Regional Economic Potential for Recycling Consumer Waste Electronics in the United States

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Abstract

Waste electronics are a growing environmental concern, but also contain materials with great economic value. If properly recycled, waste electronics could enhance the sustainability of vital metal supply chains by offsetting the increasing demand for virgin mining. However, rapid changes in size and composition of electronics complicate their end-of-life (EOL) management. Herein, we couple material flow and geospatial analyses on over 90 critical consumer electronic products and find that over 1 billion devices, representing up to 1.5 million tonnes of mass, could be discarded annually in the United States (U.S.) by 2033. Emerging electronics such as connected home, health, and AR/VR devices have become the fastest-growing types in the waste stream. We highlight policy opportunities to develop various sustainable circularity strategies around metal supply chains, by showing the potential to integrate electronic waste and virgin mining pathways in Western U.S. regions, while new infrastructure designed specifically for waste electronics treatment is favorable in the Central and Eastern U.S. Further, we show the importance of building national-level refining and tear-down databases to improve electronics EOL management in the next decade.

Due to the growing consumption of electronic equipment, and the relatively short lifetimes of many of these devices, the amount of discarded electronics within the waste streams (waste electronics) is rapidly increasing. Globally, the annual waste electronics generated has grown from less than 25 million tonnes (Mt) per year in 2009 to around 53.6 Mt in 2019.[1-3] The number of waste electronics generated in the United States (U.S.) in 2019 was 6.9 Mt (approximately 12.9% of world generation), corresponding to a generation per capita of around 21 kg, which is approximately three times the world's average value (7.3 kg). [3]

Only 17% of the waste electronics generated globally is properly recycled and the recycling rate in the U.S. is around 14% to 40% depending on the reporting agency and selected types of electronics.[3,4] Domestic waste electronics that are exported for recycling are hard to regulate, owing to the different levels of maturities in terms of recycling technology and policy incentives between countries.[5,6] Due to the high heterogeneity between types and brands, waste electronics are a special stream of municipal solid waste that requires complex considerations during end-of-life (EOL) management.[7,8] Without safe and effective EOL processes and government oversight, which is the case for several developing nations, the receiving regions face various environmental pollution and public health concerns such as heavy metal poisoning and food chain contamination.[5,9-11]

However, with proper EOL management, waste electronics can have positive socio-economic impacts as they contain materials of significant value that could allow proper recycling to have economic benefits. In terms of overall material composition, waste electronics are a combination of plastics, metals, etc. The current waste electronics recycling process includes preprocessing and metal recycling. A general waste electronics device includes plastic covers, and printed circuit boards (PCBs) that hold the various electronic parts (i.e., resistors, capacitors), batteries, etc.[12] Each of these components offers unique value upon recycling. Existing techno-economic analysis (TEA) studies have demonstrated the potential of making profits via recovering metal resources, particularly gold, from the PCBs being the main source of revenue.[13-15]

Therefore, while improvements in international regulations of waste electronics recycling could be beneficial, it is also critical to predict and assess potential waste management strategies within the U.S. around metal recovery from waste electronics to identify favorable economic and environmental pathways, obviate future resource scarcities, and create a more circular economy to increase the resiliency of domestic material supply.

Within waste electronics, small to mid-size consumer electronics (i.e., smartphones, fitness devices, connected home devices, AR/VR equipment, drones, and computers) represent an emerging stream in recent years that are heavily affected by the evolvement of technology development and consumer behaviors. Material flow analysis (MFA) is an effective and strategic way of predicting the quantity and composition of waste materials based on information such as historical sales and possession data, which has been applied to model waste electronic generation in different parts of the world.[16-18] However, existing MFAs on waste electronics in the U.S. has focused mostly on the temporal changes of common and relatively conventional small-to-midsize waste electronics (i.e., TVs, mobile phones, computers, and monitors) within the past decade.[19-21]

Due to potential challenges such as data availability at the time of these studies and the rapid change in consumer behaviors, limited research has been conducted regarding the impacts of the emerging small-to-midsize electronics that have been introduced in recent years. Also, the variance of the metal compositions for different types of electronics is rarely taken into account. Lastly, existing research on the geospatial modeling of waste electronics recycling reports is limited to selected waste electronics in selected states.[22]

Based on these knowledge gaps, herein we couple geospatial analysis on top of state-of-the-art MFA to comprehensively capture the temporal variations and predict future trends regarding the amount, composition, and potential value within these consumer waste electronics generated in the U.S. We also predict how the newly-developed, emerging electronic products can potentially reshape the resource availability from waste electronics, and how these changes will potentially affect the future metal refining infrastructure in the U.S.

Since previous analyses showed that gold holds most of the metallic values (up to or higher than 80%) within the waste electronics,[13,14,23] in this analysis we use gold as the primary indicator to examine the economic potential (Fig. 1). The MFA results are used in subsequent geospatial models to characterize the spatial distribution of waste electronics and the embedded value within the U.S. This study identifies the underlying potential connections between gold recovery and the current metal refining industries within the U.S. and offers recommendations on creating an electronics-centered circular economy for different future scenarios. Other secondary resources, such as base metals (i.e., copper, aluminum), and plastics can also add additional value to the recycling of electronics waste, which are recognized and discussed as well (Fig. 1).

Results

Temporal and spatial distribution of waste electronics

Fig. 2a shows the modeled number of waste electronics in the next decade, based on the historical sales data and their predicted lifespans. With the fast growth scenario, the amount of small to mid-size waste electronics produced in 2033 could exceed 1 billion units, and the slow growth will lead to approximately 700 million units. In terms of mass, waste electronics generated in the U.S. are estimated to reach from 1.2 to 1.5 million tonnes (Fig. 2b), with the shift toward smaller electronics partially offsetting the growth in the number of units. Note that in this study, heavy consumer appliance electronics (i.e., fridges or ovens) are not included therefore, both the number and mass are conservative estimates.

Figs. 2c and 2d show the mean and general growth trend of representative resources in waste electronics over the next decade, within which PCBs contain the most valuable materials recoverable, including precious metals such as gold (Fig. 2 c).[13,14] The steady trend of gold availability from waste electronics in recent years (i.e., 2017-2021) is consistent with previous studies. For example, Althaf et al. 2021 [21] and Golev et al. 2016 [24] both estimated a steady and slow decline in gold availability from 2015-2018 among conventional electronics in U.S. and Australia, respectively, owning to a trends towards smaller electronic devices and more efficient use of gold within those electronics.

However, existing tear-down studies on emerging smart devices, which often contain more complex electronics (i.e., smartphones, and tablets) have shown higher PCB and gold content than that of larger, stationary, and wired electronics (e.g., DVDs and VCRs) [25]. Even though the total amount of gold used in electronics has declined in recent years, which influences the economics of recovery, the number of more complex devices with higher PCB and gold content has been increasing. These tradeoffs indicate that as more smart electronics start to emerge, the amount of both PCB and gold that are recoverable from waste electronics could start to increase within the next decade.

Due to limited publicly-available tear-down analyses, the modeled PCB and gold content assumed in different types of electronic devices has a relatively large range (Figs. 2c and 2d). Thus, the impact of composition is much higher than that of the growth scenario, which further affects the economic potentials analyzed in the discussion section.

In terms of zip-code level distributions in the U.S., as the model is developed based on the population and household possession data (See *Methods* and Supplementary Note 4) [26-28], the waste electronics densities are heavier in the coastal and metropolitan areas (Fig. 3a). It is notable that in the densest regions (i.e., certain places New York City and Los Angles), roughly over 160,000 kg of waste electronics could be generated annually within one square kilometer.

For metal extraction, the mining and refining sector is an established industry in the U.S. that can potentially be utilized to treat waste electronics or their embedded PCBs, as both involve hydro or pyrometallurgical processes.[7] In terms of the treatment process, after the waste PCBs are dismantled, shredded, and physically separated into metal scraps (upstream recycling), the metallurgical processes (downstream recycling) are fairly similar whether refining metal from these waste or virgin mines.[29,30] In fact, a majority of the metal recovery from waste electronics is still based on pyrometallurgical pathways, which is also the primary virgin mining process with a minor difference between feedstocks (i.e., precious metal vs. base metal refining).[31-33]

Virgin gold mines and refining plants mostly exist in the western states (i.e., Nevada and Arizona) of the U.S., as shown in Fig. 3b. The rest of the virgin gold mines are scattered around the U.S., but relatively more concentrated in the mountain areas (i.e., Utah and Colorado). Again, before the waste electronics could be processed in metal refinery plants, they would need to be collected and pre-processed (i.e., sorting shredding, and physical separation) by different recyclers.

Collection of waste electronics from consumers is out of the scope of this study, but Fig. 3b shows an estimate of the locations of certified waste electronics recyclers as recognized by the USEPA[34] (green dots), and their relationship to the current virgin gold mines and/or refineries (triangles). Locations of the certified waste electronics recyclers generally show good agreement with the distribution of waste electronics generated in Fig. 3a and also indicate that there are unique challenges and opportunities for handling waste electronics among the different regions in the U.S. For example, there could be a potential overlap between virgin mining production and the potential metal recovery from waste electronics mostly in the western part of the U.S., whereas there could be more potential for building new waste electronic mining facilities in the Central or Eastern regions.

Growth of different types of waste electronics

This study shows that currently, the U.S. is experiencing a dramatic change in waste electronics composition. The total amount of small-to-midsize consumer waste electronics and the potential precious metal (gold) recoverable from that waste has been steady in recent years, however, our model suggests that the value of waste electronics will likely increase in the next decade owing to the changes in metal composition and shipments from emerging electronics. Specifically, Fig. 4a shows the predicted growth of representative waste electronics in 2021-2022 and 2032-2033 (See the whole list in Supplementary Dataset). Most of the waste electronics growing in 2033 also have positive growth rates in 2022. The overall scale of the difference in growth rates in 2022 is much larger (up to over 400%) than that of 2033 (up to 30%) owing to one or two recent spikes between 2018-2021, whose effect is diminished when projected to 2033. Notably, several of the waste from several emerging types of electronics, such as 5G smartphones and gateways, electric scooters, and wireless earbuds have large range of predicted growth rates due to high sales fluctuations in recent years. For these electronics, further market analysis is recommended to provide more accurate growth predictions. Also, note that for the future scenario (2032-2033), the MFA model prediction in this study is a conservative estimate because this study does not account for completely new electronics that might enter the market with potentially high growth rates.

Furthermore, emerging electronics such as AR/VR, connected home devices, and internet of things products (defined as electronics requiring constant wireless communications) are leading the growth rate in 2032-2033. Other waste smart electronics (i.e., wireless headphones, drones) did not make it to the top 10 growing list but also have close to, or higher than 10% growth rate from 2032 to 2033. On the other hand, most of the conventional waste electronics (i.e., desktops PCs, printers, DVDs) are generated at a steady rate or declining. These dramatic differences in the growth patterns between different waste electronics show that the U.S. is currently experiencing a shift in the composition of waste electronics, towards smaller, portable, and more complex electronics, which potentially contain more resource value in terms of weight percentage[25].

In terms of mass generated, Figs. 4 (b and c) show that certain heavy electronics such as LCD TVs greatly contribute to the overall mass of waste electronics, similar to how CRT TVs dominated the mass of waste electronics in the early 21st century.[21] Other heavy electronics, such as printers and desktop PCs are still among the top ten waste electronics by mass. Lastly, smaller computers such as laptops and tablets will likely exceed conventional desktops or monitors in the waste stream by 2033.

Discussion

Economic Potential

The geospatial modeling shows that there are potential underlying connections and opportunities between virgin mining and recycling in the U.S., which can be used to help create a circular economy around metal recovery from waste electronics. By evaluating the capacity and profitability of the virgin mining refineries, we find that it is worthwhile considering the integrated pathway of recycled waste electronics and virgin metal recovery routes in the U.S.

Since gold can represent over 85% of the embedded value within consumer electronics[13-15], it is used as the primary indicator to study the direct economic potential of treating electronics. One important criterion is to compare the potential gold productivity from the waste electronics with the current gold productivity throughout the U.S., which is approximately 220 tonnes annually [35]. Fig 5a shows that the gold recoverable from the waste electronics can potentially reach the same magnitude as the national productivity from virgin resources when assuming gold compositions within the electronics are on the higher end of values found in the literature.[21,24,25,36]

Theoretically, the virgin mining refining plants have the capacity of to handle the total quantity of waste electronics for precious metal (gold) recovery. However, after considering the geological distributions and current gold mining production, virgin mining with large handling capacities for waste electronics is concentrated in the West and Mountain areas of the U.S. The Central and East regions may have more need to create new recycling infrastructure targeting waste electronics.

To elaborate, on the state level (estimated in Supplementary Note 5), Nevada and Alaska are the leading states for virgin gold production (Fig. 5b), with capabilities of approximately 173 metric tonnes and 21 metric tonnes per year (2018 value published in 2021), respectively.[35] Due to its high virgin gold productivity, refining plants at mines in Nevada should theoretically have the capacity necessary to handle all of the waste electronics in the U.S. but would face extra burdens (i.e., time, cost, emissions) when transporting waste electronics that are generated far from the region.

If the embedded gold from waste electronics in certain regions reaches the maximum allocated productivity (light blue color), it would need to be transported to the next nearest facility with excess productivity (dark blue color). In this case, the transportation burden increases with the distance, which is qualitatively represented by the darkness of the yellow color in Figs. 5(c-h),

In recent years, there have been emerging research and proposals on new technologies to recover metals from waste electronics, such as electrochemical treatment, supercritical aided extraction, photocatalysis, bioleaching, etc.[7,31,37,38] In the near future, it is possible that more efforts will be made to commercialize these technologies specifically to recover resources from waste electronics treatment. These new facilities may need to compete with virgin mining refineries that integrate electronic waste recycling into their production capacity. Thus, a higher transportation burden to integrated virgin refineries indicates greater potential to build such new facilities (represented by dark yellow color). In Figs. 5(c-h), the darker blue color represents a higher opportunity to integrate waste electronics with existing virgin mining refineries, whereas the darker yellow color represents the higher economic potential for new facilities.

The MFA results (Fig. 3) and Fig. 5a show that the uncertainties in the embedded gold content have a much higher influence compared with the growth scenario, therefore are chosen as one of the main parameters for sensitivity to the recycling economic potential. Other key parameters include first, the level of involvement, which denotes how much productivity can the virgin refineries allocate to use waste electronics as feedstock. Second, the influence of exportation is also studied, as it directly relates to the level of domestic recycling of waste electronics. We have found that the reported degree of waste electronics exportation in the U.S. has high variation depending on the time of study and reporting agencies.[20,39]

Fig. 5 shows that within the uncertainties studied, the economic potential is most sensitive to the metal content, as shown when comparing Figs. 5(c-e) with Figs. 5(f-h). In comparison, the level of exportation and involvement of the current virgin mining industry will affect the East Central regions if the embedded values are low, as shown in Figs. 5(f-h). Figs. 5(c-e) show that if the embedded metal content is high, there is high economic potential to develop new infrastructure around waste electronics recycling even if there is high exportation, or if the virgin mines shift a large portion (up to around 70%) of their productivity to be generated from waste electronics.

It is important to note that metal compositions are different between waste electronics and virgin mines, [36,40] which would require more separation stages. Results from this section imply that quantifying the economic trade-off between the exact procedures that need to be added for the virgin mines to handle electronics can make a significant difference in examining the nationwide profitability. Thus for this purpose, future research is recommended on the techno-economic comparison between adapting virgin metal refineries, particularly gold, to include separated electronics as part of the feed stream, versus building completely new plants.

Future Outlooks

The above discussions highlight potential opportunities to enhance the circular economic potential of metal recovery from waste electronics recycling and help address several major challenges identified in this study. Future research should focus on process development for both upstream (recyclers and collectors) and downstream refineries for this integrated waste and virgin mining pathway to enhance the economic potential. Additionally, policy efforts should be focused on creating a national-level database that includes the composition-level tear-down data, location of small-scale refineries, and collection plants for various electronics to help narrow the range for future MFAs and offer a more complete geospatial analysis of metal recovery from waste electronics.

First and most importantly, a better understanding of metal compositions within different types of electronics is needed, especially among emerging smart electronics. The availability range plotted in Fig. 2 and Fig. 5 is relatively large due to the fact that limited tear-down studies are available for waste electronics. Between the two main uncertainties included in this analysis, the composition has a significantly higher impact on the available gold within the waste electronics than the growth scenarios.

The large range of resource availability indicates that different management strategies might be needed when aiming to create a circular economy around waste electronics. A database that includes the compositions of metals for different types of electronics would help anticipate future recycling infrastructure needs. Such a database could be achieved via high-quality tear-down analysis, as well as help from the electronics manufacturers without exposing company intellectual properties.

Second, there has been limited transparency at the national level on both the upstream recyclers (green dots in Fig. 3b) and metal refineries (triangles in Fig. 3b). There are many waste electronics recyclers and refineries (i.e., small-scale and/or regional certified facilities) with minimal publicly available information and transparency that may require a national-level survey or reporting database.

Furthermore, although gold is chosen as the primary driven factor for economics due to its high embedded cost values, other resources in waste electronics can also add value to the circular economic potential of waste electronics recycling. For example, plastics in waste electronics, which can occupy up to 30 wt%,[41] could be recycled for re-manufacture or energy conversion purposes[42]. However, it is important to note that certain detoxification procedures might be required to eliminate the effects of brominated flame retardants during the high-temperature treatments.[31,43] Other metals, such as copper and aluminum, are not as valuable as gold but are also important to other manufacturing industries. More importantly, rare earth elements in magnetics and PCBs, and cobalt and lithium in batteries, can help with increasing the supply chain resiliency of critical materials[44,45] and should be considered in future studies.

Lastly, note that since this study does not include all of the consumer or non-consuming waste electronics, the economic potential and profitability is a relatively conservative estimate. If other sources of waste electronics (i.e., the growing electronics in vehicles and industrial plants) are included, the yellow portion of the profitability maps can potentially be expanded.

Methods

Material Flow Analysis

Compared with the previous MFA models for waste electronics,[19-21] we expanded the types of waste electronics from the 20 common electronics (i.e., waste cell phones, TVs) to over 90 different types of electronic devices. The waste electronics covered in this study included emerging waste electronics such as wearable fitness and health products, portable and wireless devices, smart home improvement devices, AR/VR sets, and consumer drones. The sales data from the Consumer Technology Association (CTA) was used.[46] The types of electronics modeled in this study were included in the supplementary dataset.

The sales data of the target consumer electronics after 2021 was predicted via a logistic-based model, which is known to be capable of capturing the market behavior of consumer products.[47-49] The logistic model could be described by equations 1 and 2.

$$sales = \frac{\partial}{1+e^{\beta(t-\gamma)}} \quad (1)$$

$$sales = \frac{\partial}{1+e^{-\beta(t-\gamma)}} \quad (2)$$

where t denoted the number of years for market sales; ∂ (saturation), β (steepness), and γ (midpoint), were the logistic parameters. Note that Equation 1 was used for the declining electronics, and Equation 2 was used for the growing/increasing electronics.

To account for the robust change in consumer behaviors, the last-reported 3 years of sales data for different electronics were first used to categorize the electronics into “decreasing” or “increasing” patterns. For the electronics that had decreasing sales patterns, we compared the logistic fitting since the maximum reported value and the 5 most-recent values, and selected the one with the larger r square value to predict the future sales data. The same method was used to predict the sales data beyond the reported years if the reporting stopped before 2021. For the increasing electronics, we set the defined "fast growth" and "slow growth" scenarios using logistic fitting based on different assumptions of maximum sales penetration per household values. More details on categorizing the growth scenarios and sales data prediction were included in Supplementary Note 1.

A Weibull probability function was used to predict the temporal evolution of waste electronics in the MFA model, which has been used in previous studies to predict the flow of waste electronics based on their life span.[21,50] In this model, we assumed that the probability of a certain type of electronic device (j) reaching its end of life within its maximum usage year (n) followed a Weibull distribution, which could be described by Equations (3) and (4) [19-21].

$$f(\eta, \delta, t) = \frac{\delta}{\eta}\left(\frac{t}{\eta}\right)^{(\delta-1)} e^{-\left(\frac{t}{\eta}\right)^{\delta}} \quad (3)$$

In the probability density function (3), t represented time, and δ and η were the parameters used to describe the Weibull probably function. The probability of reaching end-of-life (P) could be then used, along with the historical sales data (S) to calculate the flow (N) of waste electronics j generated after a lifespan of i years within its maximum life span (n).[21]

$$N_{j,t} = \sum_{i=1}^{n} P_{j,i} \times S_{j,t-i} \quad (4)$$

The above-mentioned MFA model was applied to the U.S. shipment data of various electronics evaluated in this study. The model is conducted using the open-source MATLAB code as described in Althaf et al. 2021,[21] with adjustments to the numbers and types of electronics, Weibull parameters, average mass, compositions, etc.

For the common electronics that were analyzed in previous studies (i.e., waste cell phones, TVs), we combined the previously-published Weibull parameters and life span from different sources.[19,21] It was noted that the sum of probabilities function derived from the previous Weibull parameters is slightly less than 1 if added up to the same reported maximum life span in previous literature, in which the deviation probability was assumed to be the devices that can be further reused when predicting the amount of waste generated. But the reused or refurbished electronics were not included for further analysis (also included later in *Key assumptions and uncertainties*).

For the relatively sparsely-studied electronics (i.e., smart electronics, wireless electronics, AR/VR sets), their MFA parameters were determined from those of the 20 common electronics based on UNU classification codes, Harmonized System (HS) trade codes, and functionalities.[51,52] Details of the decision tree and sources for determining the MFA parameters are included in Supplementary Notes 2 and 3. The material compositions of different waste electronics were determined from previous literature. The upper and lower bounds of the reported values were used as the "high content" and "low content" scenarios, respectively, with details shown in Supplementary Note 3.

Geospatial Modeling

To model the spatial distribution of the waste electronics generated across the U.S., the total MFA results were distributed to each zip code area based on the population density and amount of electronics in residential households and commercial office buildings within different geological regions of the U.S.(i.e., New England, Pacific, etc.)[27,28] Regional results were normalized to waste electronics generated per capita for different zip code areas with the region.

The average percentage of ownership across different regions of the U.S. were calculated based on the possession and ownership data for sixteen types of electronics (i.e., smartphones, TVs, cell phones, desktop, and laptop computers) in residential households and five types of electronics in commercial office buildings provided by the U.S. Energy Information Administration (USEIA)[27,28]. The total amount of waste electronics generated from the MFA was corrected and distributed to different regions according to their average percentage of ownership and divided by their total population to obtain the average generation/capita for different regions. Note that due to this assumption, the broader distribution of ownership per household of various electronics might be different than the representative types of electronics used.

Waste electronics generated per capita for each geological region were multiplied by the population density data for each zip code in the U.S. to estimate the waste electronics generated for each zip code. The waste electronics generated per zip code were combined with corresponding geospatial data (shape, boundary, longitude, latitudes, etc.) to plot the distribution of the U.S. Nation-wide geological shape data used in this study was obtained from the U.S. Census Bureau.[53]

To assess the potential connections between waste electronics recycling and virgin refineries, the geospatial coordinates for the mines, mining plants, and their state-level productivities in the U.S. were obtained from various U.S. Geological Survey (USGS) sources.[35,54-56] The nationwide certified recycler data was provided by Sustainable Electronics Recycling International (SERI) [57] based on their certified recycler lists across the U.S.

Note that besides virgin mining, there are also several existing major refineries that list waste electronics as part of the feedstocks (See Supplementary Table S4) to produce high-quality metals for the technology industry.[58,59] As there is limited information on the gold productivity and feedstock composition for these refineries, we estimated their influence on the economic potential in Supplementary Note 6, by comparing with virgin plants' productivities, previous techno-economic analysis, and tear-down studies.[13,14,21,60]

Further, we apply a distance matrix to first determine the potential capability for treating waste electronics at the nearest existing facility, either through integrating with virgin mining refineries. We assume that these facilities can allocate/expand a certain portion of their current gold productivity to waste electronics. We further characterize the U.S. into five greater regions shown in the legend of Fig. 5 and analyzes their handling capabilities in Figs. 5(c-h). More details on the geospatial modeling, and productivity and profitability analyses were included in Supplementary Notes 4 to 6.

Key Assumptions and Uncertainties

This section summarizes the key source of uncertainties and assumptions used in this study. All of the uncertainties and assumptions were also discussed in the previous text or the Supplementary Notes 1-6 when they were applied to the corresponding analysis. To summarize, the key assumptions and sources of uncertainties in this study were summarized as follows. First, the scope of this study includes most of the mid to small-size consumer electronics. Due to this assumption, we expect that the overall amount of waste electronics will be higher than what is predicted in this study. Second, refurbished or reused electronics are not modeled in this study. As described in the *Material flow analysis* Section, the re-use was recognized by assuming not all of the electronics sales reach end-of-life in the probability distribution based on the reported Weibull parameters and maximum life spans, but their further re-introduction to the waste stream was not included in this analysis.

For key uncertainties considered in this study, first, due to limited data availability, uncertainties in this study included the composition of resources within the electronics wastes, degree of domestic recycling (as studied by the percent export), approximation of MFA results, and spatial analysis by using representative values. Second, we recognize that there is a high potential that new types of small-to-midsize consumer electronics will be introduced in the near future, similar to how AR/VR and 5G devices have emerged in recent years. This was accounted for by qualitatively showing the possible markup of results in Fig. 2. Lastly, as discussed in the *Future Outlook* Section, although the effects of the key sources of uncertainties were studied (namely the growth scenario, content of resources, and level of export) in the *Results* and *Discussion* sections, future research would greatly benefit from narrowing these ranges via more comprehensive tear down data, and improved policy incentives as stated in the *Discussion* Section.

Data Availability

The data that support the findings of this study are available within the paper and its Supplementary Information. Supplementary dataset is available at https://github.com/ppeng-cloud/Consumer-Electronics-Recycling-Potential-in-United-States.

Code Availability

All steps used in this analysis are illustrated in the Methods section and Supplementary Notes 1-6. Supplementary scripts are available at https://github.com/ppeng-cloud/Consumer-Electronics-Recycling-Potential-in-United-States and from the corresponding author on reasonable request.

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Figure Legends/Captions

Fig. 1. **Scope and system boundary of this study.** Pie chart denotes the general distribution of values between gold (yellow) and other metals extracted from metal recycling processes of waste electronics, based on reported values from refs[14,23]. The value distribution will vary between different electronics products such as type, brand, manufacturer, etc.

Fig. 2. **Temporal changes for waste electronics generation between 2015-2033 and its geospatial distribution results. a.** Number of units generated. **b.** Mass of waste electronics generated. **c.** Mass of gold (most valuable resource) potentially recoverable from waste electronics. **d.** Printed circuit board (PCB) potentially available within waste electronics. Uncertainties are caused by the assumed fast and slow growth scenarios discussed in Supplementary Note 1 (**a** and **b**). Additional uncertainties are included for **c** and **d** when assuming different compositions within the electronics (See Supplementary Notes 1 and 3). Gradient color qualitatively addresses the possibility of increasing in the future after introducing new electronics.

***Fig. 3*. Spatial distribution of waste electronics resources, certified recyclers, and major mining plants in the U.S. a.** Estimated relative density map of waste electronics generated per zip code in the U.S. **b.** Modelled spatial distribution of waste electronics and their corresponding recyclers as well as the locations for virgin mining plants within continental U.S..[53-55,57] See detailed geospatial distribution of mines in Supplementary Note 4. The maps were created in Python v3.8.5 using GeoPandas v0.8.1 (https://geopandas.org) using the shape file from the U.S. Census Bureau[53]

Fig. 4. **The growth of representative types of waste electronics**. **a.** The average growth rate of representative electronics between 2032-2033 (dots) and their corresponding growth rate in 2021-2022 (lines). The growth of 5G Smartphones from 2021 to 2022 exceeds 400% and is not shown in the figure. Full growth data available in the Supplementary dataset. **b.** Modelled waste electronics with the largest weight percentage in 2021. **c.** Modelled waste electronics with the highest weight percentage in 2033.

Fig. 5. **Modelled distribution of valuable (gold) from waste electronics in 2033 and areas where the generated waste can be handled by virgin gold plants for gold extraction**. **a**. Relative amount of gold recoverable in 2033 compared with recent national virgin production. Error bars denote uncertainties in growth scenarios **b.** Relative state-level productivity of gold from virgin sources in the U.S. and map showing where waste electronics are handled based on closest-distance approximation**.** **c-h.** Evaluation of the potential to integrate waste electronics to virgin mining if the plant allocate/expand 30% of the plants current productivity (d, e, g, h), or 70% of the plants current productivity (c and f) to producing gold from waste electronics. High circularity (c, d, f, g) means 80% of the waste electronics are recycled domestically, and high export (e and h) refers to only 40% of the waste electronics are recycled domestically. Light blue color represents the maximum area these plants are able to cover. Dark blue means that the plants can utilize all of the waste electronics with excess capacity left. Yellow denotes the region where gold productivity from waste electronics is beyond the assumed capacity of the plants. The maps were created in Python v3.8.5 using GeoPandas v0.8.1 (https://geopandas.org) using the shape file from the U.S. Census Bureau[53]

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