1 Appendix A

1.1 Background on Climate Change Modelling

Climate models, known as Global Climate Models or General Circulation Models (GCMs), are developed and utilised for understanding and projecting the behaviour of the climate system. Through the Coupled Model Intercomparison Project (CMIP), the world's climate modelling centres coordinate the development and execution of climate simulations, allowing the climate research community to assess the results and uncertainties of climate projections (WCRP, 2025). CMIP relies on a set of shared experiments and historical simulations, common standards and infrastructure, as well as a number of endorsed Model Intercomparison Projects (MIPs) specific to each phase of CMIP. The sixth phase of CMIP (CMIP6) represents the latest coordinated effort to enhance the accuracy and reliability of the climate models, aiming to simulate past, present, and future climate conditions (Eyring et al., 2016). A selection of MIPs are aimed at developing the understanding carried over from previous phases, while some MIPs target thematic gaps of CMIP5, such as the absence of assessment of mitigation actions, their costs and benefits (Stouffer et al., 2017), which is a focal area for researchers using the model outputs in such fields as sustainable development, urban planning, global inequality and vulnerability (Calvin et al., 2017; Chen and Caldeira, 2020; Shiogama et al., 2021).

Therefore, one of the key novel MIPs in CMIP6 is the Scenario Model Intercomparison Project (ScenarioMIP), which consists of a set of long-term future experiments based on SSPs. ScenarioMIP uses a new scenario framework that links SSPs to Representative Concentration Pathways (RCPs). This approach leads to an improved understanding of impact from mitigation actions on climate and, in return, of climate impact on society (O'Neill et al., 2016). The direct integration of pre-defined scenarios into climate projections allows for a more holistic assessment of potential changes in climate and society, ensuring that the analysis of interconnected model outputs is not siloed and that results of studies from various fields, from climate to social sciences, can be overlaid and compared. Additionally, the utilisation of SSPs in climate projections is crucial for informing mitigation and adaptation policies, encouraging the interaction of researchers and decision-makers, as showcased in the study by O. Isinkaralar and K. Isinkaralar (2023) on a local scale. This can be supported by qualitative descriptions of possible futures around the key aspects of society, such as the narratives developed by O'Neill et al. (2017), explaining development with regards to different climate projections, highlighting challenges to mitigation and adaptation.

1.2 Background on Material Stock Analysis

The methodology of material stock analysis (MSA) has progressed significantly over the past two decades. Early studies primarily relied on the top-down approach (as it is currently referred to). They estimated stocks by analysing regional (Van Beers et al., 2003; Spatari et al., 2003) and global (Graedel et al., 2005) material flow accounts and trade statistics, with a focus on metals. In these studies, in-use stocks were derived as residuals from aggregated outflows subtracted from inflows. While useful at macro scales, the top-down approach is limited by low spatial resolution and has an inherent uncertainty of material lifespan assumptions. Additionally, it does not link materials to specific built environment assets and, therefore, cannot be used in projections of material stock changes affected by urbanisation and in estimations of the future material recovery potential.

Subsequently, the bottom-up approach was developed and gained traction. This method estimates stocks by compiling data from individual buildings and infrastructure assets using physical attributes, such as floor area, construction year and typology, combined with material intensity coefficients (Lichtensteiger and Baccini, 2008; Tanikawa and Hashimoto, 2009). Bottom-up models are often more accurate and spatially explicit, making them suitable for high-resolution local assessments, including risk evaluation, and for supporting urban and regional planning, as emphasised by Lanau, Liu, et al. (2019). However, they are data-intensive and often constrained by data availability necessary for input. The application of geographic information system (GIS) technologies enhanced the spatial resolution of bottom-up models. Introduced into the field by Tanikawa and Hashimoto (2009), GIS has since become a standard tool in material stock research (Kleemann et al., 2017; Honic et al., 2023). By enabling the integration of georeferenced data, such as building location, size, age and type, with material intensity values, GIS-based MSA facilitates high-resolution urban and regional stock mapping. Despite the development of approaches, Lanau, Liu, et al. (2019) in their review found that most research has concentrated on national-level analysis with limited spatial detail. Consequently, there has been a growing number of more refined, high-resolution local studies, improving estimates of embodied carbon and circular potential of material stocks in various locations (Lanau and Liu, 2020; Mao et al., 2020; Mollaei et al., 2021).

The methodology of MSA further advanced through the integration of remote sensing technologies, such as nighttime light (NTL) data (Takahashi et al., 2010; Peled and Fishman, 2021) and satellite imagery (Haberl et al., 2021). NTL data, derived from sensors that capture artificial illumination at night, have been used as proxies for human activity (Stokes et al., 2021) and urbanisation processes (Zhou et al., 2018). Although NTL data

does not directly quantify material stocks, its strong correlation with urban development patterns makes it a valuable tool for identifying areas of built environment expansion, particularly in regions lacking detailed statistical or cadastral data. NTL data are especially useful for large-scale MSA and can serve as a complementary input to other methods. More recent developments in satellite imagery have enabled large-scale assessments of building footprints, heights and volumes, which are vital inputs for quantifying material stocks with better accuracy. High-resolution datasets such as the Global Human Settlement Layer (European Commission, 2025) and the World Settlement Footprint (Earth Observation Center, 2025) provide globally consistent spatial coverage and have been used to derive material stock estimates and distribution, when combined with material intensity coefficients. An example of this work is outlined in the paper by H. Haberl et al. (2025), who estimated and mapped global building material stocks at a spatial resolution of 90 meters, by integrating data from the World Settlement Footprint with harmonised material intensity factors (Heeren and Fishman, 2019). This study classified five building types and 18 material categories, allowing not only improved material stock estimates but also unprecedented spatial and typological disaggregation (H. Haberl et al., 2025). Haberl and colleagues have created open-access, high-resolution data products, suitable for identifying spatial inequalities, localising urban mining potential and assessing climate impacts. The validation against case studies and the inclusion of the uncertainty analysis highlight the reliability of the dataset for the application in further studies.

Material stock studies vary not only in spatial scope but also in the materials and building components assessed. The most frequently analysed materials include concrete, steel, brick, gypsum, aluminum, and wood (Mohammadiziazi and Bilec, 2022). Some studies assess building components, such as structural elements (e.g., beams, columns, slabs), envelopes (e.g., windows, roofs), and finishes (e.g., flooring, internal partitions) (Stephan and Athanassiadis, 2017; Arora et al., 2019). Such disaggregated analysis allows for more nuanced understanding of material composition and reuse potential. Building and infrastructure end-use categories are also central to material stock assessments. Lanau, Liu, et al. (2019) note three dominant infrastructure sectors: supply and disposal systems, energy infrastructure and transport networks. Buildings are generally categorised as residential and non-residential, although subcategories vary by study, limiting comparability across them (Mohammadiziazi and Bilec, 2022). These distinctions are essential for defining archetypes, which represent groups of buildings and infrastructure with similar characteristics. Archetypes are critical for the bottom-up MSA to tackle the challenges of data collection, however, they introduce some degree of generalisation, by making a heterogeneous stock more homogenous.

The evolution of MSA methods has enabled the application of their results to other

fields of research, spatial planning and policy-making. While the high-resolution bottom-up approach remains the most common for localised assessments, it is more frequently complemented by remote sensing methods that offer broader applicability.

2 Appendix B

The national-level exposure results are provided in the accompanying Excel file. All values are displayed in kilograms.

3 Appendix C

The data used in this study are available from the sources referenced throughout the manuscript. The Python code for the analysis and generation of figures presented in this study is publicly accessible via GitHub at: https://github.com/Anna-Fedotova/building-stocks-under-climate-extremes.

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