Environmental Science & Technology

pubs.acs.org/est

Article

Forecast of the U.S. Copper Demand: a Framework Based on Scenario Analysis and Stock Dynamics

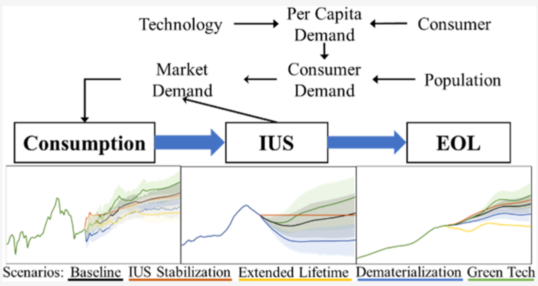
Rui He and Mitchell J. Small*

Cite This: *Environ. Sci. Technol.* 2022, 56, 2709−2717

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: In a world of finite metallic minerals, demand forecasting is crucial for managing the stocks and flows of these critical resources. Previous studies have projected copper supply and demand at the global level and the regional level of EU and China. However, no comprehensive study exists for the U.S., which has displayed unique copper consumption and dematerialization trends. In this study, we adapted the stock dynamics approach to forecast the U.S. copper in-use stock (IUS), consumption, and end-of-life (EOL) flows from 2016 to 2070 under various U.S.-specific scenarios. Assuming different socio-technological development trajectories, our model results are consistent with a stabilization range of 215−260 kg/person for the IUS. This is projected along with steady growth in the annual copper consumption and EOL copper generation driven mainly by the growing U.S. population. This stabilization trend of per capita IUS indicates that future copper consumption will largely recuperate IUS losses, allowing 34−39% of future demand to be met potentially by recycling 43% of domestic EOL copper. Despite the recent trends of "dematerialization", adaptive policies still need to be designed for enhancing the EOL recovery, especially in light of a potential transitioning to a "green technology" future with increased electrification dictating higher copper demand.



KEYWORDS: *copper, demand, scenario, forecast, U.S.*

1. INTRODUCTION

Challenged with growing demand for natural resources, worsening impacts of climate change, and deteriorating environmental quality, the U.S. society has started to embrace a fundamental socioeconomic transition to a "circular" economy, of which an integral aspect is "sustainable materials management" (SMM). SMM is promoted by the U.S. EPA as "a systemic approach to using and reusing materials more productively over their entire life cycles".[1] By improving the resource efficiency, SMM not only conserves natural resources but also contributes to the economic, environmental, and social welfare of the society. A key prerequisite to unlock the potential of SMM is to understand and anticipate the flows, stocks, and availability of resources in the future.

Copper has been essential to human civilization throughout history and is currently the third most consumed metal in the U.S., following iron and aluminum, despite its relatively low geological abundance compared to the other two.[2] The supply−demand dynamics of copper has caught the attention of many researchers in recent years due to its growing economic importance,[3,4] high consumption rate,[2] and relatively low substitutability (mainly due to inferior substitute performance).[3] Policy makers are thus always seeking plans and strategies that minimize copper consumption and maximize end-of-life (EOL) recovery in economically beneficial, technologically feasible, and socially positive or benign ways.[5]

Multiple studies have investigated contemporary and historical copper flows and stocks in the U.S. and globally using dynamic material flow analysis,[6−9] while only a few attempted to forecast copper demand with either "top-down" or "bottom-up" approaches.[10] Most "top-down" modeling approaches apply econometric methods based on market drivers, often using linear regression.[11−13] These studies typically project future copper flows based on their historic correlations with gross domestic product (GDP), population, and other covariates, such as urbanization, substitution, and technology development. The other widely adopted method is the "stock dynamics" model,[14−17] which is a "bottom-up" approach based on physical flow drivers. This approach hypothesizes that resource consumption is driven by the accumulation of per capita in-use stock (IUS), which typically follows an *S*-shape curve with an initial exponential growth phase and an eventual saturation phase as wealth accumulates in a society.

Received: July 30, 2021
Revised: December 24, 2021
Accepted: January 12, 2022
Published: January 28, 2022

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

Scenario analysis that anticipates possible futures by making assumptions on the key parameters that influence copper demand was adopted in all these studies using a variety of model formulations to address the complex nature and inherent uncertainties of the future copper market. For instance, projection of population is pivotal for it has direct causal effects on total copper demand. Additionally, there are ongoing efforts to develop a set of self-consistent future scenarios that consider the interactions among economic growth outcomes,[18] technology transitions,[16,19,20] and policy interventions.[11,12,15]

Despite existing efforts to untangle the future copper demand dynamics, major knowledge gaps persist. First, various uncertainties reside in the complex nature of this topic.[21] In the real world, copper demand is influenced by interactions among economic sectors, technology innovation and adoption, real-time market feedback, consumer behaviors, and policy interventions, none of which can be deterministically predicted by existing models. Second, the heterogeneity in different societies introduces specific copper consumption trends, which can be masked by the aggregated global averages. For example, most developed countries no longer follow the global trend of copper consumption, which is largely driven by the economic growth of developing countries.[22] Third, Elshkaki et al. pointed out that few scenario analyses had been conducted to understand the full spectrum of possible futures with regard to metal usage.[11] Many existing scenario analyses are based on generic global economic development scenarios, with limited adaptation to local socioeconomic contexts and metal-specific technology adoptions. For example, generic global GDP forecast scenarios are insufficient for predicting how electric vehicles (EVs) and renewable energy penetration will impact future copper demand in the U.S.

This study does not intend to resolve all of these complexities but rather to provide a robust, adaptable framework for forecasting regional demand of resources. The framework is applied to estimate the effects of critical technology, social, and management assumptions on the U.S. copper demand outcomes through 2070. The analysis is focused less on the absolute quantities of copper projections but rather on the shift in stocks and flows predicted under different future scenarios. In the remainder of the paper, we first examine existing demand forecast models through the lens of system dynamics to understand their implications and assumptions. Then, the stock dynamics approach is adapted to reflect the unique copper consumption trends of the U.S. society. Finally, U.S.-specific technological and socioeconomic development scenarios are constructed and evaluated to project the per capita IUS, consumption, and EOL flows of copper, noting their implications for circularity and sustainability.

2. METHODS

2.1. System Dynamics Perspective on Copper Demand. System dynamics characterizes the behavior of individual components of a system as well as their interactions and overall outcomes.[23] The economic system that drives the regional supply and demand of copper is simplified and conceptualized in Figure 1 by incorporating elements of system dynamics models[24,25] into a typical metal flow analysis framework.[26] From this system dynamics perspective, consumer copper demand is determined as a product of population and per capita copper demand at a given time, which is influenced by economic factors (affluence), technology factors (copper content of products), and social factors (consumer lifestyles and preferences). The gap between consumer demand and the current level of per capita IUS generates the real-time market demand that drives copper consumption. In addition, the actual copper consumption is affected by copper price and other supply conditions. Finally, the difference between copper consumption and EOL copper exiting the use phase becomes the net accumulation of copper IUS, which closes the feedback loop for determining copper demand for the next iteration.

This system dynamics perspective not only reveals the physical material flows through the entire copper lifecycle and their interactions with various socioeconomic drivers but also provides a framework, within which all existing demand forecast models can be analyzed and compared. For example, regression models typically ignore the impact of copper price on consumption and select covariates (explanatory variables) that have direct or indirect causal relationships with copper demand to predict various copper flows. Stock dynamics models essentially make the same simplification to approximate copper consumption with market copper demand. However, instead of relying on statistical inferences, it attempts to reveal the causal relationships among these variables. This is the reason why the stock dynamics approach is believed to be better constrained and have higher reliability for long-term projections than the regression approach.[12,27]

2.2. Adaptable Demand Forecast Framework. Given the complex nature of the entire copper supply−demand system, a series of simplifications and adaptations are needed to develop a flexible yet robust framework for forecasting U.S. copper demand, with applicability toward other regions and resources.

First, it is assumed that the copper price will not dramatically increase before 2070 (detailed in Section 1.2 and further expanded in Section 3.4 of the Supporting Information). In addition, we assume that there will be neither drastic consumption policy changes nor shortages of copper supply. As a result, the system dynamics model can be dissected into two sub-systems: one on supply and one on demand. The sub-system on demand is essentially a typical stock dynamics model,[6] consisting of "consumer copper demand", "market copper demand", "copper consumption", "IUS", and "EOL copper" as highlighted in Figure 1. It is worth mentioning that copper consumption under this framework is assumed to be free from supply restrictions and market influences and is equal to market copper demand.

Many demand forecast studies have used sigmoid growth curves to correlate per capita IUS accumulation with economic growth.[17,28] However, the U.S. per capita copper IUS has already started to decline despite further GDP growth,[8] which signals the potential limitations of this assumption. The traditional *S*-shape IUS saturation hypothesis fails to incorporate product life cycles (product introduction, growth, maturity, and decline in the market), market condition shifts,[29] and consumer behavior changes.

This declining trend of copper IUS does enable the omission of "economic factors" in the model by signaling that the U.S. copper demand has, at least for the present, largely decoupled from economic growth. A few possible explanations for this decoupling include demand saturation, phasing-out of old technologies, sustainable consumption, efficiency improvements through urbanization, and use of substitutes. One

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

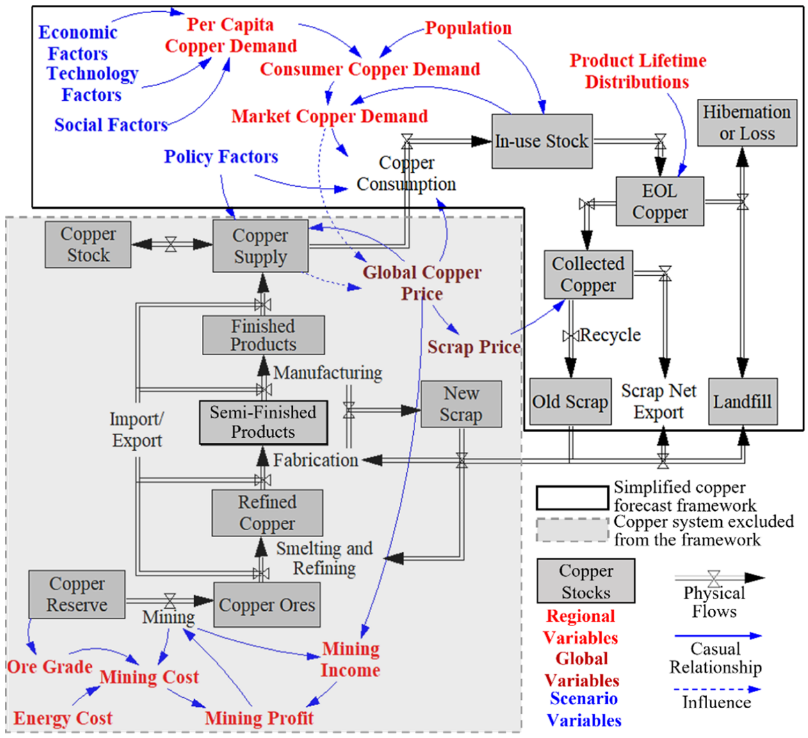


Figure 1. System dynamics perspective of regional copper supply and demand. This simplified regional perspective only includes key variables and metal flows that are relevant for this study. The regional supply system is enclosed in the gray box, while the demand system with EOL flows is highlighted within the white box. The demand forecast framework of this study is based on the regional demand system highlighted in the white box.

particular reason for the U.S. is the pent-up investments in infrastructure, estimated to account for a gap of billions of dollars.[30] Ignoring the wealth factor, the future U.S. per capita copper demand can be determined primarily by technology factors and social factors alone under normal economic development scenarios.

Typically, in a "bottom-up" stock dynamics framework, material flows and stocks are disaggregated into different end-use sectors, which are normally further broken down into specific products, to enable calculation and prediction. The same approach is adopted to determine U.S. copper flows and stocks for the five major end-use sectors of copper: building and construction ("Building"), electrical and electronic products ("EE"), industrial machinery and equipment ("Machinery"), transportation equipment ("Transportation"), and consumer and general products ("Consumer").

However, to circumvent the complexity of enumerating all the copper products, we introduce the concept of an "average product", which is the weighted average of all the copper-containing products in an end-use sector. This builds a hierarchical model structure that sits between traditional "top-down" models using macro-economic trends and "bottom-up" approaches that rely on product-level details. This design reduces data intensity and model complexity by relying on macro trends when these trends apply to the entire end-use sector homogeneously, while retaining the flexibility to disaggregate an end-use sector into individual products like a traditional "bottom-up" model. In this study, we treated the Building, Machinery, and Consumer sectors in this "aggregated" manner, while the EE and Transportation sectors were broken down into specific power generation technologies and passenger vehicle types (see details in Sections 2.3 and 2.4 of the Supporting Information).

Finally, to unify the predictions of end-use sectors at different levels of "disaggregation", we transform the technology factors and social factors of the original stock dynamics model[31] into "relative material intensity" (RMI) and "relative demand" (RD) parameters as key model inputs. Both RMI and RD parameters are dimensionless coefficients to adjust the projected per capita IUS relative to the baseline year (2015 in this study). The RMI coefficients compensate for the copper intensity of changing technologies and products and model the relative amount of copper needed to produce one unit of "average product" from an end-use sector during a specific year in comparison to that of the baseline year. For example, an RMI coefficient of 1.10 for the Transportation sector in 2050 means that the "average transportation product" in 2050 will require 10% more copper than the "average transportation product" in 2015. Similarly, the "social factor" is translated into the RD coefficients that model the relative per capita demand for the "average product" from an end-use sector during a specific year in comparison to that of the baseline year. For example, an RD coefficient of 0.90 for the Transportation sector in 2050 indicates that consumers will own 10% less "average transportation product" in 2050 as compared to 2015. When an end-use sector is disaggregated into sub-sectors (product groups or products), RMI and RD coefficients need to be assigned at the sub-sector level and the overall RMI and RD coefficients can be calculated based on mass balance.

The historical per capita IUS and EOL copper generation for each end-use sector between 1970 and 2015 are calculated based on the copper consumption data compiled by the

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

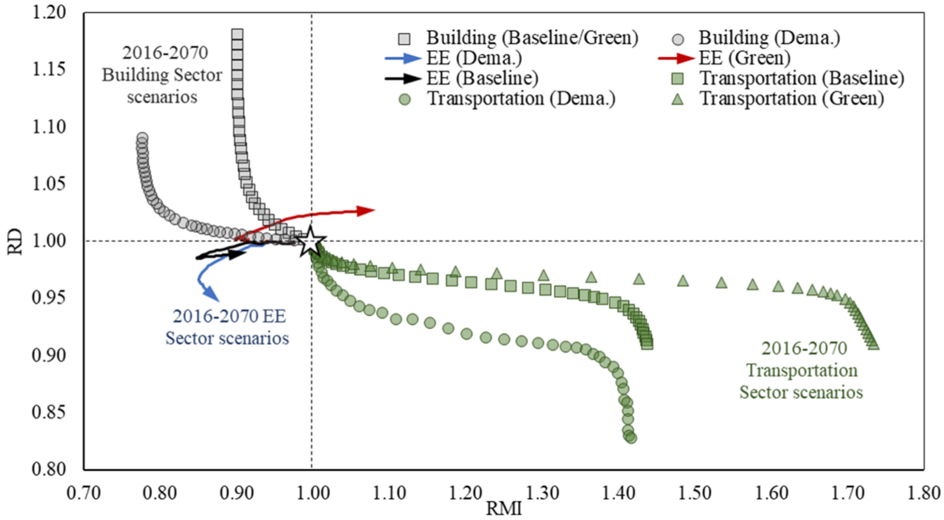


Figure 2. Assumed coevolution of RMI and RD trajectories for the Building, EE, and Transportation sectors. All scenarios begin at the 2015 baseline (denoted by the star) and evolve as shown until 2070. The IUS Stabilization Scenario assumes constant RMI and RD coefficients, and the Extended Lifetime Scenario shares the same RMI and RD coefficients as the Baseline Scenario; thus, these two scenarios are not presented.

USGS[32] and UN Comtrade Database, assuming representative lifetime distributions for an "average product" in each end-use sector. The equations for projecting IUS, consumption, and EOL generation from 2016 to 2070 are based on the demand forecast framework described above. Detailed lifetime distribution assumptions and model calculations are provided in Sections 1.2−1.4 of the Supporting Information.

2.3. Future Scenarios. Scenario analysis does not intend to predict the future but rather to identify and compare "what if" stories of future possibilities. There are five parameters in total for constructing these future scenarios: U.S. population, RMI, RD, and the mean and standard deviation of the "average product" lifetime distribution for each end-use sector. Among these parameters, the U.S. population has a linear impact on copper demand and has forecasting scenarios well established. The standard deviations of product lifetime distributions have relatively insignificant impacts on the model outputs (see details in Section 3.2 of the Supporting Information).[9] Thus, scenario development was centered on the other three parameters: RMI, RD, and mean product lifetime. Specifically, five different scenarios were constructed to envision possible future trends of technology development, consumer choices, and product lifetime expectancies in the U.S.

2.3.1. Baseline Scenario. The Baseline Scenario depicts a "currently expected future". This scenario intends to synthesize the best existing knowledge on what might happen in the future regarding the U.S. copper demand. The RMI and RD coefficients for the five end-use sectors were estimated based on government predictions, peer-reviewed journal articles, and extrapolations of current trends.[33−37]

2.3.2. IUS Stabilization Scenario. The IUS Stabilization Scenario assumes that per capita IUSs of all the end-use sectors remain at their 2015 levels (i.e., all RMI and RD coefficients are "1"), which implies that technologies, consumer behaviors, and copper products remain unchanged. This scenario is highly idealized but helps to reveal the magnitude of the copper resource needed to sustain the current levels of per capita consumption, ownership, and disposal of copper products.

2.3.3. Extended Lifetime Scenario. The Extended Lifetime Scenario shares the same assumptions as the Baseline Scenario, except that the "average product" lifetimes of all sectors are assumed to extend by 25% after 2015. Despite shorter lifespans for some products,[38] one sustainability notion is "design for longevity". This scenario aims to explore the impacts of extending life expectancies of copper products on the future consumption and EOL flows.

2.3.4. Dematerialization Scenario. The Dematerialization Scenario envisions a future with lower consumer demand (RD) thanks to sustainable consumer behaviors (sustainable consumption) and shared infrastructures enabled by urbanization. Meanwhile, this scenario has more aggressive assumptions on copper substitution, which lead to less copper usage and lower RMI coefficients.

2.3.5. Green Technology Scenario. The Green Technology Scenario envisions a future with more extensive electrification and deployment of renewable energy and EV technologies, which are believed to be potential solutions to climate change. This scenario intends to reveal the resource implications of these energy decarbonization trends.

Key assumed values of RMI and RD coefficients for the Building, EE, and Transportation sectors are presented in Figure 2. These coevolution trajectories mainly represent socio-technological trends assumed for these end-use sectors, which include electrification of passenger vehicles,[39] extensive deployment of renewable energy,[35] and continuation of dematerialization. Full scenario assumptions and parameterization are detailed in Sections 2.1 and 2.2 of the Supporting Information. Under all future scenarios, the Building sector is expected to exhibit somewhat lower copper intensity (RMI) and a distinct increase in consumer demand (RD), mainly due to substitution and an expected floorspace increase. The Transportation sector is projected with the most significant increase in RMI and moderately lower RD coefficients, mainly due to the electrification of personal vehicles and the continuation of the existing dematerialization trend. For the EE sector, highly variable trajectories are anticipated as a result of copper substitution by aluminum (in power cables) and optical fibers (in telecommunication wires) and the increasing deployment of copper-intensive renewable energy capacity. The Machinery and Consumer sectors are assumed to share similar patterns of lower RD and relatively stabilized RMI coefficients.

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

2.4. Destinations and Recovery of Consumed Copper. As shown in Figure 1, copper consumption is absorbed by four major copper "sinks": IUS, hibernation stock,[40] landfill disposal, and collected EOL scrap (for recycling or export). To understand the relative sizes of these sinks in the U.S. and the circularity implications of various future scenarios, three circularity indicators are applied: the EOL collection rate (EOL CR), which is the percentage of EOL copper that is collected; the EOL recycling rate (EOL RR), which is the percentage of EOL copper that is recycled; and the EOL recycle input rate (EOL RIR), which is the percentage of copper in the product that is from recycled EOL copper.[41] For the sake of demonstrating and comparing the sizes of domestic EOL flows, imported EOL copper is ignored.

Historical EOL RR estimates[7] and EOL copper collection and landfill data[8] are obtained to estimate the distribution of copper consumption among the four copper sinks and establish a historical baseline of copper circularity between 1970 and 2015. Given that there are no primary data on hibernation stocks in the U.S., they are calculated based on mass balance as the difference between theoretical EOL generation and total collected and landfilled copper.

For future projections, the EOL CRs for the Building, EE, Machinery, Transportation, and Consumer sectors are assumed to be 60, 30, 67, 90, and 60%, respectively, across all scenarios considering both the historical baseline and global averages.[9] In addition, it is assumed that 10% of EOL copper will be landfilled based on the historical trend, and the ratio between EOL RR and EOL CR for each end-use sector will converge to that of the global levels.[9]

3. RESULTS AND DISCUSSION

3.1. Future Copper Demand Projections. As shown for the Baseline Scenario in Figure 3a, the per capita IUS of copper is predicted to gradually drop from the baseline level of 240 kg/person to its minimum value of 227 kg/person around year 2032 before peaking at 243 kg/person in 2070 as a result of growth in some end-use sectors and shrinkage in the others. This 1.0% increase from 2015 to 2070 is small compared to an expected per capita GDP growth of about 100% during the same time span, reinforcing the decoupling between wealth and demand. The major contributors to the IUS accumulation are the Transportation sector, which is projected to grow by 30.9%, and the Building sector with 7.6% expected growth. On the other hand, the Machinery and Consumer sectors are projected to shrink by 20.8 and 10.0%, respectively, following the existing trends of dematerialization. Despite the increase in renewable energy deployment, the per capita IUS of the EE sector is anticipated to drop by 9.5%, mainly due to substitution and efficiency gains. By 2070, the Building sector is projected to be the largest "IUS sink" in the U.S., representing 48.6% of the total copper IUS (117.9 kg/person), followed by the EE sector at 23.8% (57.9 kg/person), the Transportation sector at 13.2% (32.1 kg/person), the Machinery sector at 9.2% (22.4 kg/person), and the Consumer sector at 5.1% (12.5 kg/person).

The annual EOL copper generation is expected to grow by 37% from 2.3 million metric ton (Mt) to 3.2 Mt over this 55-year span. Specifically, the Building sector is expected to increase from under 0.6 Mt to stabilizing around 1.0 Mt after 2044. The EOL copper from the Transportation sector is anticipated to yield a monotonic increase from 0.37 Mt to almost 0.69 Mt, driven by the growing population and

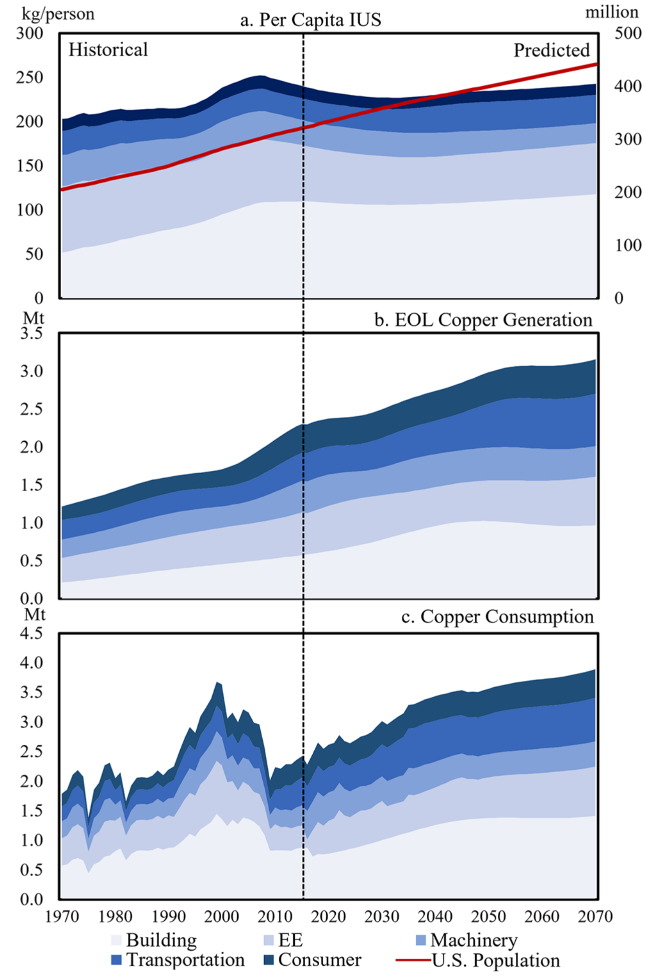


Figure 3. Simulation results of the Baseline Scenario for (a) U.S. Copper Per Capita IUS, (b) U.S. EOL Copper Generation, and (c) U.S. Copper Consumption. The results are shown for the five major end-use sectors: Building, EE, Machinery, Transportation, and Consumer products.

expanding per capita IUS. The EOL copper from the EE sector is projected to oscillate between 0.50 and 0.62 Mt before peaking at 0.64 Mt by 2070. The lowest EOL copper generation is expected around 2040, which is due to the consistently decreasing copper consumption since the early 2000s. The EOL generation from the Machinery and Consumer sectors is anticipated to be relatively stable at around 0.40 Mt. Similar to the IUS projections, major contributors to the EOL generation are anticipated to be the Building (31%), EE (20%), and Transportation (22%) sectors, suggesting that EOL copper recovery infrastructures and policies should be prioritized for these three sectors.

The projected annual copper consumption follows an upward trajectory growing from 2.4 Mt in 2015 to almost 3.9 Mt by 2070, yielding a 17% increase on a per capita basis. This seemingly high consumption growth as compared to the 1.0% per capita IUS increase will mainly compensate for the higher amounts of products reaching the end of their lifetime (i.e., higher EOL generation). On a sector basis, the EE, Building, and Transportation sectors are projected with the most significant growth of 121, 60, and 56%, respectively. The consumption growth trajectories for all end-use sectors are

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

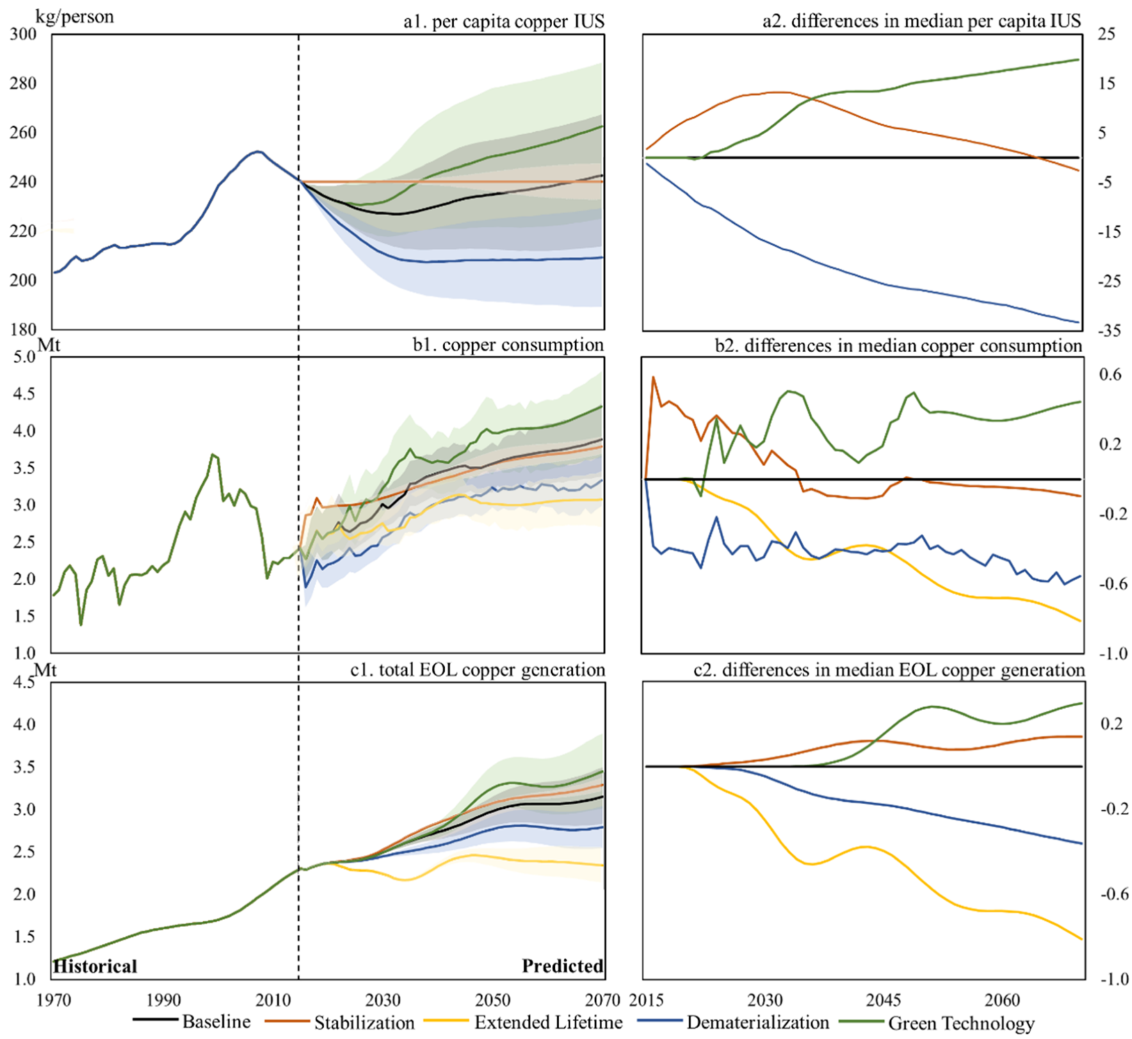


Figure 4. Comparisons of different U.S. copper demand scenarios. The solid lines represent the median values of each scenario projection and the colored bands present uncertainties, which were based on the upper and lower bounds of the copper intensities of technologies and scenario assumptions. The per capita IUS, copper consumption, and EOL copper generation for all scenarios are presented in (a1−c1), whereas the differences in median values are compared in (a2−c2), respectively.

relatively smooth, except for a spike before year 2022 for the EE sector (as shown in Figure 3c). This is mainly due to the assumption of accelerated investment in the electricity transmission infrastructure for bridging the historical infrastructure investment gap.[30]

One key implication of using demand forecast models based on stock dynamics is that the consumption projections should not be interpreted as a precise prediction of actual copper consumed but rather a depiction of general growth trends due to a lack of supply considerations. For instance, copper price has a "curbing effect" on consumption, and temporary supply shortages could occur in the cases of global pandemics, natural disasters, or wars to drive up the global copper price. Thus, the projections in our model are representative of upper bound estimates of future consumption and EOL flows.

Comparisons of different future copper demand scenarios are presented in Figure 4. As expected, the Green Technology Scenario is projected to yield the highest copper IUS accumulation (+20 kg/person as compared to the Baseline Scenario by 2070), annual copper consumption (+0.44 Mt), and EOL copper generation (+0.30 Mt) due to the higher copper intensity (RMI) of renewable energy and EV technologies. The IUS Stabilization Scenario is expected to have a similar IUS accumulation (−2.5 kg/person), consumption (−0.10 Mt), and EOL generation (+0.14 Mt) as the Baseline Scenario. However, this scenario breaks the existing dematerialization trends and expects significant increases in consumption before 2030. The long-term trajectories of this scenario emulate those of the Baseline Scenario with a higher potential for leveraging EOL recovery to meet future demand. Assuming the same IUS trajectory, the Extended Lifetime Scenario is expected to result in a much lower copper consumption (−0.81 Mt) than the Baseline Scenario, thanks to the lower EOL copper generation (−0.81 Mt). The Dematerialization Scenario is also found to be an effective consumption reduction strategy (−0.55 Mt). However, dematerialization achieves consumption reduction by significantly lowering the consumer demand (−33 kg/person), while extending the product lifetime achieves the same goal by yielding less EOL generation compared to the other scenarios.

Effective as both the Dematerialization Scenario and the Extended Lifetime Scenario are as consumption reduction strategies, policy makers still need to be aware of the implications of adopting them. Dematerialization-targeted

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

Table 1. Major Sinks of Consumed Copper and Circularity of EOL Flows in the U.S.

time/scenarios	total consumption (Mt)	major copper sinks (as % of total consumption) EOL (collected)	EOL (landfilled)	EOL (hibernation)	IUS accumulation	circularity indicators (%) EOL CR	EOL RR	EOL RIR
1970−2015	112.4	26.4	6.5	35.0	32.0	30−51	7−42	6−37
2016−2070 (Baseline)	182.4	50.5	8.4	24.8	16.4	60.4	42.7	35.7
2016−2070 (IUS Stabilization)	185.5	49.7	8.4	26.3	15.6	58.8	42.1	35.5
2016−2070 (Extended Lifetime)	158.9	48.8	8.1	24.2	18.9	60.1	42.9	34.8
2016−2070 (Dematerialization)	158.7	54.2	9.0	27.1	9.6	60.0	42.5	38.4
2016−2070 (Green Ttechnology)	197.8	48.9	8.0	23.5	19.6	60.8	42.6	34.3

policies need to incentivize consumers to reduce their copper ownership, which can be achieved by running sustainable consumption campaigns, encouraging technology innovations and efficiency improvements, promoting sustainable business models such as a “sharing economy”, and providing services instead of physical products (or “servicizing”). Extending the product lifetime requires policies to foster a resilient recycling industry to cope with shrinking EOL copper supplies as well as a strong market for product reuse, refurbish, and repair. In addition, there needs to be bilateral buy-ins from the general public on purchasing and usage decisions and manufacturers on product design for longevity. While both strategies have their own technical limits and public engagement challenges, priorities can be identified to harness the “low-hanging fruits” from both strategies in a non-exclusive way.

3.2. Destinations and Circularity of Copper in the U.S. As shown in Table 1, from 1970 to 2015, a total of 112.4 Mt of copper was consumed in the U.S., of which 32.0% contributed to expanding the copper IUS. Meanwhile, 76.4 Mt of copper products are estimated to end their service lives at different destinations as shown in Table 1. While the hibernating stock appears to be the largest copper sinks in the U.S., this might be an overestimation due to conservative estimates of the collected and landfilled copper. However, this observation does validate the concern for decaying and outdated public infrastructure in the U.S. and reveals another potential source of EOL recovery.

The EOL CR is estimated to increase from 30 to 51% from 1970 to 2015, which represents a conservative estimate given that the EOL collection data is based on primary survey responses from domestic copper collectors.[8] Meanwhile, the EOL RR was reported to drop dramatically from 40 to 7% from 1980 to 2015 due to unfavorable domestic recycling market conditions and increased exportation of collected EOL copper to Asia.[7]

It is estimated that of the cumulative consumption between 2016 and 2070, 49−54% will be collected as EOL copper, 8−9% will be landfilled, 23−27% will be hibernating or lost, and only 10−20% will contribute to the IUS accumulation. Compared to the 1970−2015 estimates, all scenarios agree that copper consumption will be mainly compensating EOL flows instead of growing IUS in the future as the per capita IUS stabilizes. The Green Technology Scenario and the Extended Lifetime Scenario are predicted to be slightly more efficient in converting consumption to IUS due to either high IUS growth or low EOL generation. In contrast, the Dematerialization Scenario has the lowest conversion rate at 9.6% because of the main scenario assumption of a shrinking per capita IUS.

Concerning the circularity potential, different scenarios share a similar EOL CR (59−61%) and EOL RR (42−43%) due to the similar distributions of EOL copper from the five end-use sectors across all scenarios. This indicates that future EOL recovery potential is relatively insensitive to future scenarios and is mainly dependent on the EOL CR and EOL RR of each end-use sector. Nevertheless, these seemingly small differences can be translated into significant physical flows when it comes to meeting future demand. For example, the EOL RIR of the Dematerialization Scenario is predicted to be 38.4%, meaning that 38.4% of copper demand can be met by recycling domestic EOL copper. Meanwhile, the Green Technology Scenario is anticipated to result in a lower EOL RIR of 34.3% due to a higher copper demand. This means that the Green Technology Scenario cumulatively requires 32.2 Mt of copper more than the Dematerialization Scenario from other supply sources (new scrap, primary production, or imports).

3.3. Sustainability of Future Copper Demand in the U.S. A few common trends and patterns are identified across all the simulated scenarios of future copper demand. First, it is projected that the per capita IUS will follow the current downward trend for the next 10 to 20 years before starting to slowly increase again due to the anticipated deployment of various “green technologies”. Overall, these relatively flat IUS trend lines suggest an IUS “stabilization” range of 215−260 kg/person for the next few decades. This “stabilization trend” suggests good potential of leveraging EOL flows to meet future demand. Based on our estimation, 34−39% of future demand can be met by recycling 43% of domestic EOL copper. Second, the annual consumption and EOL generation of copper are projected to increase, mainly driven by the anticipated population growth. Third, the Building, EE, and Transportation sectors are expected to dominate the future copper consumption, per capita IUS, and EOL flows.

The biggest sustainability challenge identified is the EOL copper recovery. The U.S. EOL RR was believed to have dropped significantly to below 10% in 2016.[7] Although being much higher than 10%, our assumed future EOL RR of 43% still barely catches up with the global average before 2010. Issues with low EOL recovery will be exacerbated by the waste import bans from China and potentially other scrap-importing countries. Thus, it is urgent to seek alternative solutions despite unfavorable domestic market conditions. One area of imminent improvement is at the regional and product levels thanks to more aggressive regional recycling plans and innovations of recycling technologies for electronic products. Another market-driven solution is temporary storage in landfills, with the hope of “landfill mining” in the future when the economics and technologies are ready. We are also optimistic about systemic improvements driven by higher copper prices and lower recovery costs in the long run.

As another key aspect of copper sustainability, consumption reduction has substantial upside. The U.S. society has been

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

undergoing a spontaneous transition into a "dematerialization state" since the late 1990s. Although no study has thoroughly investigated this phenomenon, we think that there are a few possible explanations, such as a booming Chinese construction sector that drove up the copper price, overbuilt capacity before 2000, and rising awareness of sustainability. It is also highly possible that most of the "dematerialization" was achieved through technology transition, use of substitutes, urbanization, efficiency improvements, and delays in infrastructure investments.

Many of these existing "dematerialization" trends are likely to coexist with the emerging trends of renewable energy and EV technology deployment in the future. This requires identification of adaptive policy levers to help navigate through these future scenarios in a sustainable way. While extensive future research is needed, we would like to propose three directions based on our study. First, as governments have been fueling the transitioning to renewable energy and EVs, policies that target the entire product lifecycle from the design phase to the EOL recovery should be developed to improve the circularity of these emerging technologies. Second, guidelines that reinforce the collection and recycling of construction and demolition wastes are needed to help exploit the immense untapped (hibernating) stock. Third, domestic secondary copper markets need to be revitalized for efficiency and resilience purposes, especially in light of the import bans from Asia. Although EOL copper flows are harder to recover and often of inferior quality compared to new scrap, governments can still incentivize recycling capacity building for the growing Building, EE (mainly renewable energy), and Transportation (mainly EVs) sectors. If the homogeneity and concentration of copper in these sectors can be leveraged to design and deploy targeted recycling capacity and policies, a higher degree of circularity is achievable in this "green technology" future.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c05080.

Main model and scenario assumptions, calculation methods, and additional scenario simulation results and discussion (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Mitchell J. Small − *Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States*; Phone: (412) 268-2940; Email: ms35@andrew.cmu.edu

Author

Rui He − *Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States; Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States*; orcid.org/0000-0001-9555-2884

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.1c05080

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The work leading to this paper was funded by the Mao Yisheng Fellowship to R.H. provided by Carnegie Mellon University. M.J.S. was supported by the H. John Heinz III Chair in Environmental Engineering. The authors would like to thank Miranda Gorman for providing EOL copper collection data, Yanwen Liang for helping with consumption data research, and Scott Matthews for revising and editing this paper.

■ REFERENCES

(1) U.S. EPA. *U.S. EPA Sustainable Materials Management Program Strategic Plan. Fiscal Year 2017-2022*; 2015.

(2) U.S. Geological Survey. *Mineral Commodity Summaries 2020*, 2020.

(3) Nassar, N. T.; Barr, R.; Browning, M.; Diao, Z.; Friedlander, E.; Harper, E. M.; Henly, C.; Kavlak, G.; Kwatra, S.; Jun, C.; Warren, S.; Yang, M.-Y.; Graedel, T. E. Criticality of the Geological Copper Family. *Environ. Sci. Technol.* **2012**, *46*, 1071−1078.

(4) International Copper Study Group. *The World Copper Factbook 2021*; International Copper Study Group: Lisbon, Portugal, 2021.

(5) Wang, T.; Berrill, P.; Zimmerman, J. B.; Hertwich, E. G. Copper Recycling Flow Model for the United States Economy: Impact of Scrap Quality on Potential Energy Benefit. *Environ. Sci. Technol.* **2021**, *55*, 5485−5495.

(6) Müller, E.; Hilty, L. M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environ. Sci. Technol.* **2014**, *48*, 2102−2113.

(7) Wang, M.; Liang, Y.; Yuan, M.; Cui, X.; Yang, Y.; Li, X. Dynamic Analysis of Copper Consumption, in-Use Stocks and Scrap Generation in Different Sectors in the U.S. 1900−2016. *Resour. Conserv. Recycl.* **2018**, *139*, 140−149.

(8) Gorman, M.; Dzombak, D. Stocks and Flows of Copper in the U.S.: Analysis of Circularity 1970−2015 and Potential for Increased Recovery. *Resour. Conserv. Recycl.* **2020**, *153*, 104542.

(9) Glöser, S.; Soulier, M.; Espinoza, L. A. T. Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation. *Environ. Sci. Technol.* **2013**, *47*, 6564−6572.

(10) Watari, T.; Nansai, K.; Nakajima, K. Major Metals Demand, Supply, and Environmental Impacts to 2100: A Critical Review. *Resour. Conserv. Recycl.* **2021**, *164*, 105107.

(11) Elshkaki, A.; Graedel, T. E.; Ciacci, L.; Reck, B. K. Resource Demand Scenarios for the Major Metals. *Environ. Sci. Technol.* **2018**, *52*, 2491−2497.

(12) Schipper, B. W.; Lin, H.-C.; Meloni, M. A.; Wansleeben, K.; Heijungs, R.; van der Voet, E. Estimating Global Copper Demand until 2100 with Regression and Stock Dynamics. *Resour. Conserv. Recycl.* **2018**, *132*, 28−36.

(13) Gorman, M. R.; Dzombak, D. A. An Assessment of the Environmental Sustainability and Circularity of Future Scenarios of the Copper Life Cycle in the U.S. *Sustain* **2019**, *11*, 5624.

(14) Watari, T.; Nansai, K.; Giurco, D.; Nakajima, K.; Mclellan, B.; Helbig, C. Global Metal Use Targets in Line with Climate Goals. *Environ. Sci. Technol.* **2020**, *54*, 12476−12483.

(15) Dong, D.; Tukker, A.; van der Voet, E. Modeling Copper Demand in China up to 2050: A Business-as-Usual Scenario Based on Dynamic Stock and Flow Analysis. *J. Ind. Ecol.* **2019**, *23*, 1363−1380.

(16) Deetman, S.; Pauliuk, S.; Van Vuuren, D. P.; Van Der Voet, E.; Tukker, A. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. *Environ. Sci. Technol.* **2018**, *52*, 4950−4959.

(17) Gerst, M. D. Linking Material Flow Analysis and Resource Policy via Future Scenarios of In-Use Stock: An Example for Copper. *Environ. Sci. Technol.* **2009**, *43*, 6320−6325.

(18) Wu, Z.; Schaffartzik, A.; Shao, Q.; Wang, D.; Li, G.; Su, Y.; Rao, L. Does Economic Recession Reduce Material Use? Empirical Evidence Based on 157 Economies Worldwide. *J. Clean. Prod.* **2019**, *214*, 823−836.

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717

(19) Rietveld, E.; Boonman, H.; van Harmelen, T.; Hauck, M.; Bastein, T. *Global Energy Transition and Metal Demand*; TNO, 2019.
(20) Fishman, T.; Myers, R.; Rios, O.; Graedel, T. E. Implications of Emerging Vehicle Technologies on Rare Earth Supply and Demand in the United States. *Resources* **2018**, *7*, 9.
(21) Northey, S. A.; Mudd, G. M.; Werner, T. T. Unresolved Complexity in Assessments of Mineral Resource Depletion and Availability. *Nat. Resour. Res.* **2018**, *27*, 241−255.
(22) Bleischwitz, R.; Nechifor, V.; Winning, M.; Huang, B.; Geng, Y. Extrapolation or Saturation − Revisiting Growth Patterns, Development Stages and Decoupling. *Global Environ. Change* **2018**, *48*, 86−96.
(23) Forrester, J. W. Industrial Dynamics. *J. Oper. Res. Soc.* **1997**, *48*, 1037−1041.
(24) Sverdrup, H. U.; Ragnarsdottir, K. V.; Koca, D. On Modelling the Global Copper Mining Rates, Market Supply, Copper Price and the End of Copper Reserves. *Resour. Conserv. Recycl.* **2014**, *87*, 158−174.
(25) Auping, W. L.; Pruyt, E.; Kwakkel, J. H. Analysing the Uncertain Future of Copper with Three Exploratory System Dynamics Models. *International System Dynamics Society Conference*: System Dynamics Society, 2012.
(26) Graedel, T. E.; Van Beers, D.; Bertram, M.; Fuse, K.; Gordon, R. B.; Gritsinin, A.; Kapur, A.; Klee, R. J.; Lifset, R. J.; Memon, L.; Rechberger, H.; Spatari, S.; Vexler, D. Multilevel Cycle of Anthropogenic Copper. *Environ. Sci. Technol.* **2004**, *38*, 1242−1252.
(27) Müller, E.; Hilty, L. M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environ. Sci. Technol.* **2014**, *48*, 2102−2113.
(28) Cao, Z.; Shen, L.; Løvik, A. N.; Müller, D. B.; Liu, G. Elaborating the History of Our Cementing Societies: An in-Use Stock Perspective. *Environ. Sci. Technol.* **2017**, *51*, 11468−11475.
(29) Chen, W.-Q.; Graedel, T. E. In-Use Product Stocks Link Manufactured Capital to Natural Capital. *Proc. Natl. Acad. Sci. U.S.A.* **2015**, *112*, 6265−6270.
(30) EDRG. *Failure to Act: Closing the Infrastructure Investment Gap for America's Economic Future*; EDRG: Washington, DC, 2016.
(31) Müller, D. B. Stock Dynamics for Forecasting Material Flows-Case Study for Housing in The Netherlands Dynamic Modelling Prospects for Resource Demand Waste Management Vintage Effects Diffusion Processes. *Ecol. Econ.* **2005**, *9*, 142−156.
(32) U.S. Geological Survey. Copper statistics [through 2015; last modified December 13, 2018], in Kelly, T.D., and Matos, G.R., comps., Historical statistics for mineral and material commodities in the United States (2017 version): U.S. Geological Survey Data Series 140. https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states (accessed Mar 20, 2020).
(33) U.S. Census Bureau. *The Baby Boom Cohort in the United States: 2012 to 2060*; U.S. Census Bureau: Washington, DC, 2014.
(34) U.S. Energy Information Administration. Commercial Buildings Energy Consumption Survey (CBECS). https://www.eia.gov/consumption/commercial/ (accessed Dec 29, 2019).
(35) U.S. Energy Information Administration. *Annual Energy Outlook 2021 with Projections to 2050*; U.S. Energy Information Administration: Washington, DC, 2021.
(36) Wood, E. W.; Rames, C. L.; Muratori, M.; Srinivasa Raghavan, S.; Melaina, M. W. *National Plug-In Electric Vehicle Infrastructure Analysis*; NREL, 2017.
(37) Bureau of Transportation Statistics. Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances. https://www.bts.gov/content/number-us-aircraft-vehicles-vessels-and-other-conveyances (accessed Dec 11, 2019).
(38) Babbitt, C. W.; Kahhat, R.; Williams, E.; Babbitt, G. A. Evolution of Product Lifespan and Implications for Environmental Assessment and Management: A Case Study of Personal Computers in Higher Education. *Environ. Sci. Technol.* **2009**, *43*, 5106−5112.
(39) IEA Global. *EV Outlook 2019*; IEA Global: Paris, 2019.
(40) Daigo, I.; Iwata, K.; Ohkata, I.; Goto, Y. Macroscopic Evidence for the Hibernating Behavior of Materials Stock. *Environ. Sci. Technol.* **2015**, *49*, 8691−8696.
(41) Espinoza, L. A. T.; Soulier, M. Defining Regional Recycling Indicators for Metals. *Resour. Conserv. Recycl.* **2018**, *129*, 120−128.

https://doi.org/10.1021/acs.est.1c05080
Environ. Sci. Technol. 2022, 56, 2709−2717