A socio-metabolic analysis of bulk materials in electricity systems: Insights from a stock-flow-service nexus perspective and outlook to 2050

Thematic area: (9) Kritische Rohstoffe / Kreislaufwirtschaft

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Motivation and research question

Most studies on material requirements of electricity sector transformations focus on possibly critical materials. Bulk materials (iron/steel, concrete, copper, aluminum), however, experienced limited attention so far, despite their substantial embodied greenhouse gas (GHG) emissions, their circularity potential, and their significance for electricity infrastructures. In the context of overall socio-metabolic material flows, we here present a synthesis of our recent studies on bulk materials in global electricity systems (see bibliography), thereby estimating GHG emissions related to bulk material use and investigating if there is empirical evidence for a positive correlation between material stocks, quality of energy services, and societal well-being.

Methodology

We apply a "stock-flow-service nexus perspective" in building a global country-level inventory of infrastructures, considering power plants, transmission and distribution grids, and transformers. We estimate material stocks using material intensity factors from the literature. We characterize national electricity systems in terms of material stock-flow relations and examine the relevance of power sectors in total bulk material consumption and stocks, as well as embodied GHG emissions. The relevance for societal well-being is investigated by relating material stocks on the country level with Social Progress Indicators (SPI), taking country-specific income levels into account. From a comprehensive scenario database published by the Integrated Assessment Modelling Consortium, we extract 281 global electricity sector scenarios and select 5 scenarios that reflect a wide range of conceivable futures. We apply a dynamic material stock-flow model based on historical stock developments and component-specific lifetimes to calculate annual and cumulative bulk material requirements to 2050. We develop different projections for material-specific GHG-intensities (GHG emissions per mass unit of material use) and calculate the cumulative GHG emissions related to bulk material consumption. By identifying core influencing factors, we discuss leverage points for limiting material-related GHG emissions to levels compatible with ambitious climate targets.

Results and Conclusions

According to our calculations, material stocks incorporated in global power systems have nearly quadrupled from 1980 to 2017. Power plants dominate total stocks of electricity infrastructures whereas grids contain the majority of aluminum and copper stocks (Fig. 1). 50% of the iron/steel stocks are contained in power plants. Transformers are of rather minor importance. Annualized emissions embodied in the total material stocks account for less than 1% of fuel combustion emissions from power plants. Material intensities and power generation mixes are highly diverse among technologies and countries, respectively. However, electricity supply quality and well-being indicators at the country level are correlated with per-capita metal stocks in electricity infrastructures. The material requirements of providing universal access to electricity until 2050 while decarbonizing the electricity sector are considerable. High-renewables scenarios imply significantly higher material requirements than scenarios relying on fossil fuels, nuclear energy, or CCS. If carbon mitigation in the production of bulk material is neglected, the total GHG emissions in high-renewables scenarios could amount to more than one-tenth of the entire remaining carbon budget for limiting global temperature increase to 1.5°C. Material sparing technologies (especially wind and solar), closing material loops, and applying low-carbon technologies in extraction and processing of bulk materials should thus be integral components of decarbonization strategies.

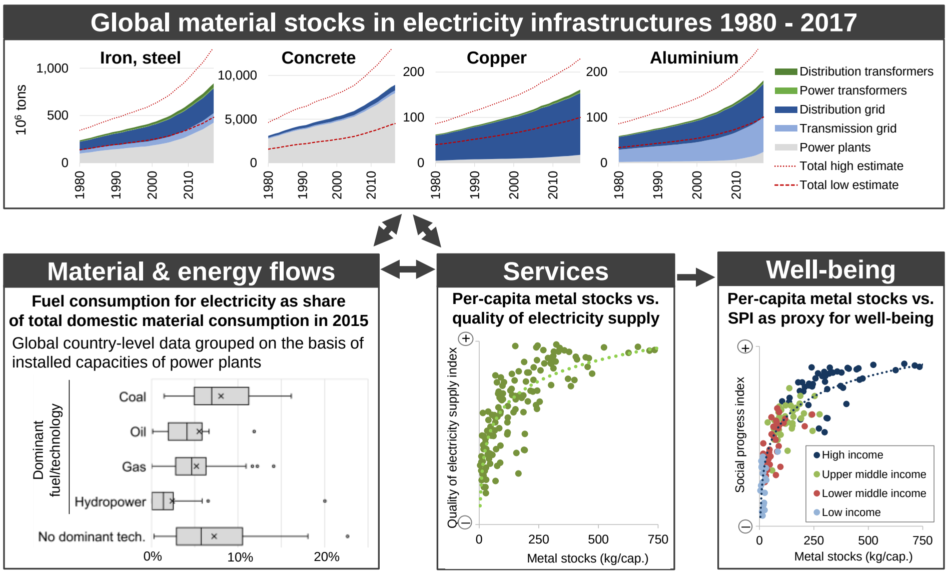

Figure 1: Schematic illustration of the stock-flow service nexus assessment of global electricity infrastructures. (Graphical abstract to Kalt et al., 2021a)

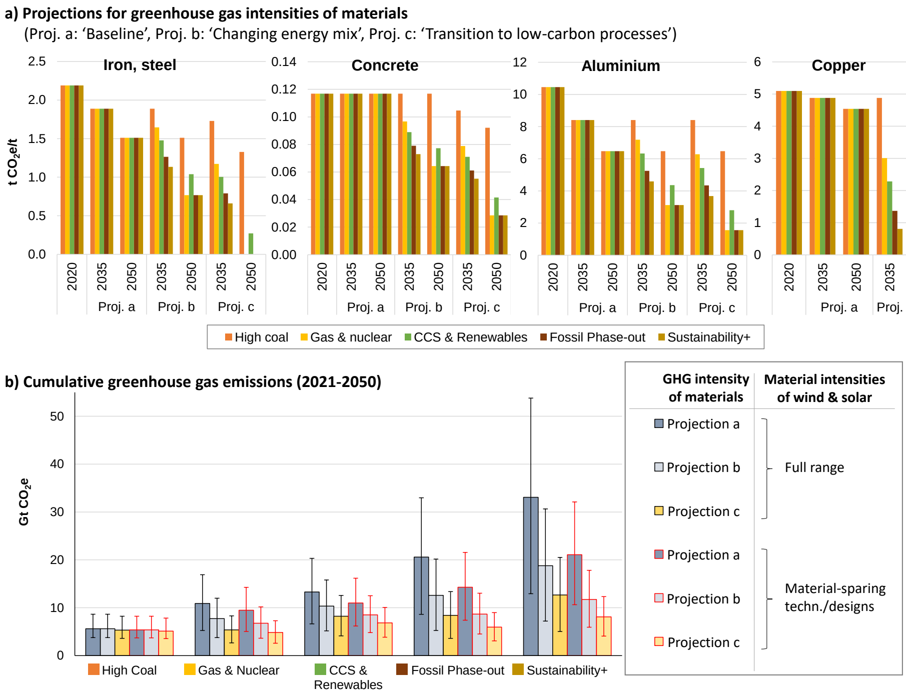

Figure 2: a) Projections for the greenhouse gas intensities of the four bulk solids. b) Cumulative greenhouse gas emissions related to the use of bulk materials in 5 electricity sector pathways. Uncertainty bars come from high and low estimates of material intensities.

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Bibliography

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., Haberl, H., 2021a. Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus. Resources, Conservation and Recycling (submitted).

Kalt, G., Thunshirn, P., & Haberl, H., 2021b. A global inventory of electricity infrastructures from 1980 to 2017: Country-level data on power plants, grids and transformers. Data in Brief (submitted).

Kalt, G., Thunshirn, P., Krausmann, F., Haberl, H., 2021c. Bulk material requirements of global electricity sector pathways to 2050 and associated greenhouse gas emissions. Global Environmental Change (submitted).