

Waste Electronics in the United States: Future Trends and Economical Potential

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Waste Electronics in the United States: Future Trends and Economical Potential

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Abstract

Waste electronics are a growing environmental concern, but with proper end-of-life (EOL) management strategies, they can have great economic value due to their embedded resources such as precious metals. Recycling resources from waste electronics is a growing area of research, and recent studies have modeled the growth of common waste electronics (i.e., TVs, phones, computers) in several countries around the world. One challenge with waste electronics is that the distribution of embedded resource is highly related to equipment type and region. The recent growth and development of new electronics may reshape the resource availability and nationwide EOL strategies for creating a circular economy around waste electronics. Herein, our material flow analysis shows that 1.6 billion small to midsize electronic devices, representing 2.6 million tons, could be discarded annually in the United State by 2031. Emerging types of electronics such as AR/VR devices and connected monitoring devices have become the fastest growing types of electronics devices, which could significantly impact the electronic waste stream. By combing the geospatial distribution of waste electronics and U.S. virgin mining resources, we show that it is feasible and profitable to integrate the waste and virgin mining pathways in certain U.S. regions. New infrastructure designed specifically for waste electronics treatment are favorable in the Central and Eastern regions of the U.S. We further quantify how uncertainties in metal composition can lead to distinct EOL scenarios of waste electronics in the next decade and demonstrate why improved tear down analyses of waste electronics are needed.

Introduction

Due to the growing consumption of electronic equipment, and the relatively short lifetimes of many of these devices, the amount of waste electronics has been increasing rapidly. Globally, the annual waste electronics generated has grown from less than 25 million tons (Mt) per year in 2009 to around 53.6 Mt in 2019.¹⁻⁴ The amount of waste electronics generated in the 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).^{3,4}

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.^{3,5} The rapid growth of waste electronics and their lack of proper end-of-life management solutions has led to various environmental and public health threats such as heavy metal poisoning and food chain contamination^{6,7} Waste electronics, however, contain materials of significant value that could allow proper recycling to have economic benefits.

In terms of overall material composition, waste electronics is a combination of both plastics and metals. The current waste electronics recycling process includes preprocessing and metal recycling. A general piece of waste electronics device includes plastic covers, printed circuit boards that hold the various electronic parts (i.e., resistors, capacitors), batteries, etc.^{8,9} Each of these components offers unique value upon recycling. The existing techno-economic analysis

(TEA) studies have demonstrated the potential of making profits via recovering metal resources from the printed circuit boards (PCBs) being the main source of revenue.¹⁰⁻¹²

A significant amount of the waste electronics in the U.S. that are recycled have been exported, and trading electronics internationally makes the recycling process hard to regulate, owing to the different policy and economic incentives between countries.¹³ 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 United States (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.

There are several electronics material flow analyses (MFA) from organizations such as the U.S. Environmental Protection Agency (USEPA)¹⁴ and Solving the E-waste Problem (StEP) Initiative¹⁵, as well as peer-reviewed literature.¹⁶ These studies have been focused mostly on common and relatively conventional waste electronics such as TVs, mobile phones, computers, and monitors, etc. Limited research has been conducted regarding the impacts of the emerging electronics that have been growing rapidly in recent years, such as wireless electronics, AR/VR devices, and smart home products. 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 are limited to selected waste electronics in selected states.¹⁷

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

Since previous TEAs concluded that gold holds most of the metallic values (above 80%) within the waste electronics,^{10, 11} we use gold recovery to represent the potential metal resources. 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 the current metal refining industries within the U.S. and offers recommendations on creating an electronics-centered circular economy for different future scenarios.

Results

Temporal and spatial distribution of waste electronics

Figure 1a shows the modelled 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 2031 could exceed 1.6 billion units, and the slow growth will lead to approximately 500 million units. In terms of mass, waste electronics generated in the U.S. are estimated to reach from 1.4 to 2.8 million tons (Figure 1b). 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.

Figures 1c and 1d show the mean and general growth trend of representative resources in waste electronics over the next decade. Printed circuit boards (PCBs) from waste electronics contain the most valuable materials recoverable, including precious metals such as gold (Figure 1 c).^{10, 11, 18}

The plateau of gold availability from waste electronics in recent years (i.e., 2017-2021) that is presented here is consistent with previous studies. For example, Althaf et al. 2020¹⁶ and Golev et al. 2016¹⁹ both estimated a steady and slow decline in gold availability from 2015-2018 among conventional electronics in U.S. and Australia, respectively. However, existing tear down studies on emerging smart electronics, which are smaller, wireless, and often more complex electronics (i.e., smart phones, and tablets) have shown higher PCB and gold content than that of larger, stationary, and wired electronics (e.g., DVDs and VCRs)²⁰, indicating that as greater types of smart electronics start to emerge the amount of both PCB and gold that are recoverable from waste electronics could increase within the next decade.

Due to limited publicly available tear down analyses, as described in Section S2 of the supplementary information, the modelled PCB and gold content assumed in different types of electronic devices has a relatively large range (Figures 1c and 1d). Note that the relative impact (calculated in Supplementary Section S2.2) of composition is much higher than that of the growth scenario, meaning that the composition will have greater influence on how much of these materials can potentially be recovered, which is analyzed in the discussion section.

Figure 1e shows an electronics generation density map in the U.S. for each zip code, as modelled via geospatial analysis described in the Methods and Supplementary Section S3.1. As the model is developed based on the population and household possession data^{21,22}, the waste electronics densities are heavier in the coastal and metropolitan areas. It is notable that currently in the densest regions (i.e., New York City and Los Angeles), over 16,000 kg of waste electronics can 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 could be achieved via hydro or pyrometallurgical processes.^{23,24} 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.^{25,26} In fact, a majority of the metal recovery from waste electronics are still based on pyrometallurgical pathways, which is also the primary virgin mining process with minor difference between feedstocks (i.e., precious metal vs. base metal refining).²⁷⁻

²⁹

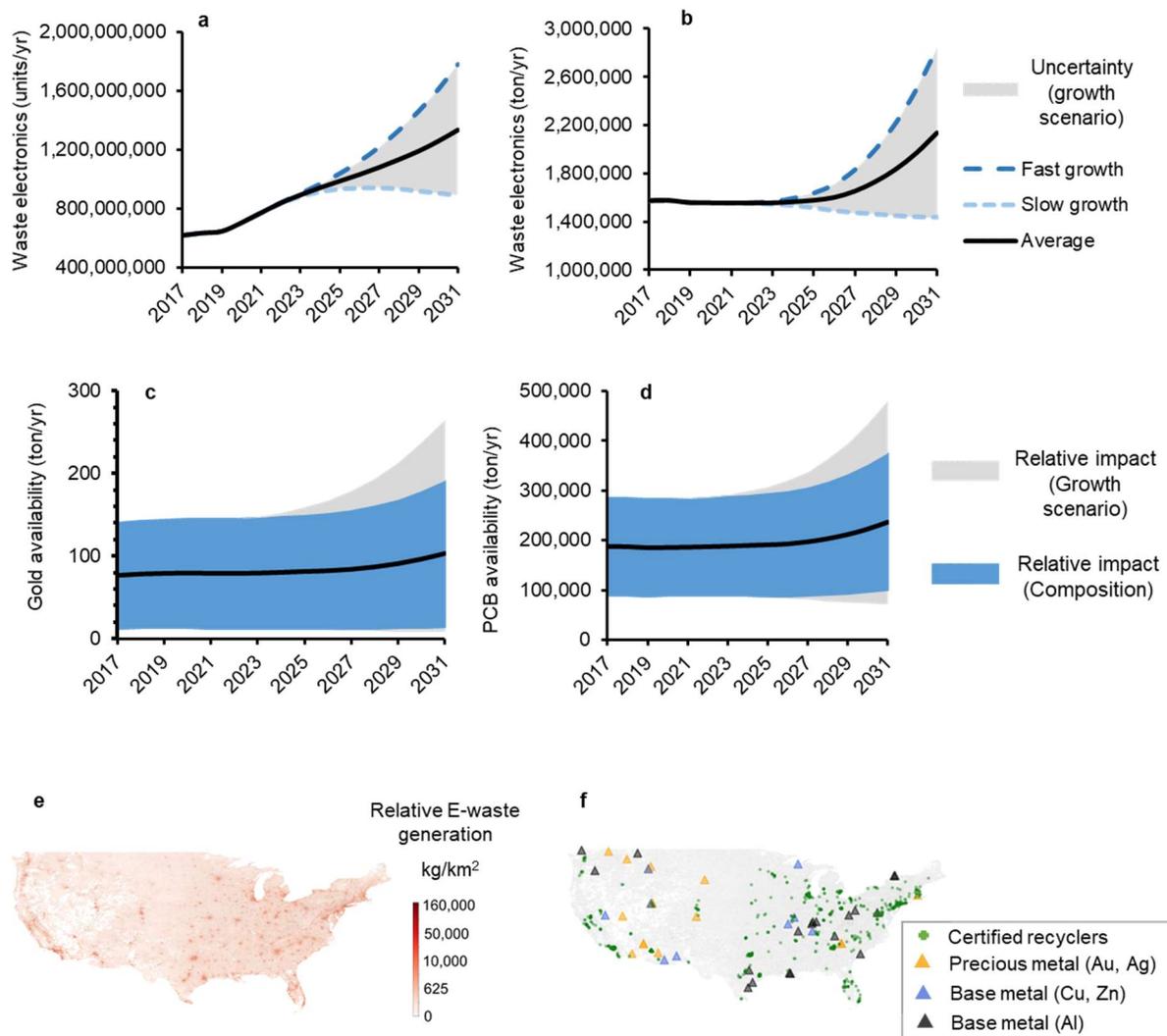


Figure 1. Temporal changes for waste electronics generation between 2017-2031 and its geospatial distribution results. a. Number of units generated. **b.** Mass of waste electronics generated. **c.** Mass of gold (most valuable resource) potentially recoverable from waste electronics. **d.** Printed circuit board (PCB) available within waste electronics. Uncertainties are caused by the assumed fast and slow growth scenarios discussed in Supplementary Section S2.2 (**a** and **b**). Additional uncertainties are included for **c** and **d** when assuming different compositions within the electronics (See Supplementary Section S1 and S2.2). **e.** Density map of waste electronics generated per zip code in the U.S.. **f.** Modelled spatial distribution of waste electronics and their corresponding recyclers as well as the locations for virgin mining plants within continental U.S.. See detailed geospatial distribution of mines in Supplementary Section S3.1.

Virgin gold mines and refining plants mostly exist in the western states (i.e., Nevada and Arizona) of the U.S., as shown in Figure 1f. The rest of the virgin gold mines are scattered around U.S., but relatively more concentrated in the mountain areas (i.e., Utah and Colorado). Again, before the waste electronics can be processed in the metal refinery plants, they must be collected, and processes (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 1f shows an estimate of the locations of certified waste electronics recyclers as recognized by the USEPA³⁰

(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 Figure 1e, 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 the virgin mining production and the potential metal recovery from waste electronics mostly in the west part of the U.S., whereas there could be more potential of building new electronic waste mining facilities in the Central or Eastern regions.

Growth of different types of waste electronics

Figure 2a shows the predicted growth of select waste electronics in 2030-2031. The complete list is included in the Supplementary dataset. The results show that most of the waste electronics growing in 2031 also have positive growth rates in 2022. The overall scale of the difference in growth rate in 2022 is much larger (up to 500%) than that of 2031 (up to 30%) owing to one or two recent spikes between 2018-2021, whose effect is diminished when projected to 2031. It is notable that several of the waste from several emerging types of electronics, such as wearable fitness devices, tablets, and desktop PC have large range of predicted growth rates due to high uncertainties of growth scenarios relating to demand, supply chain, etc. For these electronics, further market analysis is recommended to provide more accurate growth predictions. Also, note that for the future scenario (2030-3031), 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, smart (i.e., smart home products, smart door bells), and internet of things products (defined as electronics requiring constant wireless communications) are becoming an increasing part of the electronic waste composition. Other waste smart electronics (i.e., home robots, smart watch, drones) did not make to the top 10 growing list, but also have higher than 10% growth rate in 2021 to 2022. 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 percentage²⁰.

In terms of mass generated, Figures 2 (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.¹⁶ Other heavy electronics, such as printers and desktop PCs are still of the top ten waste electronics by mass. Lastly, smaller computers such as laptops and tablets will likely to exceed the conventional desktops or monitors 2031.

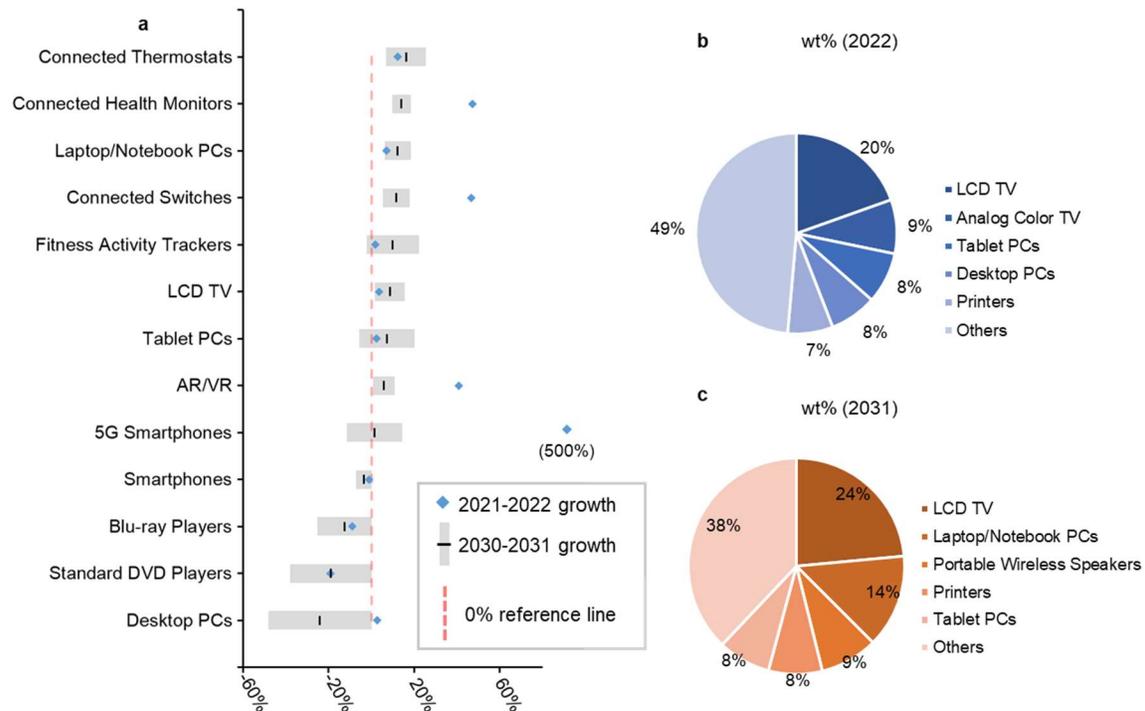


Figure 2. The growth of representative types of waste electronics. **a.** The average growth rate of representative electronics between 2030-2031 and their corresponding growth rate in 2021-2022. Uncertainties are caused by the different fast and slow potential growth scenarios (See Supplementary Section S2.2). Uncertainty by growth scenario for 2021-2022 is negligible (tracked data available until 2021), therefore is not studied is not plotted. Full growth data **b.** Modelled waste electronics with the largest weight percentage in between 2022. **c.** Modelled waste electronics with the highest weight percentage in 2031.

Discussion

Economic Potential

Since gold can represent over 85% of the embedded value within consumer electronics¹⁰⁻¹², it is used as the primary indicator to study the economic potential of treating electronics. One important criteria is to compare the potential gold productivity from the waste electronics with the current gold productivity throughout the U.S., which is approximately 220 tons annually³¹. Recall from Figure 1c, under the fast growth scenario, the gold recoverable from the waste electronics can exceed the national productivity of gold mining, when assuming gold compositions within the electronics are on the higher end of values found in literature.^{16, 19, 20, 32-34} Even for the slow growth scenario, if gold content is high, the potential gold that can be recovered from waste electronics is approximately 60% of U.S.'s national productivity. Figure 3a shows that on the state level, Nevada and Alaska are the leading states for virgin gold production, with capabilities of approximately 173 metric tons and 21 metric tons per year (2018 value published in 2021), respectively.³¹ Details on how the productivity of each state is estimated can be found in Supplementary Sections S3. Due to its high virgin gold productivity, plants in Nevada should theoretically have the capacity necessary to handle all of the waste electronics in the U.S, but would face extra burden (i.e., time, cost, emission) when transporting waste electronics that are generated far from the region.

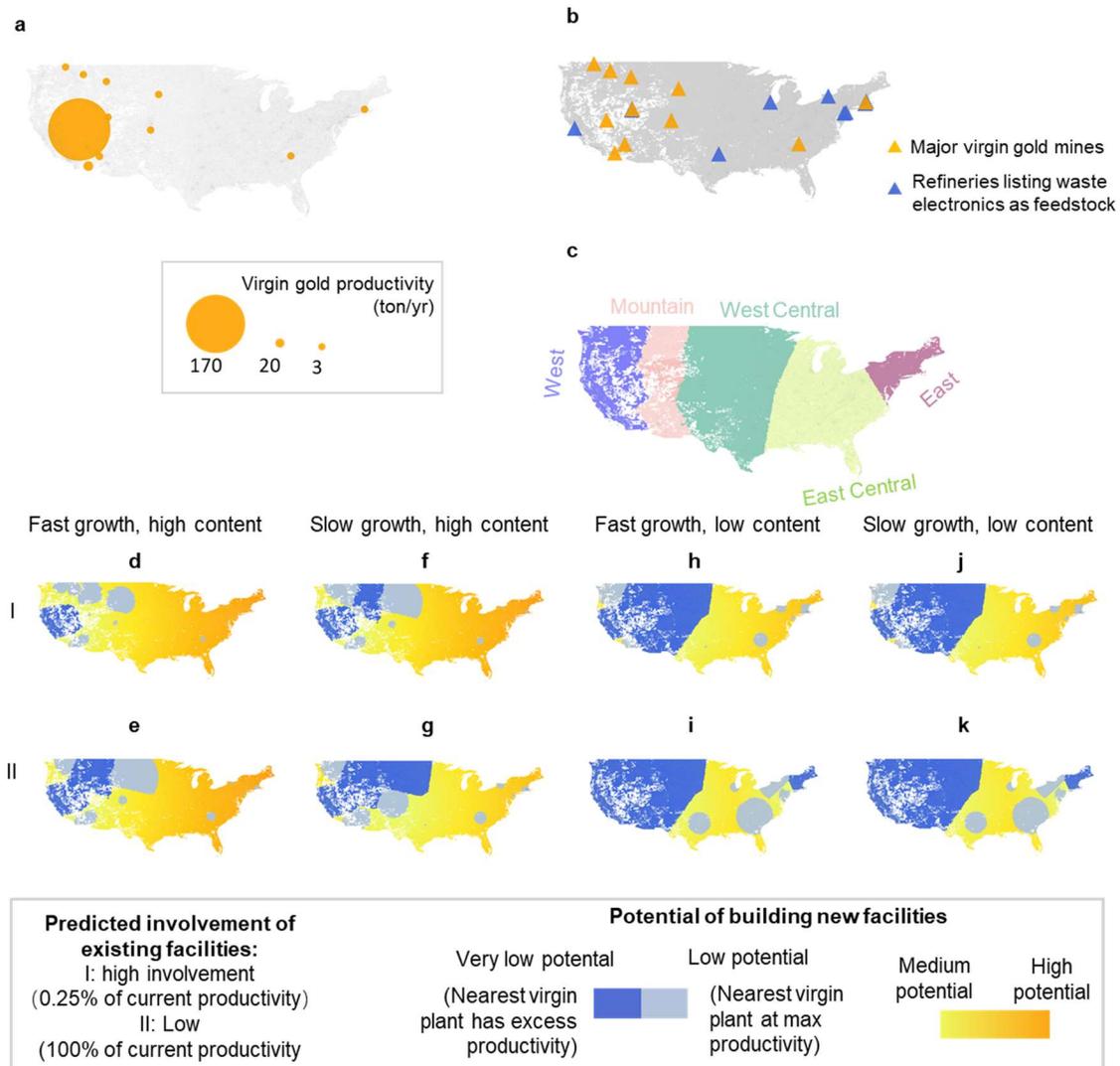


Figure 3. Modelled distribution of valuable (gold) from waste electronics in 2031 and areas where the generated waste can be handled by virgin gold plants for gold extraction. a. Relative state-level productivity of gold from virgin sources in the U.S. **b.** Map showing where waste electronics are handled based on closest-distance approximation. **c.** Map showing the greater regions for analyzing the economic potential in this study **d-k.** Evaluation of the potential to integrate waste electronics to virgin mining if the plant allocate/expand 25% of the plants current productivity (scenario I for d, f, h, and j), or 100% of the plants current productivity (scenario II for e, g, i, and k) to producing gold from waste electronics. Blue color represents the maximum area these plants are able to cover. Grey 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. Alaska is not plotted because nearly all of the gold can be recovered under the high-content scenarios utilizing 25% of the current virgin productivity.

Note that besides virgin mining, there are also several existing major refineries that lists waste electronics as part of the feedstocks (See Supplementary Table S3). These refineries take waste metal scraps or metal products from virgin plants to produce high-quality metals for the technology industry.^{35, 36} 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 Section S3.3, by comparing with virgin plants' productivities, previous techno-economic analysis, and tear down studies.^{10, 11, 16, 32}

In this study, 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 or metal refineries. We assume that these facilities can allocate/expand certain portion of their current gold productivity to waste electronics. We further characterize the U.S. into five greater regions shown in Figure 3c, and analyzes their handling capabilities in Figures 3 (d-k). If the embedded gold from waste electronics in certain regions reaches the maximum allocated productivity (light blue color), they 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 Figures 3 (d-k).

In recent years, there have been emerging research on new technologies to recover metals from waste electronics, such as electro-chemical treatment, super-critical aided extraction, and bioleaching.^{27, 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. For these new facilities, higher productivity from virgin integration and existing refineries means more competition. Thus, higher transportation burden to virgin integration indicates greater potential to build such new facilities. In Figures 3 (d-k), darker blue color represents higher opportunity to integrate waste electronics with existing virgin plants, whereas darker yellow color represents higher economic potential for new facilities.

The gold content within waste electronics is the primary driver of economic potential, as there are dramatic changes in economic potential between Figures 3 (e-g) and Figures 3 (h-k) Therefore, more tear down analysis for the emerging electronics are recommended to provide a better understanding of material compositions and policy guidance on waste electronics EOL management.

Table 4 summarizes the overall economic potential for building new facilities in the five regions in Figure 3. Based on existing information, the West region has the lowest potential of building new waste electronics recovery plants due to the domination of gold production in Nevada. Mountain (i.e., Utah and Colorado) and West Central (i.e., South Dakota and Nebraska) are also regions with relatively active virgin production, but could still have potential of new plants if the gold content in the waste electronics is high. The new plant potential in the Mountain region is highly sensitive to how much capacity the virgin plants can allocate to waste electronics, as in these regions the waste electronics per area is low. The West Coast and Mountain regions, therefore, would most likely benefit from integrating waste electronics recovery with virgin metal recovery.

The East Central (i.e., South and North Carolina) region has the highest potential of building new facilities for waste electronics, followed by the East region (i.e., New York and Massachusetts). For the East Central region, there is large amount of area where waste electronics are not likely to be handled by nearby virgin plants and refineries regardless of growth scenarios. For the East region, the economic potential depends highly on the level of involvement of virgin plants and refineries when the gold content is low. Under low gold content conditions, existing facilities can saturate the waste electronics generated in the East region if they are able to allocate/expand equivalent amount of their current gold production to be recovered from waste electronics (Figure 3 (i-k)).

Table 1. Economic potential of building new facilities for metal recovery from waste electronics in different regions. Number of stars represents the level of economic potential, where 1 star to 5 stars represent the lowest to highest potential

	Growth	Involvement of existing facilities	West	Mountain	West Central	East Central	East
High content	Fast	Low	☆☆	☆☆☆	☆☆☆☆	☆☆☆☆☆	☆☆☆☆☆ ☆
	Fast	High	☆	☆☆	☆☆☆	☆☆☆☆☆	☆☆☆☆☆ ☆
	Slow	Low	☆	☆☆	☆☆☆	☆☆☆☆☆	☆☆☆☆☆ ☆
	Slow	High	☆	☆	☆☆	☆☆☆☆	☆☆☆☆☆ ☆
Low content	Fast	Low	☆	☆	☆☆☆	☆☆☆☆	☆☆☆☆
	Fast	High	☆	☆	☆☆	☆☆☆	☆
	Slow	Low	☆	☆	☆☆☆	☆☆☆☆	☆☆☆☆
	Slow	High	☆	☆	☆☆	☆☆☆	☆

It is important to note that for waste electronics, certain detoxification procedures might be required to eliminate the effects of brominated flame retardants during the high-temperature treatments.^{27, 39} Also, metal compositions are different between waste electronics and virgin mines,^{34, 40} which would require more separation stages. Results from this section imply that quantifying the economics trade-off between the exact procedures that needs to be added for the virgin mines to handle electronics can make a significant difference in examining the nation-wide 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 Directions

The above discussions highlight potential opportunities to enhance the circular economic potential of metal recovery from waste electronic and help solve several major challenges identified in this study. 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 Figure 1 and Figure 3 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 for 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 manufactures without exposing company intellectual properties (IPs).

Second, there has been limited transparency at the national level on both the upstream recyclers (green dots in Figure 1f), and metal refineries (blue triangles in Figure 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 may require a national-level survey or reporting database.

Third, since the MFA in this study is primarily based on the historical sales data of various consumer electronics, further research is required on import and export data to further estimate the amount of waste electronics that are currently available for domestic treatment. Additionally, in terms of geospatial modeling, the current study uses straight line distances from the source of the waste generation to the refineries to estimate the economic potential. More detailed route optimization, especially from the collection plants shown in Figure 3 to the refineries, will be beneficial to further quantify the transportation impacts.

Furthermore, although gold can represent the potential economic value of metals recoverable from waste electronics, other metals such as copper, nickel, and rare earth elements (with potential underlying supply chain constraints⁴¹) should be considered in future studies. Besides metals, organic plastic components can occupy up to 30 wt%,⁴² and can influence the planning and regulating of waste electronics EOL.

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

Conclusions

This study uses material flow analysis (MFA) based on the historical data from both the private and public sectors for mid to small size consumer electronics to analyze and predict the changes in total quantity, composition, and potential value that could be recovered from their wastes. This study shows that currently, the U.S. is experiencing a dramatic change in waste electronics composition. The total amount of mid to small size consumer electronic waste, and the potential precious metal (gold) recoverable from that waste has been steady in recent years, however, our model suggests that the value in waste electronics will likely increase in the next decade owing to the changes in metal composition and shipments of emerging electronics. The amount of small to mid-size consumer waste electronics may exceed 1.6 billion in number of units and 2.6 million tons in mass per year by 2030. The potential gold that can be recovered from these electronics can be comparable to the virgin production in the U.S.

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 for the virgin mining refineries, we conclude that it is worthwhile considering the integrated pathway of recycled waste electronics and virgin metal recovery routes in the U.S. Theoretically, the virgin refining plants have the capacity of handling most waste electronics to recover precious metal (gold) from waste electronics in terms of total quantity. However, after considering the geological distributions and current gold mining production, virgin plants in the West and Mountain areas of the U.S. have large handling capacities for waste electronics. The Central and East regions may have more need to create new infrastructures targeting waste electronics.

Future research should focus on route optimization, and process development for both upstream (recyclers and collectors) and downstream refineries for this integrated waste and virgin mining pathway to enhance the economic potential. Also, policy efforts should be focused on creating national-level database that include 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 more complete geospatial analysis on metal recovery from waste electronics.

Materials and Methods

Material flow analysis

A Weibull probability function was used to predict the temporal evolution of waste electronics to conduct the material flow analysis (MFA), which has been used in previous studies to predict the flow of waste electronics based on their life span.^{16, 43} In this model, we assumed that the probability (P) of a certain type of electronic device (j) reaching its end of life in a certain year (t) within its maximum usage year (n) followed a Weibull distribution, which could be described by Equations (1) and (2)¹⁴⁻¹⁶.

$$P_j(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (1)$$

In Equation (1), β and η were the shape (Weibull slope) and scale parameters used to describe the Weibull probability function. The probability could be then used, along with the historical sales data (S) to calculate the number of waste electronics j (N) generated at the number of years used (i) within its maximum life span (n).

$$N_j(t) = \sum_{i=1}^n P_j(i) \times S_j(t - i) \quad (2)$$

The above-mentioned MFA model were applied to the U.S. shipments data of various electronics modelled in this study. The model is conducted using the open-source MATLAB code as described in Althaf et al. 2020,¹⁶ with adjustments to the numbers and types of electronics, Weibull parameters, and average mass, compositions, etc.

Compared with the previous material flow analysis for waste electronics,¹⁴⁻¹⁶ we expanded the types of waste electronics from the 20 common electronics (i.e., waste cell phones, TVs) to covering 96 types of electronics. The waste electronics covered in this study include the emerging waste electronics such as wearable fitness and health products, portable and wireless devices, smart home improvement devices, AR/VR sets, and drones, based on data from the NPD Group, HTF Market Report, and ABI Research, as well as data from the U.S. Consumer Technology Association (CTA). The types of electronics modeled in this study are included in the supplementary data set.

For the common electronics that were analyzed in previous studies (numbers 1 to 20), we combined the previous published Weibull parameters from different sources.^{14, 16} For the relatively sparsely-studied electronics (i.e., smart electronics, wireless electronics, AR/VR sets), their MFA parameters were determined based on UNU classification codes, Harmonized System (HS) trade codes, and functionalities.^{44, 45} Details of the decision tree and sources for determining the MFA parameters are included in the supplementary Section S2.

Geospatial modeling

To model the spatial distribution of the waste electronics generated across the U.S., the total MFA results were distributed based on the amount of electronics in households and offices within

different geological regions of the U.S.(i.e., New England, Pacific, etc.)²² 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 five types of electronics (smart phones, TVs, cell phones, desktop and laptop computers) provided by the U.S. Energy Information Administration (USEIA)²², which are tabulated in the supplementary information. The total amount of waste electronics generated from the MFA was distributed to different regions according to their average percentage of ownership and divided by their total population density to obtain the average generation/capita for different regions.

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 and 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.⁴⁶

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.^{31, 47-49} The nation-wide certified recycler data was provided by Sustainable Electronics Recycling International (SERI)⁵⁰ based on their certified recycler lists across the U.S. More details on the geospatial modeling, and productivity and profitability analyses were included in Supplementary Section S3.

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Competing Interest Statement: There is no competing interest.

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