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Mapping operational and embodied emissions in relation to household and ownership profiles with bottom-up building stock analysis: The case of Vaud, Switzerland

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ABSTRACT

We conducted a bottom-up, spatially explicit building stock analysis to examine the social and spatial heterogeneity of operational and embodied emissions of residential buildings in Canton Vaud, Switzerland. Variations emerged between locations, household profiles and ownership types. Urban households exhibited lower embodied emissions per resident, but higher annual operational emissions (1500–1900 kg CO_2/resident), compared to rural households, which showed greater overall variation (1200–2200 kg CO_2/resident). Ownership patterns were less geographically distinct but stratified by type: mixed-ownership buildings exhibited the highest embodied energy, largest material stock and the most modern buildings, whereas community-owned buildings showed the widest variation in annual operational emissions (1500–2300 kg CO_2/resident). Our findings suggest that tailoring emission-reduction interventions to specific social and physical housing contexts would enhance the materials-energy nexus in the built environment. We discuss avenues for reducing energy losses, closing material loops, and incorporating sufficiency into building stock management.

1. Introduction

The built environment provides necessary services such as shelter and mobility for the well-being of people. However, current building and planning practices for construction and demolition, the use of appliances and equipment, and the heating, cooling and lighting of buildings contribute to nearly one-third of global final energy consumption and 38 % of global greenhouse gas emissions (IEA, 2023; UNEP, 2020). As the climate crisis unfolds and disparities in access to services increase, urgent measures are needed to mitigate environmental impacts while meeting human needs (O'Neill et al., 2018). Decarbonisation and circular economy strategies seek to improve and recirculate energy and material flows with the installation of technologies such as photovoltaics and heat pumps, and through the reuse and recycling of material outputs from construction and demolition activities as inputs in new construction (FOEN, 2020). In order to address trade-offs within the materials-energy nexus and move beyond end-of-pipe solutions, sustainability measures need to be aligned with the realities and constraints of the existing building stock and recognise the implications of different building stock-flow configurations on service provision (Haberl et al., 2017; Pauliuk and Müller, 2014).

Building stock analysis quantifies and qualifies the material and energy intensity of buildings across a territory to inform resource and environmental policy (Lanau et al., 2019). The lifecycle of the building stock is determined by more than physical factors; it is influenced by exogenous factors such as urbanisation patterns, and endogenous factors such as inhabitants' behaviour (Thomsen and van der Flier, 2011). It is therefore challenging to capture contextual drivers, impacts, and potentials of a territory without linking the building stock to its social and spatial context (Marin and De Meulder, 2018; Lanau et al., 2019). The social structures within which stocks and flows are embedded provide insights into who governs and influences their management (Binder, 2007; Moreau et al., 2017). The geographic distribution of stocks in a territory can bring to light where there are variations in material and energy intensities, and who shoulders the burdens and benefits of these variations (Bahers et al., 2022; Wuyts and Marjanović, 2023). A lack of attention to socio-spatial context has been identified as a key challenge for informing local decision-makers on how to facilitate the management of resource and energy flows in the urban metabolism (Verga and Khan, 2022; Williams, 2021).

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As such, this article explores the historical and social heterogeneity of residential buildings in the canton of Vaud in Switzerland, in answer to the research question: *How are the material and energy intensities of dwellings associated with their location, household profile, and ownership structure, and what does this imply for a sustainable energy-material nexus in the built environment?*

We conducted a bottom-up, spatially explicit building stock analysis to quantify the material composition of buildings and their associated embodied carbon, and utilised energy certification data to compute their operational energy demand. Previous studies have quantified anthropogenic stocks and flows of building materials using bottom-up approaches for a variety of geographic and sectoral scales in Switzerland (Lichtensteiger and Baccini, 2008; Ostermeyer et al., 2018; Heeren and Hellweg, 2019). Additionally, recent studies have examined the materials-energy nexus by modelling embodied energy and operational energy for different building typologies (Streicher et al., 2018; Priore et al., 2022; Shinde et al., 2024), and exploring scenarios for the future development of the Swiss building stock and its ability to meet climate targets such as the '2000W-society' vision — which envisions inhabitants meeting their needs within an annual energy consumption of 2000 W per person (Pfeiffer et al., 2005; Roca-Puigròs et al., 2020; Röck et al., 2020). We build upon and advance this scholarship by linking our building stock data to national statistical data on ownership and household profiles of dwellings, in order to identify who influences and who is impacted by interventions in the residential built environment. Through this, we aim to contribute to more equitable policies (i.e. subsidy distribution) and better characterise the relationship between societal needs and their associated resource use and emissions.

The article is organised as follows. Section 2 provides a description of the methodology, including a description of the diverse data sources used and how they are combined together. Section 3 provides the findings of the analysis, first presenting the results of calculating the embodied and operational energy of buildings based on their construction period, typology, and energy certification, and then associating it to household profiles and building ownership. Section 4 discusses the implications of our results, limitations and further research. Finally, Section 5 summarises the main conclusions of the analysis.

2. Material and methods

2.1. Case study

Vaud is a canton in the French-speaking region of Switzerland. From 2000–2010, its population was relatively stable, with a total increase of 1.5 %. However, 2010–2020 has marked a decade of growth for the canton, with a 12.5 % increase resulting in a current population of 810,000 residents (OFS, 2021). The dwelling vacancy rate of 1.4 % is markedly lower than the average for Switzerland, implying low tenant mobility and a challenge for newcomers to find housing (OFS, 2021; Pagani et al., 2021). Six new housing units are constructed per 1000 residents every year, with a current stock of 138,000 residential buildings, comprising of 438,000 dwellings (OFS, 2021). The residential building stock consists of over 20 % buildings that predate 1919, and 20 % that were built after 2000, reflecting multiple evolutions in construction methods and materials. In the main urban conglomeration of Lausanne, demolition permits are given for 30–60 buildings per year (A. da Silva, personal communication, 30 January 2024). Vaud subsidises energy retrofits of buildings, for which they mandate an energy performance audit (CECB). This entails an assessment of building elements, the current thermal performance of the envelope, and the state of the heating system by an accredited energy consultant (Canton de Vaud, 2024). The growing need for housing, stable building tenancy, mixed urban-suburban-rural character, and policy ambitions for decarbonisation make it a fitting case study for examining the implications of social, spatial and building heterogeneity on the materials-energy nexus.

2.2. Data collection

This research relies on the following datasets:

i) The CECB database contains information on building envelopes, heating systems, and energy consumption for over 130,000 buildings in Switzerland as of August 2022. This includes data on current energy consumption from electricity, space, and water heating (in kWh for the audit year), as well carbon emissions (in kg CO_2/m^2), which are calculated as the direct CO_2 emissions from fossil fuel combustion on site (CECB, 2023a, 2023b). A single CECB is issued for an entire building envelope and systems, even in buildings with multiple ownership or use types. We extracted 33,066 audits for buildings in Vaud.

ii) The national building register (StatBL) maintained by the Swiss Federal Statistical Office (OFS, 2022) contains information on buildings and dwellings, as well as statistics on the resident populations. At the building level, we extracted geographical coordinates, building category, ownership, construction period, building area, number of dwellings, and heating systems for water and space. Each building is identified by a unique federal building identification number (EGID), allowing us to link this data with the CECB dataset. At the dwelling level, we extracted dwelling area, household composition and age, number of residents per dwelling and the identification number (EWID).

iii) We cross-referenced detailed studies on Swiss buildings (eREN, 2017; Fivet et al., 2024) with building material compositions computed from architectural models and residential stock studies (Shinde et al., 2024; Heeren and Hellweg, 2019) to infer material intensity coefficients across construction periods and building heights. Material intensities are presented for six aggregated categories (in tons/m^2): timber, bricks, concrete, combustibles, metals, and minerals (Gauch et al., 2016). See Appendix A for details on material groups and coefficient calculations.

iv) The KBOB-écobilans database provides environmental impact data for construction materials and building technologies available in Switzerland. It covers life cycle stages from raw material extraction and processing to transportation and end-of-life treatment. Greenhouse gas emissions are expressed as global warming potential, measured in carbon dioxide equivalents (CO_2-eq), and calculated using the 100-year characterisation factors provided by the IPCC (Frischknecht, 2022; KBOB, 2024). In order to calculate the embodied emissions for each building (in kg CO_2-eq), we aggregate the KBOB material categories to match them to the material intensity categories, and then take the median value of emissions for each material group (Appendix A).

v) The OFS delineates the degree of urbanity for a location based on a combination of geographical contiguity and population density, in accordance with definitions set by Eurostat and the OECD (OFS, 2020). We utilise geographic data on local administrative units ("communes") and their classification as: cities, towns and suburbs, or rural areas.

2.3. Data processing

After preprocessing the data (Appendix B), building-level data from StatBL was integrated with CECB certifications using the EGID as a linking identifier. Dwelling-level data were merged based on geographic coordinates, employing a spatial join to match the point to the building footprint. This process yielded two distinct datasets: one at the building level and one at the dwelling level. The objects in both datasets were geolocated, and categorised by degree of urbanity. We cross-verified the datasets based on construction periods, building areas, and categories between the CECB audits and StatBL datasets. To maintain consistency, StatBL data were used as the legitimate source where variables were mismatched. Information was aggregated by commune for a dataset at the territorial level. The final datasets include information on 19,641 buildings (comprising 69,209 dwellings, located in 308 communes), and represents approximately 15 % of the total residential building stock in Vaud. The analysis was conducted on this section of Vaud's building stock, and our results refer to these buildings.

2.4. Building stock analysis

In this study, we take a static, bottom-up approach, which means that building typologies are aggregated by function, form and age, and then the corresponding material intensities for each typology are applied (Augiseau and Barles, 2017). The approach is 'static' because it captures the characteristics of the building stock at a single point in time, without modelling future changes or dynamics such as construction, demolition, or renovation. We examine the relationship between the material and energy intensities of dwellings, their location, the household profile (defined by age, number of occupants, and family composition) and building ownership (Fig. 1). We calculate total material stocks (in tons), operational energy (in kWh), operational emissions (in kg CO_2), and embodied carbon (in kg CO_2-eq) per building, per dwelling, per square metre, and per resident (Appendix C). We use descriptive statistics, focusing on central tendency measures such as median material stock, operational energy use, and emissions across different construction periods, building categories, household profiles, and ownership types to identify variations in resource use and emissions across the territory. Linking building characteristics to their geographic location allows for a spatial analysis of differences between urban, suburban, and rural areas. This approach enables us to map the social and spatial patterns of resource and energy use in the built environment.

3. Results

3.1. Material and energy demand profile of building stock

Fig. 2 illustrates the trends of material use, operational energy demand, and operational and embodied carbon per square metre for single-family buildings, multi-family buildings and mixed-use buildings. The data reveals increasing operational energy demand per square metre for buildings constructed till the 1960s and then a decline over the following construction periods (Fig. 2). Space heating demand decreases in buildings constructed after 2000, water heating demand remains relatively constant throughout construction periods, however, electricity demand (for lighting, appliances, ventilation) increases. The median energy demand per square metre for single-family buildings constructed in the 1950s is 220 kWh, for those constructed in the 1980s it is 110 kWh, and for the 2020s it is 85 kWh. Multi-family buildings and mixed-use buildings follow a similar pattern, however mixed-use buildings display greater variability.

Multi-family and mixed-use buildings have become more material intense over time, notably since the 1980s (Fig. 2). In contrast, the material composition of single-family buildings has changed, but the median material 'weight' has stayed comparable. Buildings constructed before 1900 primarily utilised monolithic rubble masonry with exposed natural stone and timber for roofs and floors (Schwab, 2016). The 1920s marked the introduction of concrete for ground slabs and floors, with facades commonly rendered in monolithic bricks. From the 1940s to 1960s, concrete became widespread, and the 1960s saw the introduction of prefabricated concrete facades, followed by poured concrete facades for high-rise buildings in the 1970s (Marchand and Savoyat, 2012, pp. 1920–1975). The use of bricks and timber has declined with the advent of concrete, with the largest stock held within buildings constructed pre-1960. The stock of combustibles, including insulation, and floor and

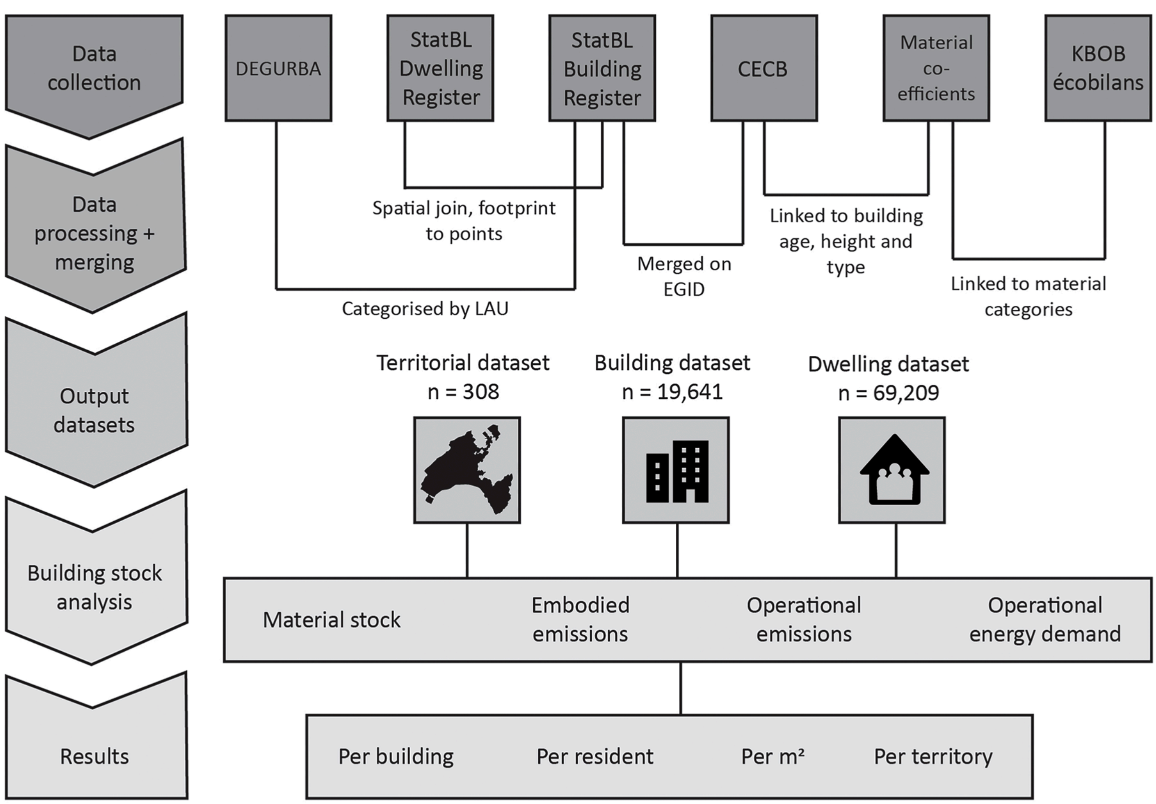

Fig. 1. Methodological framework. Data from the StatBL dwelling and building registers, DEGURBA, CECB, and KBOB were integrated, processed and merged into three outputs: a territorial dataset ($n = 308$), a building dataset ($n = 19,641$), and a dwelling dataset ($n = 69,209$). They are used to analyse material stock, embodied emissions, operational emissions and operational energy demand across the residential building stock in Vaud.

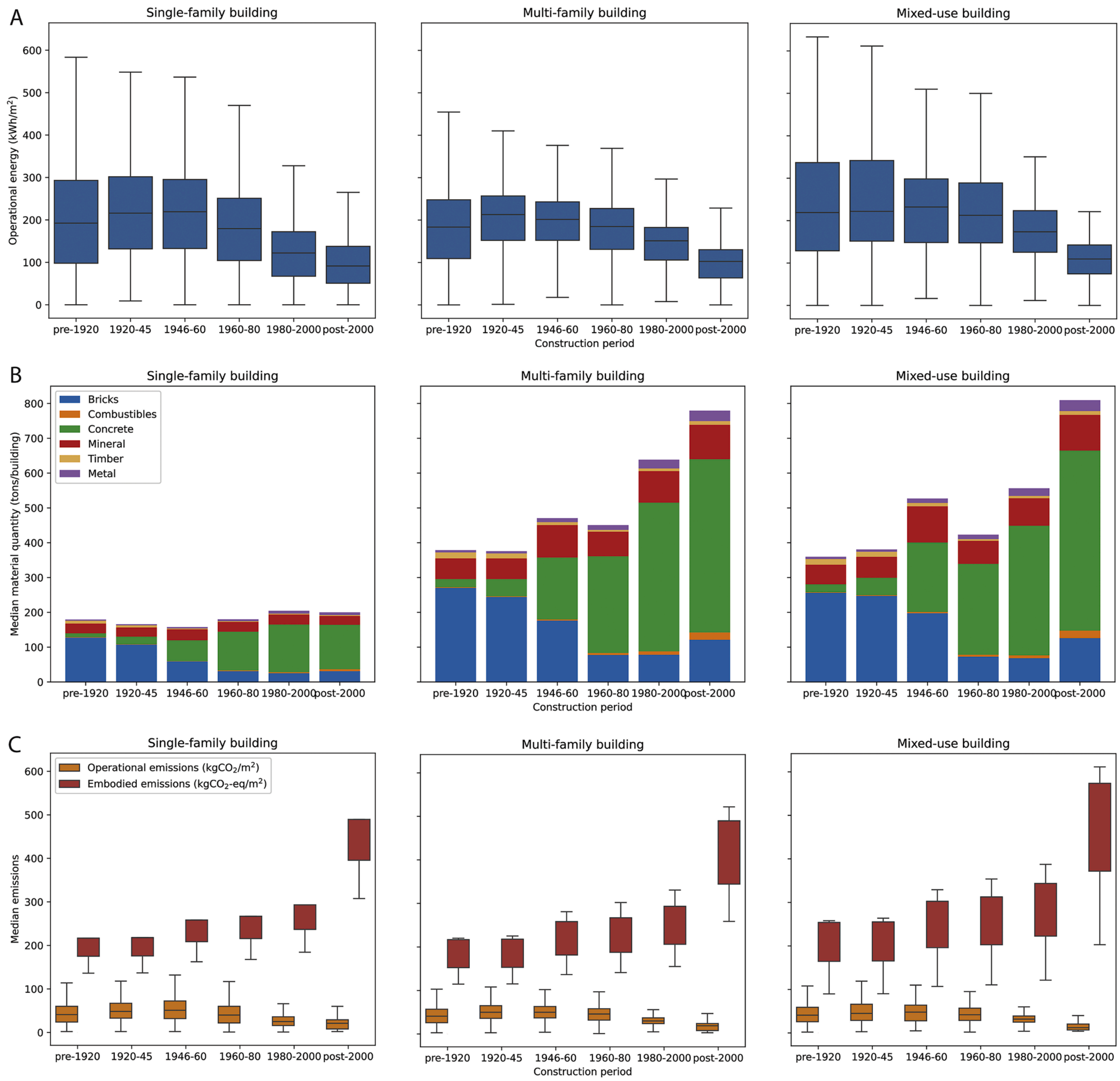

Fig. 2. Material and energy intensity per construction period and per building category. Panel A shows the median annual operational energy demand (kWh/m^2). Panel B shows the median material stock per building (tons/building). Panel C shows the median operational (kg CO_2/m^2) and embodied emissions (kg CO_2-eq/m^2).

wall coverings has increased in buildings constructed post-1980s, with metal following a similar trend. Both remain a small proportion of the total building stock.

The evolution of material compositions is associated with an increase in embodied carbon (Fig. 2). For buildings constructed in the early 1900s the median embodied carbon is 215 kg CO_2-eq/m^2, whereas for construction in the 2000s it has more than doubled to 490 kg CO_2-eq/m^2. In 1998, the first federal energy law was introduced alongside the establishment of the 'Minergie' label for energy-efficient buildings (Haefeli et al., 2006), which alongside the development of synthetic insulation materials like polystyrene and polyurethane foam, and later glass wool, made installation of insulation widespread. The manufacturing of synthetic insulation materials, floor coverings and structural concrete is energy intensive (KBOB, 2024). The increase in embodied carbon across construction periods reflects the high energy costs associated with the construction of modern buildings, while the new materials in the building envelope are aligned with decreasing operational emissions after the 1970s. It highlights the trade-off between high one-time emissions related to the construction of a building for low daily operational energy demand, versus the low carbon embodied in existing, ageing buildings that have a high daily operational demand due to a weak thermal envelope and outdated heating systems.

The communes in canton Vaud are not homogenous. The urban agglomeration of Lausanne and the surrounding towns along Lake Léman exhibit a higher median material stock per building compared to their rural surroundings (Fig. 3). Median material intensities in buildings are 1.4 tons/m^2 in cities, 1.2 tons/m^2 in towns and 1.1 tons/m^2 in rural areas. The differentiating factor is newer, taller constructions with a higher intensity of structural concrete in cities, towns and suburbs.

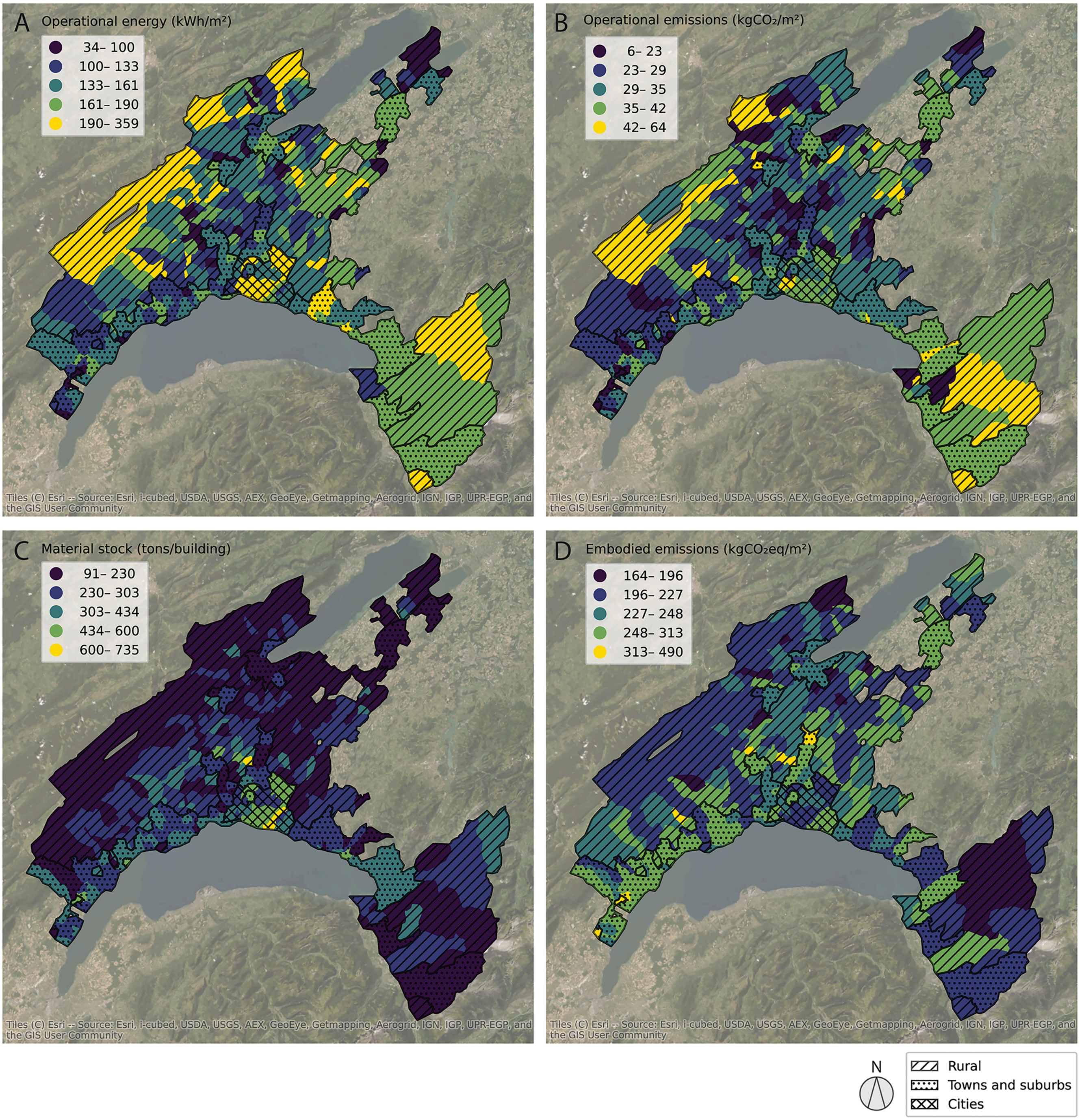

Fig. 3. Spatial distribution of material and energy profiles across communes in canton Vaud. Panel A shows the median annual operational energy demand (kWh/m^2). Panel B visualises median annual operational emissions (kg CO_2/m^2). Panel C shows median material stock (tons/building). Panel D shows the median embodied carbon (kg CO_2-eq/m^2).

Considering the territory as a whole, the differences in embodied carbon are relatively small across degrees of urbanisation, ranging from a median of 240 kg CO_2-eq/m^2 in cities and towns to 215 kg CO_2-eq/m^2 in rural areas.

Rural buildings in central and western Vaud show lower operational energy demand and emissions per square metre than the rest of the canton (Fig. 3). Single-family buildings in towns show the lowest median energy consumption per square metre (145 kWh/m^2). Mixed-use buildings in cities exhibit the highest energy demand (220 kWh/m^2), followed by multi-family buildings (175 kWh/m^2) and then single-family buildings (160 kWh/m^2). Along similar lines, operational emissions in cities are driven primarily by mixed-use (43 kg CO_2/m^2) and multi-family buildings (39 kg CO_2/m^2), and are the lowest in single-family buildings in rural areas (29 kg CO_2/m^2).

3.2. Household and ownership profiles

Occupancy patterns of buildings differ across the communes. Single-person households live in the oldest and most urbanised building stock, have the highest floor area per resident, and have the highest operational energy demand and emissions (Fig. 4). In cities, they occupy the largest proportion of the housing stock, followed by two-adult

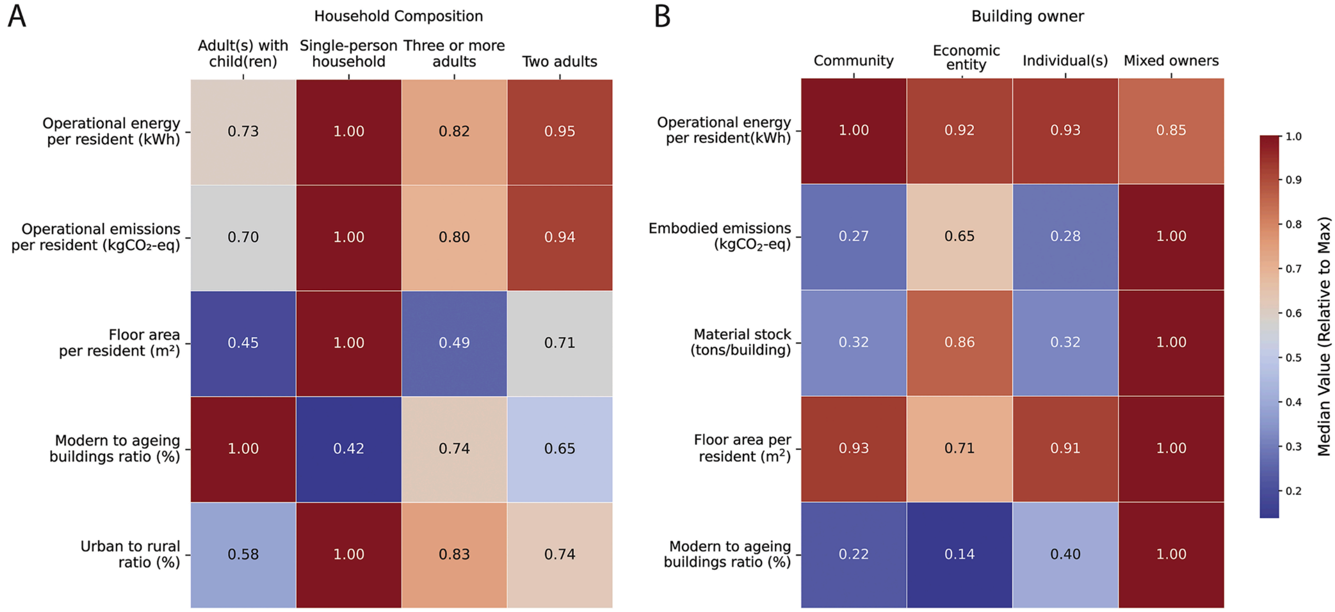

Fig. 4. Comparative analysis of occupancy patterns. Panel A compares median values (relative to maximum) across household types. Panel B compares values across building owners. 'Modern to ageing building ratio' refers to the proportion of buildings that were constructed post-2000. 'Urban to rural ratio' refers to the proportion of buildings in urban areas compared to towns, suburbs or rural areas.

households, and then adult(s) with child(ren). Single-person households in cities typically reside in buildings constructed between 1940 and 1960, with a median living space of 60 m^2 per resident and an energy demand of 8200 kWh per resident. In towns and rural areas, households with children constitute the largest share, followed by two-adult households and single-person households. In towns, households with children predominantly occupy buildings from 1960 to 1980, with a median space of 32 m^2 per resident and an energy demand of 5900 kWh per resident. In rural areas, these households live in the oldest buildings, constructed before 1919, with a median space of 32 m^2 per resident and an energy demand of 5600 kWh per resident. Across the urban-rural spectrum, the oldest households (dwellings in which all inhabitants are over 65 years) have the largest median living spaces (68 m^2 per resident) and typically reside in ageing buildings. The trend is pronounced in rural areas, where 18 % of elderly residents live in buildings constructed before 1919, with a median energy demand of 10,300 kWh per resident.

In single-person and two-adult households, the median energy demand is currently 8000 kWh per resident. As a point of comparison, the '2000W-society' envisions an average annual housing-related energy use of 3900 kWh or emissions equating to 210 kg CO_2-eq/resident in order to meet sustainability objectives in Switzerland (SIA, 2017; Swiss Federal Council, 2007). Larger households perform better towards this vision, as each additional member increases overall demand by a smaller margin. In rural multi-family buildings, households with children exhibit the lowest median operational energy demand at 5400 kWh per resident, despite these buildings showing a high energy demand per square metre. Whereas urban areas are more densely populated overall, rural dwellings achieve higher occupancy density within multi-family buildings, which contributes to their lower per capita energy consumption.

Less than one-third of residents in Switzerland live in owner-occupied dwellings (OFS, 2021), meaning the majority of households are tenants. In Vaud, 43 % of residential buildings are owned by private individuals, while 35 % are held by economic entities such as foundations, financial institutions, and real estate companies. The oldest building stock, particularly buildings constructed before 1919, is predominantly owned by private individuals, who also hold the largest share of single-family houses, reflecting dispersed ownership of buildings across many small actors. Economic entities own a significant proportion of mixed-use buildings, aligned with an interest in properties that generate multiple streams of income. Their share of ownership in cities is higher than in suburbs and rural areas. Collective ownership structures, including partnerships and heirships, account for 7 % of total ownership, with the remaining 15 % belonging to a mix of these groups. The share of buildings owned by mixed groups is higher in recent construction periods, particularly after 2000, while community ownership has declined after the 1990s.

The building stock owned by mixed groups has the highest embodied energy, largest material stock and the most modern buildings (Fig. 4). Economic entities construct buildings with a lower living space per resident than the average (41 m^2), yet oversee a substantial material stock due to a higher proportion of modern buildings and significant share of multi-family buildings. The median operational energy demand is 7200 kWh per resident. In contrast, buildings owned by communities and private individuals provide more space per resident (50 m^2), and are inhabited largely by households with children. The median operational energy demand is highest in buildings owned by communities at 8400 kWh per resident, while the embodied carbon is lowest for their building stock at 220 kg CO_2-eq/m^2. According to CECB audits, 8 % of the certified building stock has undergone window replacements in the past two decades, 33 % has installed heat recovery systems, 13 % use solar thermal systems, and 0.4 % generate electricity through photovoltaic panels. Not all interventions increase energy efficiency; 5 % of the certified building stock has installed a cooling system. Although detailed reporting on retrofits is limited, interventions are more common in buildings owned by private individuals and occupied by single-person households.

Fig. 5 summarises embodied and operational emission patterns. Urban households are clustered in the upper left quadrant, with comparatively low embodied emissions (11,000–12,500 kg CO_2-eq/resident) but higher annual operational emissions (1400–2000 kg CO_2/resident). Rural households display the widest range, with larger households of three or more individuals achieving lower emissions per resident. Single-person households are positioned towards the higher end of operational emissions, underscoring the resource intensity of single-occupancy living. Two-adult households cluster more centrally, suggesting moderate performance across both emission types. Overall,

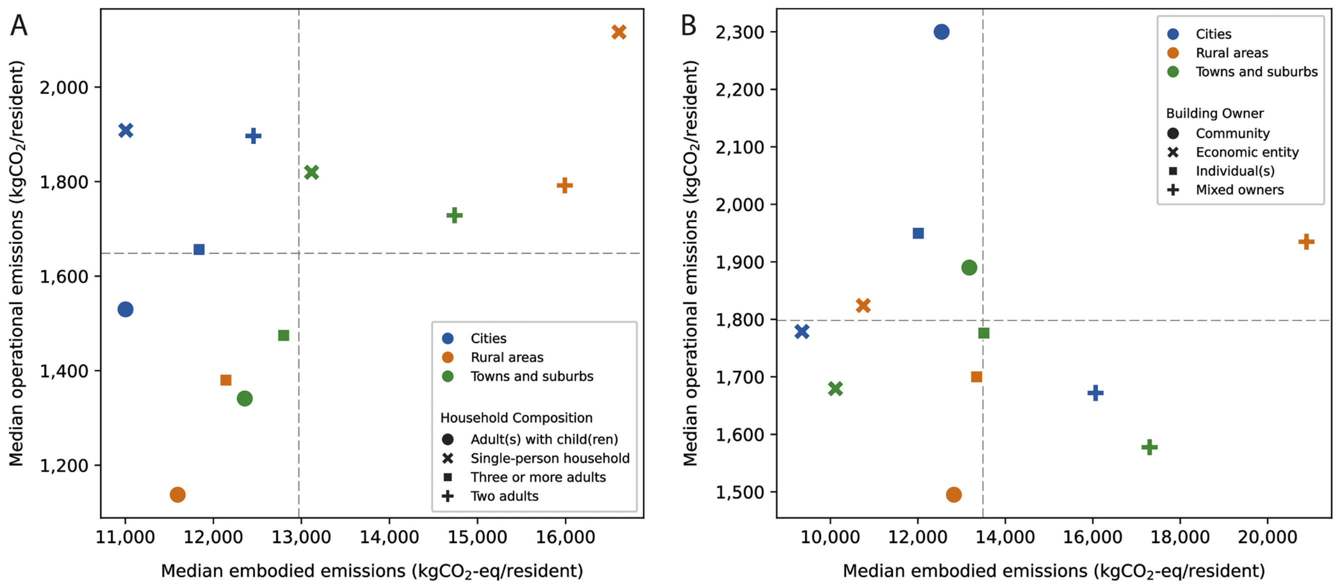

Fig. 5. Relationship between embodied and operational emissions per resident in the urban-rural gradient. Panel A shows the relationship across different household compositions. Panel B displays the relationship categorised by building ownership. The dotted lines indicate the mean values.

household size clearly influences emissions distribution, with larger households benefiting from efficiencies of scale, particularly in rural contexts where the building stock appears more homogeneous. Ownership patterns are less geographically distinct but more clearly stratified by owner type. Mixed ownership buildings exhibit the highest embodied emissions (18,000 kg CO_2-eq/resident), while community-owned buildings display a wide variation in operational emissions (1500–2300 kg CO_2/resident). In contrast, economic entity-owned buildings are tightly clustered in the lower left quadrant, with comparatively lower embodied (11,000–13,000 kg CO_2-eq/resident) and operational emissions (1400–1700 kg CO_2/resident). The considerable variation between household profiles and building owners suggests that emission-reduction interventions should be tailored to specific social contexts as well as physical building parameters.

4. Discussion

Our findings have highlighted material and energy patterns in the building stock associated with location, household profile, and ownership structure. In this section, we outline three strategies that could reduce operational and embodied emissions: reducing energy losses, closing material loops, and incorporating sufficiency in the built environment, as well as the opportunities and challenges they present for implementation.

4.1. Reducing energy losses

From a technical perspective, buildings with high operational emissions (Fig. 5, upper quadrants) require immediate interventions, such as improvements to the thermal envelope (e.g., insulation, window glazing) and upgrades to thermal systems (e.g., electrification of space and water heating). However, the variations in emissions observed across different ownership and household profiles within each building typology suggest that the changes required are not so clear cut.

First, high emissions linked to consumption patterns are not directly resolved through thermal retrofits. Research has shown that household practices related to energy use are routinised, socially shared, and embedded in everyday life (Shove, 2014; Shove and Walker, 2014). These include expectations concerning indoor temperatures, the frequency of laundry, and appliance use (Shove, 2003). Interventions that improve the building envelope or upgrade heating and cooling systems may reduce energy losses, but they can also help maintain and spread resource-intensive lifestyles (Sonnberger and Gross, 2018). Low carbon strategies focused on behavioural modifications to *preserve* the status quo are unlikely to lead to significant modification towards practises that ultimately reduce energy emissions (Shove, 2014). Second, energy efficiency and renovation behaviours are situated within the household life cycle. As household composition and size change over time, energy consumption patterns may also shift, for example, through the reconfiguration of appliances, equipment, or dwelling size (Heinrich et al., 2022; Lévy and Belaïd, 2018). This counters the more static assumption that households are motivated to renovate in order to save energy and money, but are constrained by uncertainties around financial returns, and contractor quality and reliability (Wilson et al., 2015). Rather, the challenges that elderly residents face with reducing energy losses are different to those from young families or single-person households; the household life cycle is associated both with changing needs and with the fact that each generation faces specific energy conditions and therefore develops its own energy culture (Heinrich et al., 2022; Stephenson et al., 2010). Finally, the large number of dwellings owned by individuals or mixed groups presents a challenge in coordinating thermal retrofits, particularly in the multi-family building stock. Fragmented ownership complicates planning and implementation, as owners do not necessarily share the same vision, objectives, or capacity for action (Buessler et al., 2017). Moreover, in contexts such as Switzerland, where private owners are strongly protected by law and hold considerable influence in the planning process, they are in a position to accelerate or delay the implementation of public plans (Gerber and Debrunner, 2022). As a result, reaching consensus on retrofitting can take years (Buessler et al., 2017).

From a policy perspective, this suggests that holistic support for reducing energy losses in the building stock should target transitional phases within the household life cycle, when opportunities for reconfiguring choices and behaviours arise (Heinrich et al., 2022), and there is a need to develop know-how on the social aspects and organisation of owner-groups in order to identify what is holding back individuals from action, and collaboratively developing a group strategy (Buessler et al., 2017).

4.2. Closing material loops

For buildings with low operational but high embodied energy (Fig. 5, lower right quadrants), the task is to maintain and preserve the value of already extracted and refined material resources. Currently, regulatory frameworks encourage the incorporation of up to 20 % recycled concrete aggregate in new constructions in order to encourage the sorting and recycling of demolition waste (OCEV, 2021). However the processes of transporting, cleaning, sorting and recycling concrete aggregate remain energy- and material-intensive (Knoeri et al., 2013). Dismantling buildings to reuse components and material slabs can reduce the need for primary construction materials (and therefore embodied carbon), yet this practice remains rare in Switzerland (Küpfer et al., 2023). Each year, 30 to 60 buildings in the urban agglomeration of Lausanne are granted demolition permits, and there are plans to establish a cantonal material bank for construction materials (S. Dubart, personal communication, 15 November 2023). The already existing material banks in neighbouring cantons Geneva and Fribourg have engaged with inhabitants through more than material exchange: they offer community space and sharing (De Wolf et al., 2023). The proximity of a new material bank in Vaud could further reduce barriers for material preservation within the territory.

These interventions align with the circular economy framework, which offers strategies for reducing reliance on resource extraction by recirculating waste flows back into the construction process, thereby replacing the need for virgin materials (Gallaud and Laperche, 2016). The concept promotes the reuse and recycling of building components at the end of their lifecycles (Pomponi and Moncaster, 2017). However, the construction of new neighbourhoods outpaces demolition (OFS, 2023), meaning that even if all materials were theoretically reused or recycled, they would not meet the rising demand for new constructions. To implement a circular economy effectively, it is therefore essential to examine and address the intertwined drivers of demolition and construction in the region and to focus on extending the lifespan of existing buildings (Kohler et al., 2009; Huuhka and Vestergaard, 2019). Studies suggest that buildings are generally not demolished because they are in a dilapidated state; rather, they are in a dilapidated state because they are planned to be demolished (Aksözen et al., 2017; Power, 2010). Policies that regulate embodied carbon impacts as well as operational impacts can better balance the upfront and future emissions of buildings and bring nuance to the outdated beliefs that new buildings will contribute a more positive result through lower operational carbon (Huuhka, 2023).

4.3. Towards sufficiency?

Buildings with comparatively low embodied and operational emissions (Fig. 5, lower left quadrants) are still approximately five times higher than the 210 kg CO_2-eq/resident target (SIA, 2017; Swiss Federal Council, 2007). Sufficiency includes an ecosystem of principles related to housing provision within ecological limits, including voluntary simplicity, social housing, tiny houses, co-living, cooperative ownership, and adaptive reuse (Nelson et al., 2019). It calls into reflection if more can be done with what is already built, which new constructions are contributing to housing ‘shortages’, and whose housing needs are being met at the cost of others (zu Ermgassen et al., 2022).

Our results highlight space consumption as a key determinant of energy and material usage. Current housing trends, particularly among single-person households, exceed the needs-based living space threshold of approximately 20 m^2 per person (Rao and Min, 2018; Fuchs et al., 2021) by at least twofold. There is a minimum threshold of functions and appliances required regardless of number of residents, which skews the results against single-person households. As these households are the fastest-growing demographic (Swissinfo, 2023), sufficiency principles encourage alternative housing arrangements, such as co-housing, shared common spaces and/or appliances to reduce material and energy consumption per capita. This is relevant not only to younger households, who already disproportionately live in shared adult households in cities, but also to the elderly, who currently occupy the largest per capita living spaces. Housing innovations require careful, intentional planning and functional layouts that balance individual and communal needs, and sensitivity to the emotional and socially constructed meaning of home as more than a physical building (Pagani and Binder, 2021). Space consumption is only one facet of addressing sufficiency in the materials-energy nexus. While sufficiency at the dwelling level could reduce the marginal operational energy demand per resident, systemic, political changes to construction and planning practices are necessary to counter the constant increase in material stock and consequent embodied carbon due to new constructions (Xue, 2022; Savini, 2023).

4.4. Limitations and further research

This study and its conclusions are subject to a few limitations. First, our analysis covers only 15 % of the residential building stock in Vaud, focusing on buildings with a CECB audit. While our case study is not exhaustive, a comparison with StatBL data for the total building stock in Vaud shows a comparable distribution in terms of construction periods and building sizes, though single-family homes are overrepresented in the CECB audits. To mitigate this, we present results separately for each building category to avoid skewing the overall outcomes. Second, our material stock estimates depend on sparse material coefficient data for Switzerland, and it was therefore necessary to integrate information from different sources, which is a key contribution of our study. However, we recognise that our results would be improved by working with specific materials rather than material groups for calculating material stocks and embodied carbon. This is a key issue that has been recognised in multiple recent studies (Fivet et al., 2024; Shinde et al., 2024). We offer ranges of material coefficient values in Appendix A, in order to facilitate further refining in future work. Third, due to a lack of information on if, when and which changes such as retrofits have occurred, it is challenging to move beyond a static study of the building stock and consider the dynamics of material, energy and dwelling occupancy changes over time. Further work on the energy-materials nexus in the built environment could incorporate household and building owner decision-making processes in order to better understand triggers and constraints for the decarbonisation, circular economy and sufficiency in the building stock.

5. Conclusions

In this study, we explored the social and spatial heterogeneity of operational and embodied emissions in the residential built environment. Taking canton Vaud in Switzerland as an example, we linked geographic, household and ownership data to material stock and energy consumption data. We found that while operational and embodied energy are associated with construction period and building type, this alone does not explain the variation in operational emissions between buildings. Our results reveal opportunities and challenges for the materials-energy nexus of the building stock.

From a technical perspective, buildings with high operational emissions require immediate thermal retrofits. However, the variations in emissions observed across different ownership and household profiles within each building typology suggest that the required changes are not so clear cut. Interventions that improve the building envelope or upgrade heating and cooling systems may help reduce technical energy losses but they can also perpetuate resource-intensive lifestyles. Policy support for reducing energy losses in the building stock should target transitional phases within the household life cycle, when opportunities for reconfiguring choices and behaviours arise. Furthermore, there is a need to develop know-how on the social aspects and organisation of owner-groups in order to identify what is holding back individuals from action, and collaboratively developing a group strategy. From a material perspective, efforts are needed to preserve and extend functional lifespans of buildings; as modern buildings require a significantly longer building lifespan to rationalise their embodied carbon. Recycling and reuse cannot meet demand material as long as the construction of new neighbourhoods outpaces demolition. Thus, it is fruitful to examine and address the drivers of construction and demolition in the region. As single-person households continue to rise, interventions must target reducing resource and energy consumption per resident, not just per square metre, to meet emission targets. Sufficiency measures offer a systemic approach and opportunity to lowering energy and resource demand.

CRediT authorship contribution statement

Ankita Singhvi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mikhail Sirenko:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Aristide Athanassiadis:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Claudia R. Binder:** Writing – review & editing, Supervision, Resources, 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.

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Appendix A

Material intensity coefficients were calculated as follows:

$$\textit{Material intensity}_{i,j}\ \left(kg / m^2\right) = M_{\%,i} \times V_{GFA,j} \times \rho$$

Where:

- *Material intensity*$_{i,j}$ is the material group intensity for construction period i and building type j.
- $M_{\%,i}$ is the material group (as defined in Table A.1) for construction period i (in volume, as given in Table A.2).
- $V_{GFA,j}$ is the volume of material per gross floor area (in m^3/m^2) for building type j (Table A.4).
- ρ is the constant material density (in kg/m^3), applicable across all periods and building types (Table A.3).

The resulting ranges for material coefficients are presented in Tables A.5, 6, 7.

Table A.1
Material groups based on (Gauch et al., 2016), page 23.

Material group	Defined as:
Concrete	Lean, precast, structural, reinforced concrete
Bricks	Sand limestone, clay bricks, earth blocks
Combustibles	Highly flammable products: insulation, and floor and wall coverings
Timber	Wood and wood-based materials: hardboard, plywood, cross-laminated timber, solid construction timber
Metal	Steel sheets, aluminium profiles, tin, reinforcement steel
Mineral	Gypsum, ceramic, stoneware, mortars and plasters

Table A.2
Material group (in % volume) per construction period from (Shinde et al., 2024).

Material group	< 1900	1900–1945	1946–1960	1961–1675	1976–2000	> 2000
Concrete	0.06	0.13	0.38	0.59	0.63	0.54
Bricks	0.64	0.60	0.37	0.16	0.11	0.13
Combustibles	0.05	0.05	0.07	0.12	0.14	0.22
Timber	0.17	0.14	0.07	0.04	0.05	0.05
Metal	0.00	0.00	0.01	0.01	0.01	0.01
Mineral	0.08	0.08	0.10	0.08	0.07	0.06

Table A.3
Material density range based on (Shinde et al., 2024).

Material group	Average	Minimum	Maximum
p Concrete	2075	1750	2400
p Brick	2150	1900	2400
p Combustible	218	28	408
p Timber	520	140	900
p Metal	8500	2000	15,000
p Mineral	4000	2000	6000

Table A.4
vol of material (in m^3/m^2) per building type based on (Fivet et al., 2024).

Material group	Average	Minimum	Maximum
Single-family building	0.56	0.44	0.7
Multi-family building	0.49	0.37	0.65
Mixed-use building	0.53	0.29	0.82

Table A.5
Calculated single-family building material coefficients.

Single-family building (kg/m^2)	< 1900	1900–1945	1946–1960	1961–1675	1976–2000	> 2000
Concrete Min	52.95	114.13	349.68	539.58	573.36	496.67
Concrete Max	84.25	181.56	556.31	858.43	912.17	790.16
Brick Min	608.28	563.82	346.24	150.41	105.01	121.09
Brick Max	967.72	896.98	550.83	239.30	167.06	192.64
Combustible Min	4.99	5.18	6.52	11.61	13.24	20.91
Combustible Max	7.94	8.24	10.38	18.46	21.06	33.27
Timber Min	38.44	32.95	16.47	9.84	10.30	10.52
Timber Max	61.15	52.42	26.21	15.65	16.38	16.74
Metal Min	14.96	14.96	22.44	26.18	33.66	29.92
Metal Max	23.80	23.80	35.70	41.65	53.55	47.60
Mineral Min	133.76	137.28	183.04	137.28	121.44	98.56
Mineral Max	212.80	218.40	291.20	218.40	193.20	156.80

Table A.6
Calculated multi-family building material coefficients.

Multi-family building (kg/m^2)	< 1900	1900–1945	1946–1960	1961–1675	1976–2000	> 2000
Concrete Min	44.53	95.97	294.05	453.74	482.15	417.66
Concrete Max	78.23	168.59	516.57	797.11	847.02	733.72
Brick Min	511.51	474.12	291.15	126.48	88.30	101.82
Brick Max	898.59	832.91	511.49	222.20	155.12	178.88
Combustible Min	4.19	4.36	5.48	9.76	11.13	17.58
Combustible Max	7.37	7.65	9.64	17.15	19.55	30.89
Timber Min	32.32	27.71	13.85	8.27	8.66	8.85
Timber Max	56.78	48.67	24.34	14.53	15.21	15.55
Metal Min	12.58	12.58	18.87	22.02	28.31	25.16
Metal Max	22.10	22.10	33.15	38.68	49.73	44.20
Mineral Min	112.48	115.44	153.92	115.44	102.12	82.88
Mineral Max	197.60	202.80	270.40	202.80	179.40	145.60

Table A.7
Calculated mixed-use building material coefficients.

Mixed-use building (kg/m^2)	< 1900	1900–1945	1946–1960	1961–1675	1976–2000	> 2000
Concrete Min	34.90	75.22	230.47	355.63	377.90	327.35
Concrete Max	98.69	212.69	651.67	1005.59	1068.54	925.62
Brick Min	400.91	371.61	228.20	99.14	69.21	79.81
Brick Max	1133.61	1050.75	645.26	280.32	195.69	225.66
Combustible Min	3.29	3.41	4.30	7.65	8.72	13.78
Combustible Max	9.30	9.65	12.16	21.63	24.67	38.97
Timber Min	25.33	21.72	10.86	6.48	6.79	6.94
Timber Max	71.64	61.40	30.70	18.34	19.19	19.61

(continued on next page)

Table A.7 (*continued*)

Mixed-use building (kg/m^2)	< 1900	1900–1945	1946–1960	1961–1675	1976–2000	> 2000
Metal Min	9.86	9.86	14.79	17.26	22.19	19.72
Metal Max	27.88	27.88	41.82	48.79	62.73	55.76
Mineral Min	88.16	90.48	120.64	90.48	80.04	64.96
Mineral Max	249.28	255.84	341.12	255.84	226.32	183.68

Table A.8
Carbon coefficients based on (KBOB, 2024).

GHG emissions per material category in kg CO_2-eq/ton of material KBOB Ecobilans category reference numbers	Concrete 01	Bricks 02	Mineral 03, 04	Timber 07	Combustibles 10, 11
Minimum	62.800	57.000	13.300	97.800	95.600
Median	148.000	196.000	362.500	311.500	7440.000
Maximum	324.000	428.000	2380.000	1430.000	48,700.000

Appendix B

The CECB database includes information on building envelopes, heating systems, and energy consumption (Table B.1). The audits database contains 132,378 entries in Switzerland as of August 2022. This includes data on energy consumption from electricity, space, and water heating, as well as on-site carbon emissions for single-family, multi-family, and mixed-use buildings. We processed the database as follows:

1. Subset data to canton Vaud. There were 33,066 audits for buildings in Vaud.
2. Removed 3469 rows missing an EGID, energy consumption data or carbon emissions information, and rows with negative values for construction year or carbon emissions. In the case of duplicate EGIDs, the most recent audit was kept.
3. Manual identification of variables with outliers or incorrectly filled in audits, and then quantile method to remove the highest and lowest 1 % of the following variables:
   a. Total energy consumption per square metre, building area, carbon emissions per square metre. Excluded 1929 rows.
4. Merged the resulting Vaud dataset with the StatBL buildings register (Table B.2), using EGID.
5. Removed buildings with 0 residents
6. Extracted the coordinates from StatBL dwelling register (Table B.3), and spatial joined the dwelling points to building footprints from StatBL buildings register. 8027 points did not match a footprint, they were excluded.
7. Resulting datasets:
   a. 19,641 rows for buildings, with a unique EGID
   b. 69,209 rows for dwellings, with a unique EGID-EWID (refers to unique household)
8. Data was aggregated by local administrative unit (LAU), and categorised by degree of urbanisation (Table B.4), resulting in a dataset:
   a. 308 rows for territories, with a unique LAU

Table B.1
Data utilised from CECB.

Variable	Description
EGID	Unique identifier for buildings.
Construction year	Year
Space heating	Annual consumption kWh
Warm water heating	Annual consumption kWh
Carbon emissions	On-site carbon emissions related to operational energy demand in annual $kgCO_2eq$ / m^2
Building area EBF	Energy reference area in m^2
Building weight	Qualitative measure by auditor about heat storage capacity of building based on construction type. Very light, light, medium or heavy.
Installations	Annual demand in kWh
Electronics	Annual demand in kWh
Facilities	Annual demand in kWh
Lighting	Annual demand in kWh
Ventilation	Annual demand in kWh
Window renovation	Year of reported window renovation

Table B.2
Data utilised from StatBL buildings register.

Variable	Description
EGID	Unique identifier for buildings. For detailed explanation see: (OFS, 2025)
Coordinates	E, N coordinates
Construction period	Categorised

(*continued on next page*)

Table B.2 (*continued*)

Variable	Description
Building category	Before 1919
	Period from 1919 to 1945
	Period from 1946 to 1960
	Period from 1961 to 1970
	Period from 1971 to 1980
	Period from 1981 to 1985
	Period from 1986 to 1990
	Period from 1991 to 1995
	Period from 1996 to 2000
	Period from 2001 to 2005
	Period from 2006 to 2010
	Period from 2011 to 2015
	Period after 2015
Building height	Number of storeys
Dwellings	Number of dwellings in building
Residents	Number of residents in building
Building owner	Individual(s)
	Economic entity
	Community
	Mixed owners

Table B.3
Data utilised from StatBL dwellings register.

Variable	Description
Pseudo-anonymised EGID	Pseudo-anonymised EGID
EWID	Household identifier
Rooms	Number of rooms in dwelling
Dwelling area	Dwelling area in m^2
Residents	Number of residents in dwelling
Dwelling residents age	Under 25
	25 to 64 years old
	65 and over
	Under 25 and 25 to 64
	Under 25 and over 65
	25 to 64 and 65 and over
	Under 25, 25 to 64, 65 and over
Dwelling household composition	Single adult man
	Single adult female
	Two adults of different sex
	Two adults of the same sex
	Three or more adults
	One minor
	Two or more minors
	Single man with minor(s)
	Single woman with minor(s)
	Two adults of different sex with minor(s)
	Two adults of the same sex with minor(s)
	Three or more adults with minor(s)

Table B.4
Data utilised from DEGURBA (OFS, 2020).

Variable	Description
LAU	Spatially explicit local administrative unit (LAU) boundaries
LAU code	Commune ID
Degree of urbanisation	Densely populated area (1)
	Intermediate urbanised area (2)
	Sparsely populated area (3)

Appendix C

Material stock were calculated as follows:

$$S_{total,building} = \frac{1}{1000} \times \sum_{k=1}^{6} \left(Material\ intensity_k \times GFA_{building} \right)$$

Where:

- $S_{total,building}$ is the total material stock for the building, in tons
- $Material\ intensity_k$ is the material intensity for material k
- $GFA_{building}$ is the gross floor area of the specific building, in m^2
- k represents the material groups: concrete, bricks, metal, timber, combustibles and mineral.

Embodied carbon was calculated as follows:

$$EC_{building} = \sum_{k=1}^{6} \left(S_{building,k} \times C_{coeff,k}\right)$$

Where:

- $EC_{building}$ is the total embodied carbon for the building, in kg CO_2-eq
- $S_{building,k}$ is the material stock of material k for the building (in tons), calculated for each material
- $C_{coeff,k}$ is the carbon coefficient of material k, in kg CO_2-eq/ton (Table A.8)
- k represents the material groups: concrete, bricks, metal, timber, combustibles and mineral.

Operational energy was calculated as follows:

$$OE_{building} = E_{water} + E_{space} + E_{electricity}$$

Where:

- $OE_{building}$ is the total operational energy for the building, in annual kWh
- E_{water} is the energy used for water heating, in annual kWh
- E_{space} is the energy used for space heating, in annual kWh
- $E_{electricity}$ is the energy used for installations, lighting, appliances and ventilation, in annual kWh

Operational carbon was calculated as follows:

$$OC_{building} = OC_{GFA} \times GFA_{building}$$

- $OC_{building}$ are the total operational emissions for the building, in annual kg CO_2
- OC_{GFA} are the operational emissions, in annual kg CO_2/m^2
- $GFA_{building}$ is the gross floor area of the specific building, in m^2

Building values were divided by $GFA_{building}$ in order to have the value per m^2, or divided by $R_{building}$ to have the value per resident.
Where:

- $GFA_{building}$ is the gross floor area of the specific building, in m^2
- $R_{building}$ is the number of residents living in the building

Data availability

The data that has been used is confidential.

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