{-1} kg of EAF steel for those placed on flat roof, and 5.68 kg of aluminium, and 3 kg of EAF steel for those placed on slanted roof [34]. All building materials were UK made except for heat pumps and gas boilers that were EU made according to BEIS (2020). PVs were sourced from China [36].

3. Results and Discussion

Results show a decreasing trend in the primary energy needs of module B6 when climate change is considered (Figure 3) driven by reductions in heating demand. This agrees with studies in the cold European climate [37,38]. Cooling is ignored for comparability consistency, however, if it is to be provided no major savings should be expected.

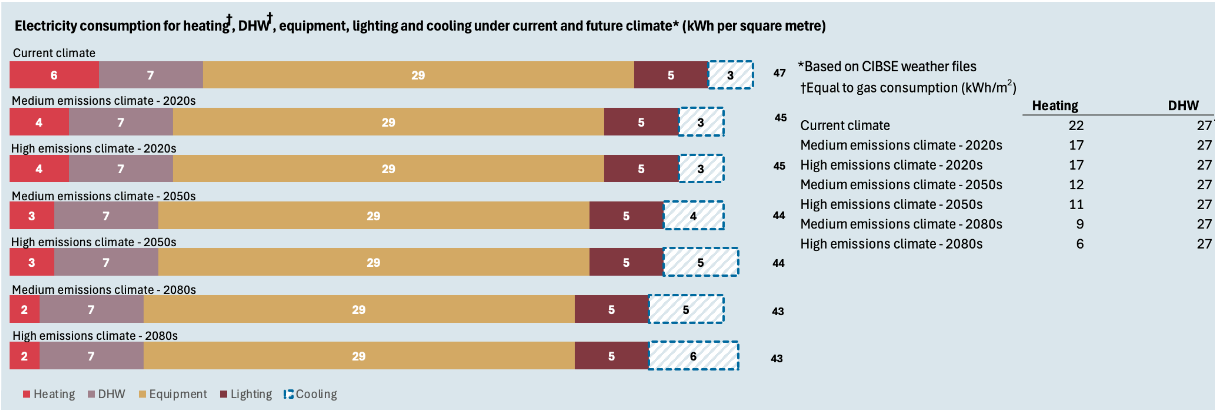

Figure 2. Energy needs of module B6 under current and future weather

Although the same building with a heat pump performs significantly better in terms of lifecycle carbon, land transformation and fossil depletion benefiting from grid decarbonisation, the pressure on beyond carbon impacts intensifies (Figure 3). This echoes research on the risks of achieving carbon targets at the expense of other indicators [39]. Following the ratification of the Montreal Protocol [40] OD has decreased and is now within the safe operating planetary boundary [41]. Nevertheless, non-ozone depleting alternatives to R134a refrigerants should be used if possible, such as R290 [42]. This is to ensure a phase out of CFCs by 2030 [40]. Metal depletion increases in the case of heat pumps highlighting the importance of recycling at EoL [6]. The increases in ecotoxicity, human toxicity and eutrophication are due to renewable electricity's higher impacts compared to gas [43]. Ionising radiation increases due to nuclear electricity [43]. Thus, minimising the overall energy consumption and maximising the exports of surplus of in situ generated electricity is needed to avoid intensifying the pressure on these impacts and balance their lifecycle account.

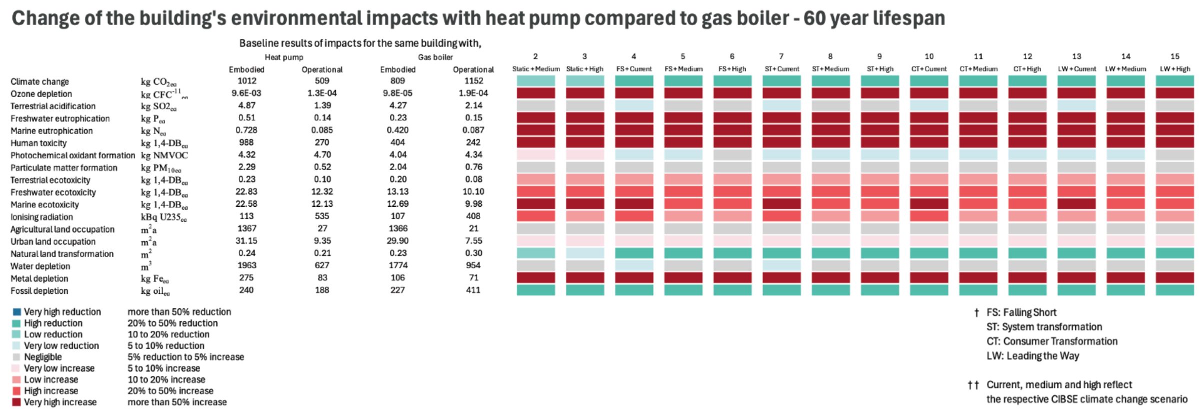

Figure 3. Lifecycle impacts of the same building with a heat pump versus a condensing gas boiler

Not only all environmental impacts are based on localised manufacturing processes, but also most beyond carbon impacts are calculated using regionalised CFs [44]. This means that there is an inherent uncertainty in all LCA studies due to a potential mismatch between the actual case and the life cycle inventory. For example, in this study switching to a heat pump leads to higher urban land occupation for the same building due to the sourcing of electricity from a grid that increases its dependency on photovoltaics. However, if the grid's PVs are to be placed on rooftops this should not be the case. Similar reasoning applies to all regionalised impacts. Thus, the trends showed in this study are indications rather than concrete evidence and it is up to future research to examine whether more granular data would corroborate the present findings.

4. Conclusions

This study investigated the influence of climate change and electricity mix evolution on the lifecycle impacts of a timber structured building in London, when switching from a gas boiler to a heat pump.

Climate change reduced the heating loads driving the overall module B6 needs down. However, if cooling demand is to be met, no major savings should be expected. Switching to a heat pump led the same building perform significantly better across carbon, land transformation, and fossil depletion benefiting from grid decarbonisation. However, this is achieved at the expense of several other beyond carbon impacts highlighting the need for holistic investigations when transitioning to Net Zero and switching technologies to avoid trade-offs and intensifying the pressure on beyond carbon impacts.

Exploring beyond carbon impacts is necessary and this paper serves as a starting point. Future research can identify the anticipated trends when other dynamic aspects are adopted, such as material manufacturing efficiency and the influence of warming temperatures on hot water demand. It can also identify which LCA impacts transgress ecological thresholds in each region of relevance, helping building designers prioritise impacts and address key hotspots. Last but not least, it can quantify the amount of electricity exports to the grid that are needed to reach break-even for impacts forecasted with trade-offs.

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