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High-resolution modelling of heating and cooling demand under societal and climate change scenarios: Implications for the operation of heat pumps in the German commercial sector

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As part of an integrated energy transition, decarbonising heating in the German building sector is a central objective of national energy and climate policy [1]. In particular, the commercial sector plays a crucial role due to its heterogeneous building stock, diverse usage patterns, and significant demand for both space heating and cooling. Effective planning of climate-neutral heat supply pathways based on electrification, renewable energy integration, and sector coupling requires an understanding of how future heat demand unfolds under interacting long-term drivers, such as climate change and societal transformation [2].

Despite its relevance, future energy demand in high resolution has been minimally studied or simplified in energy systems analysis, which leads to inaccurate assessments of electrification potential, peak electricity demand, and its flexibility.

This work aims to address this gap by presenting a methodology to model future heating and cooling demand at high temporal resolution. The approach is applied to the German commercial sector and evaluates six contrasting long-term societal scenarios in combination with three Representative Concentration Pathways (RCP) for climate change. The high-resolution demand modelling is integrated with energy system optimisation to assess the role of electrification through heat pumps, as shown in Figure 1.

Societal change scenarios are derived using a Cross-Impact Balance (CIB) analysis and translated into annual demand values and building stock development [3]. The qualitative CIB scenario narratives are quantified into future annual service demand for space heating, space cooling, and domestic hot water. In addition, projections of the future commercial building stock are being considered.

For each scenario, hourly demand profiles are then generated using an enhanced degree day methodology that accounts for building thermal properties and stock, occupancy patterns and seasonal parameterisation. Model parameters are calibrated for the German commercial sector using publicly available multi-year heating demand data, and validated against statistical and observed consumption data to ensure consistency with historical demand levels. Future climate impacts are incorporated using downscaled temperature projections from climate models. The resulting hourly profiles are then aggregated across building classes and normalized to obtain consistent heating and cooling demand time series for each scenario.

To evaluate the effects on the energy system, the demand profiles are then used as inputs to a set of stylized models of the future German energy system based on the REMix optimization framework [4]. The generated model enables a systematic assessment of how climate induced demand shifts and societal transformations influence technology choices, system costs, and demand peaks.

Results obtained for future heat demand time series across different scenarios and climate change conditions, highlight that societal transformations can influence demand beyond temperature-driven effects. In particular, some societal conditions such as energy-sufficiency strategies and reduced working hours can offset the increase in heat demand expected under severe climate conditions while other scenarios, characterised by longer working hours and a more service oriented society, lead to a higher demand even under more moderate climate pathways (Figure 2). Similarly, future cooling demand under different climate and societal scenarios was analysed (Figure 3).

Further, it was found that societal behavioural patterns can also affect the optimal capacities and operation of heat production technologies. Figure 5 shows the resulting capacities for different assumptions on renewable power generation, while Figure 4 shows an example week of operation.

Current results show that both climate change and societal developments substantially affect not only the annual heating and cooling demand but also its shape in profile, with significant implications for the integration of renewables. The findings highlight the importance of coupling high resolution demand modelling with energy system optimisation when assessing heat transition pathways and the deployment of heat pumps in the commercial building sector.

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