YSSP Report

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Assessing copper use against housing service scenarios

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Abstract

In order to curb the growing material demand without compromising human needs, the material requirement needs better assessment to address the underlying services provided to human with more consistent material intensity information. A critical metal, copper, is being extensively used in buildings and household appliances which together provide the basic services like shelter and thermal comfort for human beings that was denoted as housing service. In this paper, we adopted the projected service level (floor space per capital) from the Resource Efficiency and Climate Change (RECC) framework that offers comprehensive set of global scenarios for housing, and built a dynamic stock and flow model to estimate future demand for residential buildings and appliances. We then used the cutting-edge industrial ecology tools to extend the dataset of copper intensity with value meanings being clearly illustrated as total copper requirement, direct copper input or copper content. Strategies including supply-side technological improvement and demand-side behavioral change were evaluated, and the potential and advantage of each strategy were analyzed. The results show that appliances dominate annual total copper requirements for housing service under all strategy scenarios. Behavioral change and lifetime extension have relatively immediate effect of reducing primary copper demand, but lifetime extension needs case-by-case assessment about the associated impact like energy consumption. Increasing recycling rate becomes most effective in the latter half of the century as the system becomes more and more circular. Policy making should combine those strategies in the way that addresses behavioral change as soon as possible and at the same time incentivizes improvement in technologies like modularity design and new recycling techniques.

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Introduction

Human living depends on various materials. Although the fundamental goal of material utilization is to provide human services like housing, education and mobility[1], current usage of material is mainly derived in terms of different sectors like building and industry [2] rather than different service categories. The impact of demand-side behavioral change on material use and environmental impact is hence not fully assessed. In recent years, the links among services, in-use stocks and flows of products and materials that provide services, and environmental impacts have gained more attention [3–7]. Industrial ecology tools, for example, have the potential to estimate consumption-based material needs. However, even if the product demand by per unit of service such as floor area is well assessed, the accounting of associated material use could be confusing induced by the use of inconsistent material intensity (MI) coefficient [8]. MI has been estimated by calculating the ratio of economy-wide material consumption to gross domestic product [9], by referring to construction documents and on-site investigation [10], or by intensive literature review [8,11]. The use of MI in literature is not explicitly differentiated among per unit material content, direct material input during the production process, or total material requirement. A clearer identification of material use underlying services is needed to address the urgent issues on climate mitigation and resource depletion through behavioral change, recycling and material efficiency strategies.

As the best thermal and electrical conductor among all nonprecious metals, copper is increasingly demanded due to massive use in buildings and rapidly growing use in infrastructure and transportation sectors for economic development and transition to sustainable economy [12–14]. Whether copper resource is sufficient for the next decades is still under debate [15–19]. Primary copper production is energy intensive and has significant environmental impact especially human toxicity [20]. Thus, reducing copper demand while not compromising human welfare is highly interesting. Buildings are crucial physical requirements to provide shelter and living conditions for a decent living together with other major household appliances like air conditioners. Around 50% of current in-use stock of copper is in buildings [13,21] and 28% of the annual copper use in 2018 was for building construction. In this paper, we denoted the service provided together by the buildings and major household appliances as housing service. Due to the significant copper use in products providing housing service, better understanding of copper demand for housing service could inform potential strategies to sustain copper supply and further the study of material use underlying services.

Therefore, we in this paper modeled future copper requirements to fulfill the needs for housing services in terms of capital formation including residential buildings and major appliances and evaluated the potential to reduce primary copper demand by supply-side technological changes and demand-side behavioral changes. We seek to answer the following two questions:

- What are the copper requirements to meet future housing service scenarios?
- What are the potential opportunities of reducing primary copper use and how would these strategies compare against supply-side technological improvement and against demand-side behavioral change?

Method

The overall framework to derive copper use for housing services was shown in Figure 1. Three parts were addressed sequentially: housing service and required products (residential buildings and major appliances) to fulfill housing services; annual inflows of residential buildings and appliances; copper intensity and total requirements. To compare the strategies to reduce primary copper demand, scenarios for technological improvement and behavioral change were set up and assessed in the end. In this paper, we focused on the case of the US for detailed analysis.

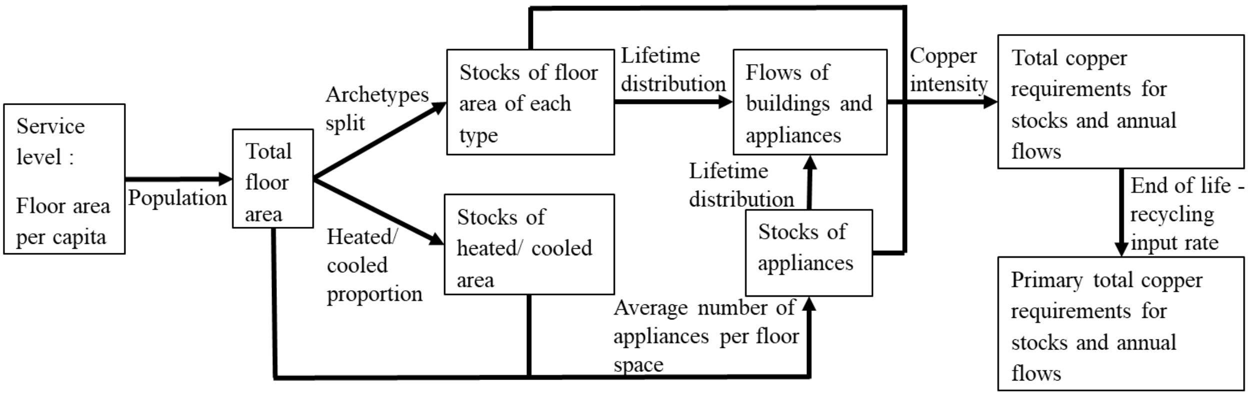

Figure 1 Overall framework of assessing copper use for housing service

Housing service and required products

The required products include residential floor space and appliances. In-use stock of product p in year t was denoted as $IUS_p(t)$ and calculated separately for residential floor space ($IUS_{p-FS}(t)$) and appliances ($IUS_{p-A}(t)$).

In-use stock of residential floor space for housing services were estimated based on future population, the service level – per capital floor area, their archetype mix or market share of different archetypes, and heated/cooled proportion in the Resource Efficiency and Climate Change (RECC) framework [4,22–25]. Following a what-if logic [26], the RECC framework defined parameters for 20 regions subject to three storyline (LED[27], SSP1, and SSP2[25]) narratives and region-specific historical trends by identifying existing scenario values in literature or by determining through time-series regression analysis and expert consensus approach. We adopted the parameters of the US in the SSP2 storyline as it represents a "Middle of the road" scenario following historical trends. The in-use stock of residential floor space was calculated as follows:

$$IUS_{p-FS}(t) \ = SL(t) * POP(t) * AS(t) \tag{1}$$

where product p includes the provided residential floor space by single family house (SFH), multifamily house (MFH) and others; SL(t) represents service level in year t; POP(t) represents population in year t; AS(t) represents archetype split among SFH, MFH and others in year t.

Appliance in-use stock was estimated by combining appliances demand per floor space ($ADP_p(t)$, in unit/m^2), total residential floor space and heated/cooled proportion ($HP(t)$ / $CP(t)$). Appliances demand per floor space was estimated based on 2015 Residential Energy Consumption Survey (RECS)[28] and was kept constant for future projections (Table 1). This paper has analyzed the copper intensity for various appliances and chose the following copper-intensive appliance types as major appliances for detailed analysis (See Results for detail): heating equipment (heat pump, central warm-air furnace, steam or hot water system, electric units, and others represented by solar), air conditioner, air cooler, clothes washing machine, television (TV), dish washer, refrigerator, clothes dryer, computer screen, desktop without screen, microwave, laptop.

$$IUS_{p-A}(t) \begin{cases} SL(t) * POP(t) * ADP_p(t), & for\ appliances\ other\ than \\ & heating/cooling\ equipment \\ SL(t) * POP(t) * HP(t) * ADP_p(t), for\ heating\ equipment \\ SL(t) * POP(t) * CP(t) * ADP_p(t), for\ cooling\ equipment \end{cases} \tag{2}$$

Annual inflows of residential buildings and appliances

As residential buildings and appliances have significantly different lifetimes (Table 1), their flows need to be assessed separately. Annual demand for residential buildings were estimated based on the building types, cohorts and lifetime distributions[4,22,23,29]. The appliance lifetime distributions were adopted from Wang et al.[30]. To be consistent with other appliances, we used the same data source of lifetime distribution for heating appliances which was lower than the assumed lifetime in Ecoinvent (e.g. lifetime for some heat pump was assumed to be 20 years in Ecoinvent). Appliance age file of 2015 was estimated from the Residential Energy Consumption Survey (RECS) and then used together with appliances lifetime distribution to project annual demand for appliances.

Table 1 Lifetime distribution and average demand per floor space of major household appliances

Appliances	Weibull parameters		Average number of appliance per thousand square meters in 2015 US based on [28]
	Shape k	Scale λ	
Heating equipment-Heat pump	1.8[30]	15.8[30]	0.70 (per heated area)
Heating equipment-Others represented by solar	1.8[30]	15.8[30]	1.65 (per heated area)
Heating equipment-Central warm-air furnace	1.8[30]	15.8[30]	3.64 (per heated area)
Heating equipment-Steam or hot water system	1.8[30]	15.8[30]	0.47 (per heated area)
Heating equipment-Electric unit	1.8[30]	15.8[30]	1.68 (per heated area)
Air conditioner (AC)	2.8[30]	12.3[30]	8.68 (per cooled area)

Air cooler	2.4[30]	13.6[30]	0.19 (per cooled area)
Clothes washing machine	2.2[30]	13.9[30]	4.42
Television (TV)	2.1[30]	12[30]	12.34
Dish washer	1.6[30]	13.1[30]	3.61
Refrigerator	2.2[30]	16.5[30]	6.91
Clothes dryer	2.6[30]	16.5[30]	4.30
Computer screen	2.5 [30] (represented by flat panel display)	7.5 [30] (represented by flat panel display)	2.65 (assume the same as Desktop)
Desktop without screen	2.1[30]	9.6[30]	2.65 (assume the same as Desktop)
Laptop	1.5[30]	5.2[30]	5.22
Microwave	0.8[30]	14.7[30]	5.36
Residential building	2.8[29]	73.5[29]	

Annual inflow in year t of product p ($AI_p(t)$) includes two parts: annual in-use stock increasing and outflow replacement of all previous years. Annual in-use stock increasing (IUSI) from year (t-1) to year (t) of a product (p) was calculated as follows:

$$IUSI_p(t) = IUS_p(t) - IUS_p(t-1) \tag{3}$$

where $IUS_p(t)$ includes both $IUS_{p-FS}(t)$ and $IUS_{p-A}(t)$.

Outflow replacement of product p of all previous years in year t ($OR_p(t)$) was determined by summing up the outflow in year t from all the age-cohorts. The earliest year was set to be 1990. $SF_p(t',t)$ represents the proportion of product p purchased in year t' that was still in-use in year t, and was calculated using its shape parameter k_p and scale parameter λ_p in Table 1.

$$SF_p(t',t) = e^{-((t-t')/\lambda_p)^{k_p}} \tag{4}$$

$Cohort_p(t')$ was the original inflow cohort of p in a previous year t' before year t ($t' \leq t$). For convenience, we at first derived the cohorts of p before 2015 by using its 2015 age file and its Weibull survival function (SF). Based on the survival amount of inflow p from previous year t' in 2015 ($SA_p(t', 2015)$) shown in the age file, $Cohort_p(t')$ was calculated below.

$$Cohort_p(t') = SA_p(t', 2015)/SF_p(t', 2015),\ t' \leq 2015 \tag{5}$$

The cohort of p after 2015 was the same as total annual inflow:

$$Cohort_p(t') = AI_p(t'),\ t' > 2015 \tag{6}$$

The outflow of p from a previous year t' in year t ($OR_p(t', t)$) was calculated as follows:

$$OR_p(t', t) = \begin{cases} Cohort_p(t', t) * (SF_p(t', (t-1)) - SF_p(t', t)),\ t' < t \\ 0,\ t' = t \end{cases}, \tag{7}$$

The total outflow of p from all previous years:

$$OR_p(t) = \sum_{t'=1990}^{t} OR_p(t', t) \tag{8}$$

Annual inflow in year t of product p was then calculated as follows:

$$AI_p(t) = IUSI_p(t) + OR_p(t) \tag{9}$$

Copper intensity

This paper consolidated the value of copper intensity by clarifying the data meanings and using various sources including input-output (IO) table, life cycle assessment (LCA) and literature review. Copper content (CC) is the copper actually embedded in copper products. It is useful in calculating current copper in-use stock and scrap generation potential. In this paper, CC was obtained by collecting data from literature review and by estimating using waste input-output material flow analysis (WIO-MFA) method[31–33] on US IO table[34,35] and EXIOBASE database[36]. Total copper requirement (TCR) is the total demand of copper considering all the upstream copper requirement at material level-usually refined copper or copper semis. TCR was estimated by LCA using the ecoinvent[37] database and by the WIO-MFA method using IO table[34–36]. Direct copper input (DCI) is the direct refined copper input into the final-stage manufacturing process of appliances and was obtained using the ecoinvent[37] database.

There is little information in literature on copper intensity of heating equipment as heating equipment varies a lot in terms of types (furnace, heat pump, electric heater, etc.), heating fuel (natural gas, electricity, wood, etc.) and power (in kW). For example, central warm-air furnace, heat pump and fireplace could all be used as main heating equipment according to RECS and the heat capacity of heating equipment could be 4 kW or 10 kW according to Ecoinvent. We matched the possible heating equipment between RECS and Ecoinvent and get the TCR and DCI for different heating equipment. Only those appliances with a capacity lower than 100 kW was considered to be used in residential buildings.

Strategies of reducing primary copper demand

Scenarios were set up to analyze the potentials of different strategies to reduce primary copper demand. We built up three types of scenarios:

- Scenario 1 - Lifetime extension. By changing the scale parameter of Weibull distribution, the mean lifetime of residential buildings constructed after 2020 was increased to 100 years while the mean lifetime of major appliances produced after 2020 was extended by 2, 4 or 6 years. Both technological improvement and behavioral change can impact product lifetime. Lifetime extension will change in-stock and annual demand for housing services.
- Scenario 2 - Faster saturation of service level due to behavioral change. The service level was set to stay constant after 2020. In-stock and annual demand for residential buildings and major appliances were reduced under this strategy.
- Scenario3 - Higher end-of-life recycling input rate (EoL-RIR) of copper during copper production due to technological improvement through higher collection and separation efficiency, high yield ratio and better scrap management like blending. Ciacci et al.[38] suggested the copper from old scrap could only meet at best 65% of future copper demand; Deetman et al.[39] estimated that the recycling building material could only cover about 55% of construction copper demand by 2050; Dong et al.[14] mentioned that only half of the copper demand by China in 2050 could be met by secondary copper. We assumed that the EoL-RIR increased from the current 19% to 50% from 2016 to 2050 with a constant annual growth rate. Although we denoted this strategy mainly as supply-side technological improvement, we understand behavioral change such as better waste sorting could improve recycling rates. Higher EoL-RIR reduces the primary portion of copper intensity.

Results and discussion

Copper intensity

Appliances

The results of copper intensity of different meanings and from various methods were shown in Figure 2. Theoretically, TCR would always be the largest value for a certain appliance compared to CC and DCI as TCR includes all the upstream copper requirements. This was the case for most of the appliances including the most copper-intensive ones like heating equipment, TV and washing machine. For refrigerator and microwave oven, TCR and DCI were between the value of the highest and lowest values of CC due to the wide range and uncertainty of CC in literature.

Copper intensity for heating and cooling equipment was significantly higher followed by other large home appliances. For the detailed copper requirements estimation in the following steps, we chose 16 types of major appliances as shown in the Method Section and used average TCR value as copper intensity as to reflect the total copper material demand in the future. For air conditioner and air cooler, we used their largest CC values as proxies for TCR.

As shown in Figure 2, this study largely enriched the dataset for more copper-intensive appliances like heating equipment. The value from WIO-MFA method using IO tables were not shown here due to their low resolution on appliances. For example, in the US IO table[34,35], household appliances are only separated into household cooking appliance, refrigerator and freezer, laundry equipment and others; heating boilers and stoves are classified into heating equipment (except warm air furnaces); warm air furnace and heating pumps are in "Air conditioning, refrigeration, and warm air heating equipment manufacturing"[40].

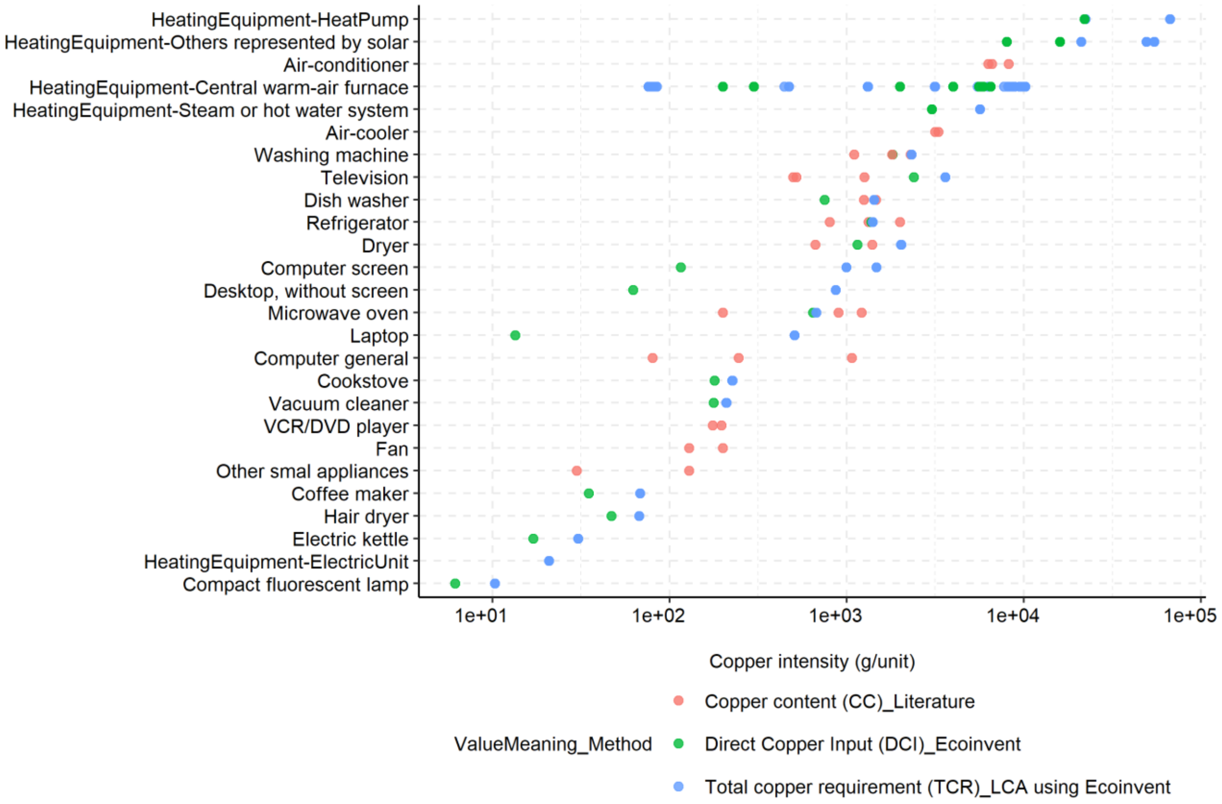

Figure 2 Copper intensity for home appliances. The appliances were ranked by the median value of their dataset including TCR, DCI and CC.

Residential buildings

As shown in Figure 3, CC results of single family and multifamily buildings from WIO-MFA method were acceptable compared with literature data for general residential buildings. Large uncertainty was noticed as the literature data includes different world regions from various years. Due to higher resolution and our focus on the US, we used the TCR results of residential buildings from WIO-MFA method using US IO table for further calculation.

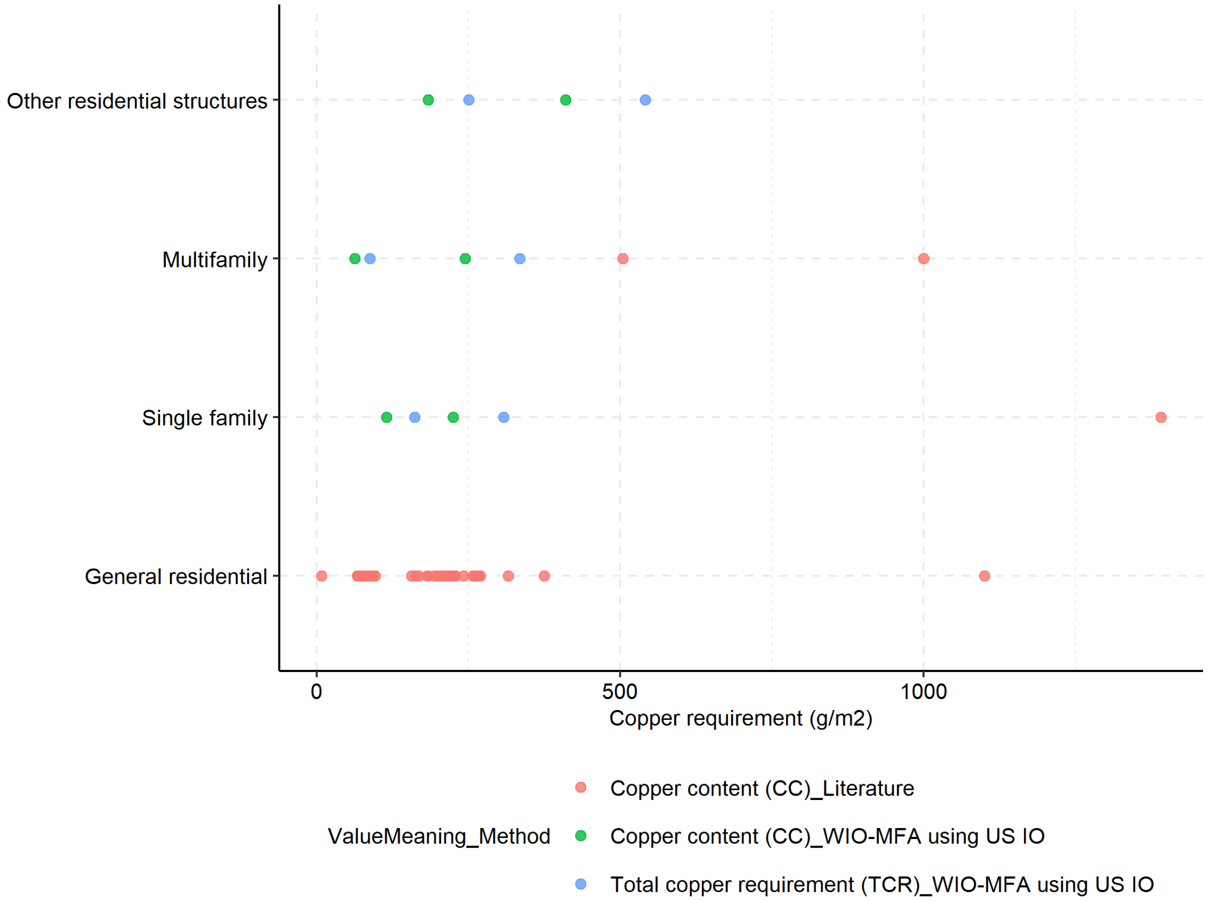

Figure 3 Copper intensity for residential buildings.

Due to the relatively low resolution of sectors, the copper intensity results using EXIOBASE was not used for further calculation in this paper.

Copper requirements for in-use stock of housing services

According to the model, remarkably more copper will be required to fulfill the in-use stock for multifamily buildings in the end of this century as there will be a larger proportion of multifamily construction in the newly built residential buildings. Copper requirements for heating and cooling equipment are about the same amount as the residential building with air conditioner being the most significant. TV, refrigerator, clothes washing machine and clothes dryer account for an important portion of the TCR.

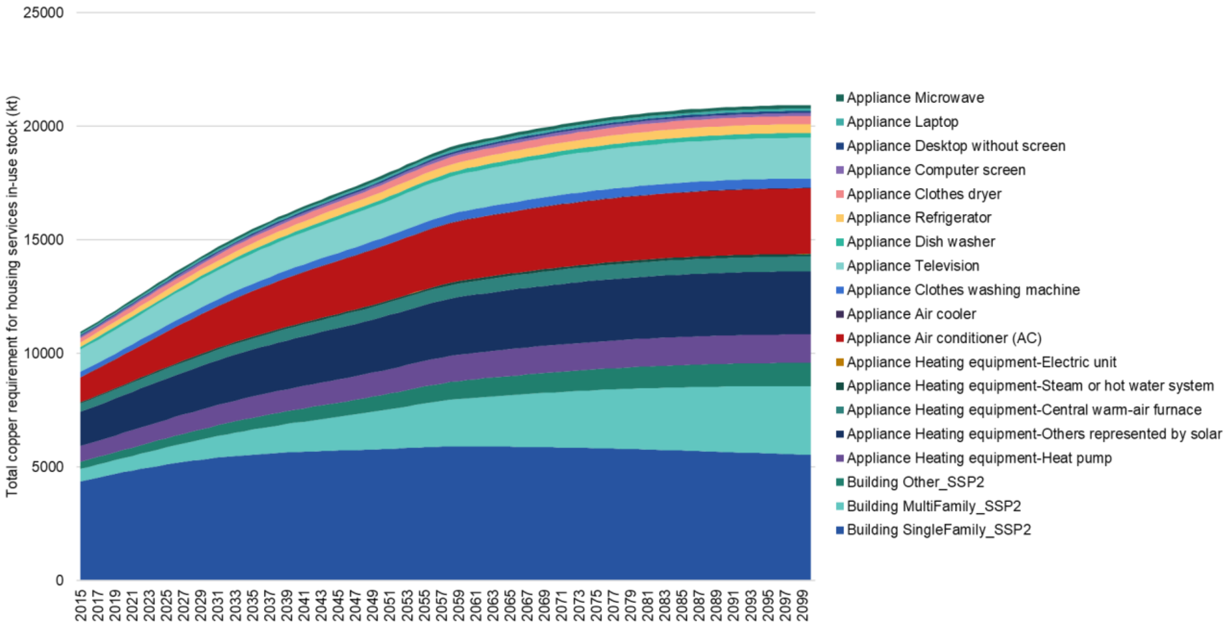

Figure 4 Copper requirements for in-use stock of housing services in the US

Copper requirements for annual demand for housing services

Although the TCR for residential buildings is comparable to that of appliances for in-use stock, the appliances, especially those for thermal comfort (heating and cooling) and TV, dominate the TCR for annual demand of housing services. The obvious hump around 2055 is mainly due to the boom of residential buildings in around 1990 and their average lifetime of around 65 years.

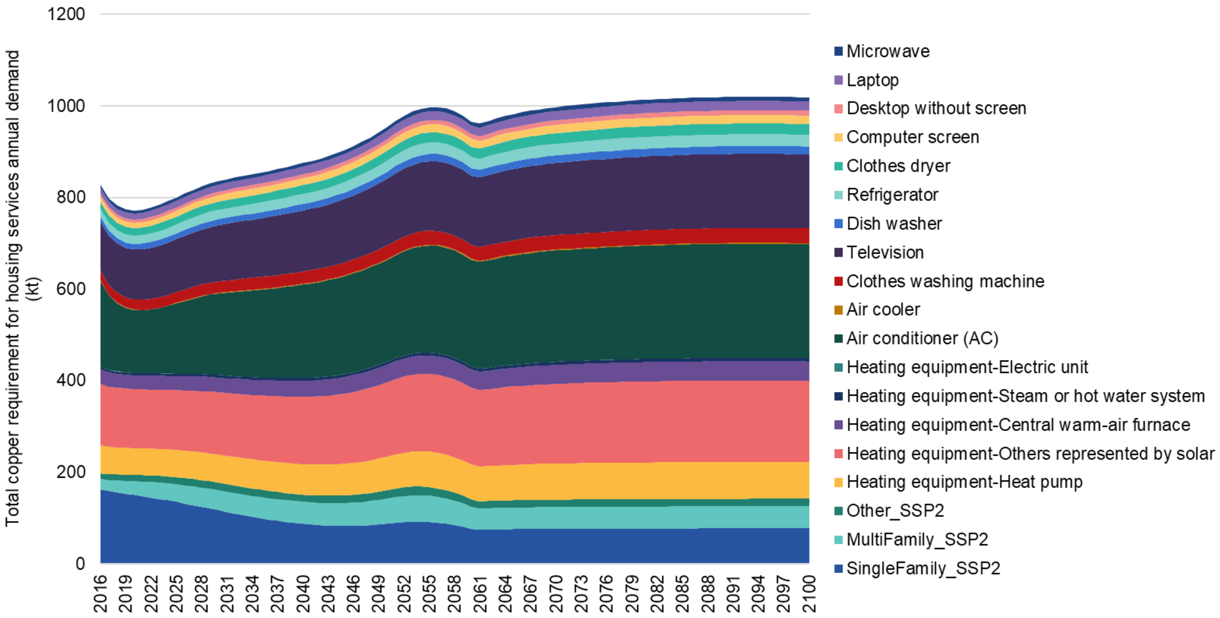

Figure 5 Copper requirements for annual demand for housing services in the US

Strategies for reducing primary copper demand

Appliances dominate the TCR for housing services under all scenarios (Figure 6). The strategy of lifetime extension for residential buildings only becomes effective in the latter half of the century due to their long lifespan, while for appliances this strategy makes significant difference after 2020. The performance of this strategy differs remarkably when extending the lifetime by different degrees. For example, when the lifetime of appliances is extended by 6 years, there are substantial amount of decrease for TCR throughout the century.

When fixing the service level after 2020, there is a sudden drop for TCR as the increased demand for both appliances and residential buildings becomes less, and population growth drives the annual demand increase after the drop. Increasing EoL-RIR significantly reduces primary copper requirements and performs best in the long run.

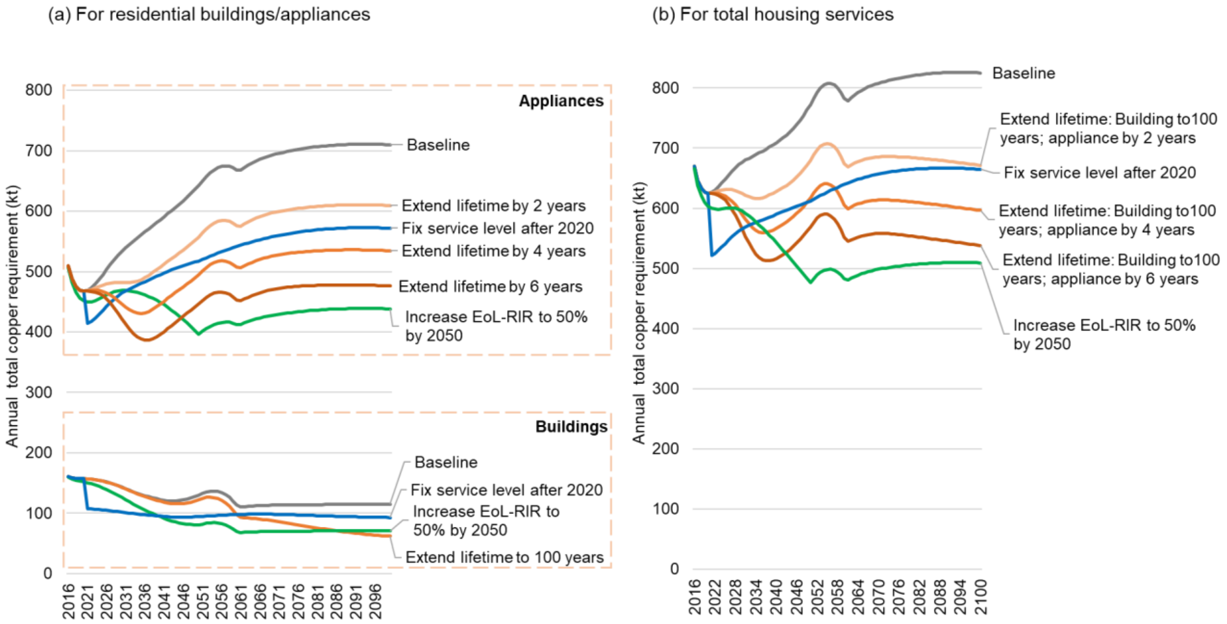

Figure 6 Annual TCR for housing services under different scenarios. (a) shows the annual TCR for residential buildings and appliances separately. (b) represents the TCR for total housing services which is the sum of the TCR for residential buildings and appliances.

Conclusion

Although there is disagreement on future copper scarcity level, copper was recognized to have high Vulnerability to Supply Restriction (VSR) at national level [41,42] and copper primary production has high environmental impact [20]. By using the cutting-edge industrial ecology tools to consolidate the highly uncertain and sometimes vague information of copper intensity, this paper for the first time estimated the future copper requirements to fulfill future human housing services and assessed both demand-side and supply-side strategies to curb primary copper demand growth.

Behavioral change and lifetime extension have relatively immediate effect of reducing copper demand. Lifetime extension of products from technological and behavioral aspects could be the most effective way to reduce primary copper demand if extended long enough (e.g. more than 6 years) but raises tradeoffs of energy saving and other environmental impact between conventional less energy efficient appliances and highly efficient new technologies. Crucial amount of TCR is for diverse appliances which currently have low EoL recycling rates [21]. Increasing recycling rate is very promising in the long-run as the system becomes more and more circular.

This paper only takes into account the capital formation of housing services. Copper requirement for operational energy use in the forms of power plant and infrastructure including transmission and distribution network will be considered in future work. More service types like transport and more material types could be assessed using the same method. Uncertainty from lifetime distribution and change of copper intensity due to technological development will be discussed in future work. The results of this paper help inform policy makers of the total copper requirements for future housing services and the potential of both supply-side technological and demand-side behavioral strategies in reducing primary copper demand.

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