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# Paper and cardboard waste in the United States: Geographic, market, and energy assessment

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ABSTRACT

Reliable data on U.S. paper and cardboard waste by location and type are critical for developing waste-reduction solutions, but detailed geographic analysis is lacking in the literature. In this study, we employ statistical and geospatial methods to assess paper and cardboard waste in the United States by type at the national, state, county, and local levels. Of the estimated 110 million tons of paper and cardboard waste managed domestically in 2019, approximately 56% was landfilled, 6% was combusted, and 38% was recycled. The estimated market value of paper and cardboard lost to landfilling in 2019 was $4 billion, and the estimated losses of embodied energy and combustion energy were equivalent to 9% and 4% of U.S. primary industrial energy consumption, respectively. Associated landfilling fees amounted to almost $4 billion. This study aims to inform efforts to implement beneficial waste-management strategies by policy makers, researchers, businesses, and communities across the United States and to provide a model for similar studies in other parts of the world.

## Introduction

Municipal solid waste (MSW) management represents a challenge and an opportunity in the United States. MSW is made up of items—such as food, electronics, and packaging—discarded by residential, industrial, institutional, and commercial entities (Hoornweg et al., 2014). Landfilling is the primary strategy for managing MSW in the United States (EPA, 2020). Modern landfills are highly engineered and regulated—from siting to design, operation, closure, and monitoring—to store waste while protecting the environment from contamination (EPA, 2022a). However, the energy and resource values of materials put into landfills are at least partially lost—although landfill gas can be captured and converted to energy (EPA, 2022b)—and fees for waste disposal must be charged. In addition, decomposition of waste in landfills is the third-largest source of anthropogenic methane emissions in the United States; MSW landfills alone are responsible for about 15 % of those emissions (EPA, 2022b, 2022c, 2022d). Landfills can be associated with local and regional problems related to odors, aesthetics, and contaminant leakage, which often entail environmental justice issues (Tufano, 2015). In the United States, the availability of land for siting landfills can also be constrained at local or regional levels (Tufano, 2015; Zimlich, 2015).

Other waste-management options can mitigate the drawbacks of landfilling and provide economic and environmental benefits. The U.S. Environmental Protection Agency (EPA) offers a waste-management hierarchy with source reduction and reuse at the top (most environmentally preferred), followed in descending order of preference by recycling and composting, energy recovery, and treatment and disposal (primarily landfilling) (EPA, 2022e, 2022f). Source reduction and reuse (e.g., donating used items, reducing packaging) prevent materials from entering the waste stream, which can reduce costs, resource use, and energy use. Recycling and composting can also provide energy, economic, and resource conservation benefits. Energy recovery converts waste into usable heat, electricity, or transportation fuel, which can reduce landfill emissions of methane and offset fossil fuel consumption. According to EPA analysis, favorable waste-management strategies can reduce greenhouse gas (GHG) emissions substantially (EPA, 2022e). All the non-landfill options also mitigate land-availability issues associated with landfills.

Paper and cardboard are major constituents of MSW in the United States. The generation of these materials has been reported in the literature at the national level (Powell and Chertow, 2019; EPA, 2021). However, detailed data showing the quantity of waste types by location are lacking in the literature. Such data are needed to inform lawmakers about where to target new policies for maximum impact, industrial

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representatives about where to invest in siting new facilities, and the research community about the potential impact of implementing new waste-management technologies at a regional scale.

Our study contributes to the literature on paper and cardboard waste management in the United States by presenting a detailed assessment of paper and cardboard waste at the regional, state, county, and local levels, as well as an alternative approach to estimating these resources. Results include waste composition by material type and region. Landfilled waste in 2019 is estimated at the state, county, and local (on-site) levels. We focus on the landfilled portion of paper and cardboard waste in our geospatial analysis to illustrate "hot spots," or areas with substantial opportunities to divert these materials from disposal facilities and recover their technical and economic value. We estimate the market and combustion-energy value of the landfilled material to illustrate these losses to the U.S. economy, as well as the embodied energy of this material to reveal the energy consumption associated with its production. We also provide national-level estimates for combusted and recycled paper and cardboard waste as a reference and to illustrate the total amount of managed material in the country in 2019.

This study complements our previous work that estimated and evaluated other biogenic MSW materials including food waste (Milbrandt et al., 2018) and plastic waste (Milbrandt et al., 2022). The collective goal of these studies is to fill data gaps, improve the level of detail and comprehensiveness of MSW estimates compared with previous studies, and drive local initiatives towards sustainable waste management in the context of a circular economy.

## Methods

This section describes the methods used for analyzing waste composition, quantity and geographic distribution of paper and cardboard waste in the United States, as well as the market and energy value of that waste. The current methodology is similar to that used in our previous study on plastic waste in the United States (Milbrandt et al., 2022), but it is different enough to require a full description here.

### *Paper and cardboard waste composition*

We reviewed 52 waste composition studies by material type at the state, county, and local levels. Table S1 in the Supplementary Information lists these sources and the year they were generated. Paper and cardboard waste components include newspaper, magazines, high-grade office paper, old corrugated containers/cardboard and kraft paper (OCC/kraft, hereafter referred to as "cardboard"), compostable paper (e.g., food-soiled paper products such as paper towels, napkins, and pizza boxes), and other materials (items that do not fit in other categories such as books, phone books, aseptic containers [e.g., shelf-stable milk, juice, and broth cartons], gable-top containers [e.g., refrigerated milk, juice, and cream cartons], junk mail, and photographs). The 52 studies represent 36 U.S. states. These studies are based on multiple samples taken from various stages in the waste management process, including transfer stations, landfills, incinerators, and in some cases material recovery facilities (MRFs). The materials from these samples were sorted in categories and weighed, and a percentage composition was averaged across all samples. The studies' methodology is based on the American Society for Testing and Materials (ASTM) D5231 – 92 Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste, which defines sampling protocols to achieve statistically valid results.

About 76 % of the composition studies were completed between 2015 and 2020, and only three states produced estimates before 2010 (Table S1). We compared older and more recent estimates where available (District of Columbia, Florida, Illinois, Massachusetts, Wisconsin, Washington, and California) and observed negligible or small (within 1 %–2%) differences in most subcategories and the overall share of paper/cardboard waste. Therefore, we assume waste composition during the 2015–2020 period remained reasonably consistent and is applicable to our study year of 2019. The negligible or small difference was observed for newspaper and magazine waste, which decreased during that period, while the share of cardboard waste increased owing to consumption trends associated with expanded e-commerce (fewer newspapers and magazines were printed, and more cardboard was consumed for packaging and delivery services). The overall contribution of paper and cardboard waste as a percentage of total MSW generation remained relatively constant during the 2015–2020 period.

When more than one study is available for a state, average values across all studies are used. For the remaining states with no data, we apply a regional average value calculated from studies conducted after 2015 (Table S2). When states are missing data for a particular material type, the data gap is filled with a regional average. Figure S1 in the Supplementary Information maps the U.S. regions used in this study. These regions were carefully chosen to represent states with similar socio-economic status. Most states in the Southwest and Rocky Mountain regions either have not completed waste composition studies or have outdated assessments; we could not generate regional values, so we apply the national average waste composition to those states. Alaska has not produced a waste composition study, and its recycling rate is much lower than the rates in other states in the region (California, Oregon, Washington, and Hawaii) (Eunomia, 2021). For this reason, and after consultation with industry and local experts, we apply national average—instead of regional—waste composition values to Alaska.

There could be differences in the waste composition between locations in a state (urban, suburban, and rural), but we propose that the state average rate compensates for these differences. Based on available data for several states (Colorado, Illinois, Indiana, Connecticut, Pennsylvania, and Maryland), the difference between locations within states is negligible or within a few percentage points. Also, urban waste is often taken to landfills in suburban and rural areas, making the delineation between locations unclear.

### *Paper and cardboard waste quantity and geographic distribution*

We estimate the quantity of landfilled and combusted paper and cardboard waste by applying the waste composition data (Section 2.1) to the mass of MSW received at landfills and combustion facilities. We estimate the paper and cardboard waste quantity at 1,776 active landfills and 85 combustion facilities in the United States, aggregating the results at the county, state, and national levels. These landfills and combustion facilities are privately or publicly owned, and they accept various types of waste (e.g., MSW, construction and demolition waste, and industrial waste). Our analysis considers only the MSW portion of total waste received at these locations. Data for these facilities (e.g., address, ownership, operator, and type and quantity of waste received) were obtained from *Waste Business Journal* (WBJ, 2020). According to these data, 2,904 landfills were active in the United States in 2019. The 1,776 landfills we consider represent the main facilities receiving MSW. The remaining 1,128 locations receive primarily construction and demolition waste; the amount of MSW accepted at these locations represents only about 1 % of total landfilled MSW in the country. There are 99 combustion facilities in the 2019 *Waste Business Journal* database, of which 85 reported values for received MSW.

The quantity of paper and cardboard waste received at landfills and combustion facilities in the United States during 2019 is calculated as follows:

$$\boldsymbol{M_t = MSW_t * Pm_s} \tag{1}$$

where $M_t$ is paper and cardboard waste received at facility $t$ in units of tons (newspaper, magazines, office paper, cardboard, compostable paper, and other paper), $MSW_t$ is MSW received at facility $t$ in units of tons, and $Pm_s$ is the proportion of MSW in material category $m$ in state $s$.

Recycling data are provided at the national level as a reference and to provide an understanding of the total paper and cardboard waste managed in the United States. Data on the recycled quantity of paper and cardboard waste in 2018 were obtained from the latest EPA estimate (EPA, 2020). The American Forest and Paper Association also provides fiber recycling statistics, but they do not supply detailed information by material type (AF&PA, 2022). EPA provides values for the total amount of fiber recycled in the country (about 42 million tons [Mt]), as well as separate values for newspaper (3 Mt) and cardboard waste (29 Mt). The reported value for recycled newspaper accounts for about 44 % of total newspaper waste in our analysis. Based on consultation with industry experts, we apply a similar recycled percentage (40 %) for magazines and office paper waste, because these materials are often collected together as mixed recyclable paper, which translates to about 2.3 Mt and 2.6 Mt recycled, respectively. After subtracting newspaper, cardboard, magazines, and office paper from the 42 Mt of total recycled fiber, 4.7 Mt remains, and we assign this amount to an "other" category.

### *Market and energy value of paper and cardboard waste*

The market value of landfilled paper and cardboard waste, except compostable paper, is estimated using the national average prices for recovered postconsumer paper and cardboard during the period 2019–2021 provided by Recycling Markets (Recycling Markets Inc., 2022). A snapshot of 2019 prices would not capture recent market trends for these materials, so we use a 3-year average. The market value of compostable paper is estimated using the national average bulk wholesale compost price during the period 2019–2021 provided by Composting News (Composting News, 2023). It should be noted that while we use average prices, the value of these materials is a range that varies in time and by location. The market value of paper and cardboard waste is presented at the national—instead of the regional—level primarily due to incompatible regional data: the regions with price data do not contain the same combinations of states as the regions used in this study.

We estimate the total embodied energy for landfilled paper and cardboard waste using an average value of 35 MJ/kg, supported by several sources in the literature (Latka, 2017; Venkatesan et al., 2023; Mantoam et al., 2017; Victoria University of Wellington, 2023). Latka (2017) reports a range from 10.7 MJ/kg to 60 MJ/kg. A lower end value is also reported by Boustani et al. (2010), and an upper end value is also reported by Ashby (2013). We estimate the energy value of landfilled paper and cardboard using higher heating value (HHV) data from Boumanchar et al. (2019).

## Results

### *Paper and cardboard waste composition*

Waste composition refers to the components of the waste stream as a percentage of the total mass generated (Kaza et al., 2018). We estimate that paper and cardboard waste constituted about 26 % of total MSW managed nationwide in 2019. Fig. 1 breaks down the paper and cardboard waste into components by region (see the SI for region definitions). Cardboard, compostable paper, and other paper were the dominant types, each category constituting between 4 % and 9 % of MSW by region. In contrast, the percentages of office paper, magazines, and newspaper ranged from less than 1 % to less than 2 % of MSW by region. There were substantial regional variations in the percentages of waste attributed to each category. Overall, the Pacific had the lowest percentage of paper and cardboard waste from total MSW (about 17 %), and the Southeast had the highest (about 25 %). In some states (e.g., Oregon, Washington, and California), paper and cardboard waste constituted approximately 15 %–17 % of total MSW managed. In others (e.g., Tennessee, Florida, and Kansas), that material constituted about 29 %–30 % of total MSW managed.

### *Paper and cardboard waste quantity and geographic distribution*

Table 1 illustrates the quantities of paper and cardboard waste managed in 2019 at the national level in the United States by management strategy. The 110 Mt of paper and cardboard waste managed broke down as follows: cardboard (44 %), compostable paper (21 %), other paper (18 %), newspaper (6 %), high-grade/office paper (6 %), and magazines (5 %). Of the total amount of paper and cardboard waste, 56 % was landfilled, 38 % was recycled, and 6 % was combusted. High landfilling rates were observed for compostable paper (90 %) and other paper (69 %). In contrast, 60 % of cardboard was recycled; however, because this category constituted the largest absolute mass of waste, it produced the second-largest absolute amount of landfilled material.

For context, in 2019, the United States produced about 68 Mt of paper and cardboard and consumed 67 Mt (FAO, 2019). These totals do not align with our estimated total waste of 110 Mt owing to the long

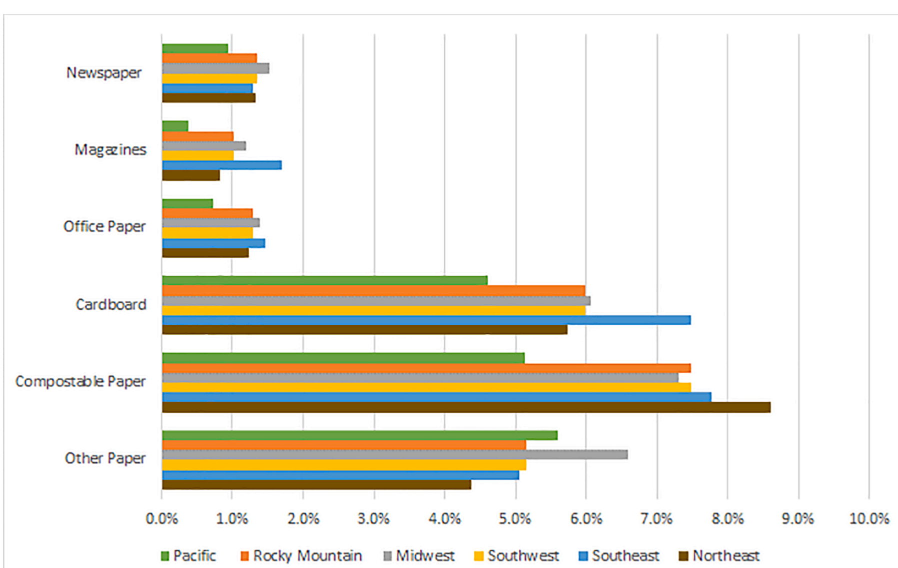


**Fig. 1.** Average regional paper and cardboard waste composition as a percentage of total MSW in the United States based on data from the 2015–2020 period. The percentages illustrate the share of paper and cardboard in total MSW generated in each region. Figure S1 maps the U.S. regions used in this study.

**Table 1**
Paper and cardboard waste quantities in the United States by management strategy in 2019. Landfilled, combusted, and recycled amounts are presented at the national level along with their percentage of total paper and cardboard waste managed in 2019.

| Waste Material | Landfilled (kt) | % | Combusted (kt) | % | Recycled (kt) | % | Total Paper and Cardboard Waste Managed (kt) | % |
|---|---|---|---|---|---|---|---|---|
| Newspaper | 3,472 | 51 % | 320 | 5 % | 2,966 | 44 % | 6,759 | 6 % |
| Magazines | 3,139 | 55 % | 287 | 5 % | 2,268 | 40 % | 5,693 | 5 % |
| Office Paper | 3,533 | 54 % | 406 | 6 % | 2,631 | 40 % | 6,570 | 6 % |
| Cardboard | 17,651 | 36 % | 1,691 | 3 % | 29,112 | 60 % | 48,454 | 44 % |
| Compostable Paper | 20,307 | 90 % | 2,271 | 10 % | Neg. | Neg. | 22,578 | 21 % |
| Other Paper | 13,556 | 69 % | 1,433 | 7 % | 4,726 | 24 % | 19,716 | 18 % |
| Total | 61,659 | 56 % | 6,407 | 6 % | 41,703 | 38 % | 109,769 | 100 % |

"Neg." negligible.

shelf life of these products, material losses during manufacturing, and imported goods arriving in paper packaging (cardboard, paperboard, and shipping bags) to the country.

Fig. 2 shows paper and cardboard waste landfilled in 2019 by type and state. These waste trends follow population trends to some extent. California, for example, is a populous state that generated and landfilled substantial waste locally. However, because of waste exports and imports, some states had less material than would be expected, and some had more. The largest MSW importers are Pennsylvania, Virginia, Michigan, and Ohio, which each receive more than 2 Mt of MSW per year (EREF, 2016; McCarthy, 2004). Georgia and South Carolina are also among the states with outsized masses of paper and cardboard waste in Fig. 2. The largest exporters are New York, New Jersey, Maryland, and Ohio, which each send out more than 1 Mt of MSW per year (EREF, 2016; McCarthy, 2004). Although data are not available for 2019, historical data from 2013 suggest the potential magnitude of MSW transported between states for disposal to be about 41 Mt (EREF, 2016). Applying our estimated proportions of MSW from paper and cardboard (26 %) to the 2013 value of 41 Mt, about 11 Mt of paper/cardboard waste may have been transported that year.

Fig. 3 illustrates the total amount of paper and cardboard waste disposed at landfills in 2019, and Figure S2 (SI Appendix) aggregates that information by county. Landfills are typically near population centers to keep transportation costs low, so populous areas landfill the most waste—often mirroring locations of highest waste generation. However, this is not always the case. For example, excess New York City waste ends up in landfills in central New York state, Pennsylvania, Virginia, and South Carolina (Kilgannon, 2019). Rural landfill tipping fees are typically lower than urban fees (WBJ, 2020), making it economically feasible to transport waste longer distances in some cases.

### *Market and energy value of paper and cardboard waste*

The estimated landfilled paper and cardboard waste in 2019 in the United States represents a resource lost to the economy (Table 2). Market prices for these materials vary depending on demand and cost of disposal, processing, and handling. Average market prices for recovered post-consumer paper and cardboard during 2019–2021 varied between \$35/t for compostable paper and \$135/t for high-grade/office paper (Composting News, 2023; Recycling Markets Inc., 2022). The estimated market value of these materials that were landfilled was \$4 billion in 2019.

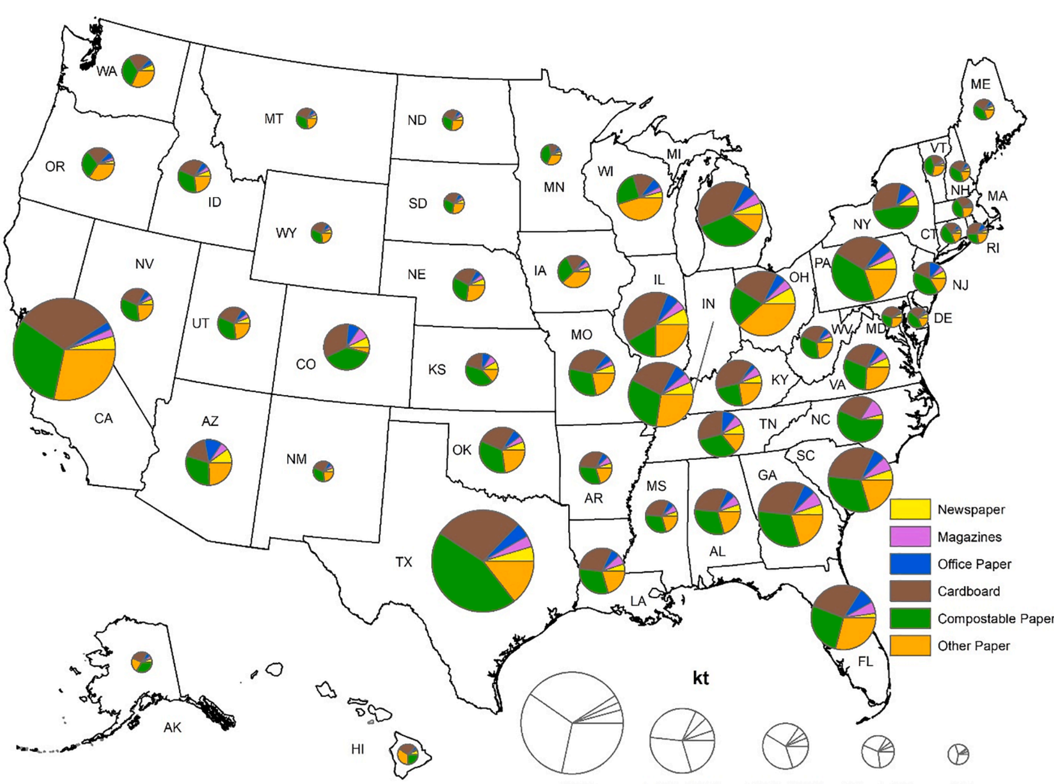


**Fig. 2.** Paper and cardboard waste landfilled in 2019 by type and state. The pie charts' sizes represent the quantity of landfilled material in kt. The material types are shown as a percentage of total landfilled material in different colors.

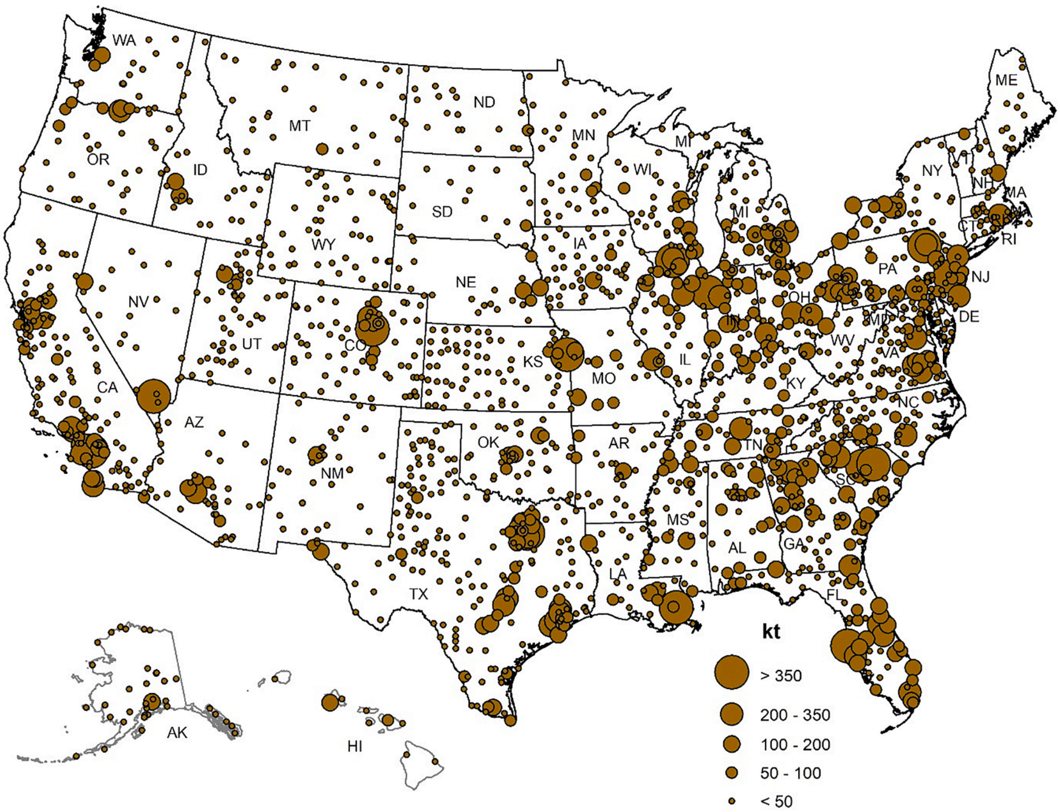


**Fig. 3.** Total paper and cardboard waste landfilled on site in 2019. The circles on the map depict landfill locations in the United States, and the size of the circles corresponds to the amount of paper and cardboard waste disposed at the landfills (kt).

**Table 2**
Market and energy value of landfilled U.S. paper and cardboard waste in 2019. Landfilled materials represented significant losses to the U.S. economy in 2019: an average of US$4 billion in market value, an average of 2 EJ as embodied energy, and about 1 EJ as an energy source.

| Waste Material | Landfilled Amount in 2019 (kt) | 2019–2021 Average Market Price (US$/t) | Average Market Value (US$MM) | Average Embodied Energy (MJ/kg) | Average Embodied Energy (PJ) | HHV (MJ/kg) | Energy Value (PJ) |
|---|---|---|---|---|---|---|---|
| Newspaper | 3,472 | $76 | $264 | – | | 17.6 | 61 |
| Magazines | 3,139 | $37 | $117 | – | – | 13.2 | 41 |
| Office Paper | 3,533 | $135 | $478 | – | – | 15.2 | 54 |
| Cardboard | 17,651 | $83 | $1,456 | – | – | 16.5 | 291 |
| Compostable Paper | 20,307 | $35 | $715 | – | – | 15.9 | 323 |
| Other Paper | 13,556 | $80 | $1,089 | – | – | 16.6 | 225 |
| Total | 61,659 | $74 | $4,119 | 35 | 2,158 | 15.8 | 995 |

"-" data not available.

In addition to lost economic value, embodied energy is lost when landfilling paper and cardboard. Embodied energy includes all the energy required to manufacture goods or services, from resource extraction/collection to final product. Given the 61.7 Mt of paper and cardboard landfilled in 2019, the average embodied energy in this landfilled material was 2,158 PJ. For context, this value equates to 9 % of primary energy consumption in the U.S. industrial sector in 2019 (24,000 PJ) (EIA, 2021).

The calorific value of cardboard and paper products—that is, the amount of heat released when the products are combusted—averages 15.8 MJ/kg on an HHV basis. The total calorific value in the cardboard and paper products landfilled in 2019 was 995 PJ, equivalent to about 4 % of U.S. primary industrial energy consumption that year (24,000 PJ), or about 3 % of primary transportation energy consumption (30,000 PJ) (EIA, 2021).

Landfilling waste not only represents a loss of the market and energy value of this resource, but it also costs communities in disposal fees. The average cost to landfill MSW in the United States was about $61/t in 2019 (EREF, 2020). Therefore, the estimated 61.7 Mt of paper and cardboard disposed of in 2019 represented almost $4 billion in disposal costs. Landfill tipping fees are highest in the Pacific states, at an average of $80/t, and lowest in the South-Central region (Arkansas, Louisiana, New Mexico, Oklahoma, and Texas) at an average of $45/t (EREF, 2020).

## Discussion

Our estimate for total paper and cardboard waste managed in the United States (110 Mt) in 2019 is larger than the estimate for 2018 by EPA (61 Mt) (EPA, 2020). The difference in reporting years (2019 versus 2018) is inconsequential owing to the small changes in EPA estimates from year to year. Rather, the difference stems from the different methods and data sources used to estimate landfilled paper and cardboard. We estimate the landfilled amount at 61.7 Mt using a bottom-up method based on onsite MSW tonnage data and geographically specific waste composition values. In contrast, EPA uses a top-down method to estimate the landfilled paper and cardboard at 15.6 Mt, based primarily on material balance data, along with other inputs such as product manufacturing data, product useful-life assumptions, and product composition data (Meyer et al., 2021). The amount of recycled paper and cardboard waste we report (42 Mt) is the same as the EPA's, and our estimate of combusted paper and cardboard differs from the EPA estimate by 3 Mt. As a result, our estimated recycling rate is 38 % (42 Mt recycled from 110 Mt of total paper and cardboard waste), compared with EPA's estimated recycling rate of 68 % (42 Mt recycled from 61 Mt of total paper and cardboard waste).

Other studies support our higher landfilled paper and cardboard waste value. EREF (2016) and Powell and Chertow (2019) found that the total mass of landfilled MSW is significantly greater than EPA estimates. Our estimate of 61.7 Mt for landfilled paper and cardboard in 2019 is similar to the estimate of 63 Mt in Powell and Chertow (2019). In addition, our estimate of landfilled and combusted carboard (19 Mt) falls within the range of 18–22 Mt reported by corrugated cardboard industry experts (Paben, 2022; Bloomberg L.P., 2022). The amount of landfilled material is important because it represents waste resources that are not being utilized thus available for applications able to recover their technical and economic value.

Expanded recycling is one way to better capture the waste resources value. In 2018, largely because of the negative impacts of contaminated single-stream waste collected for recycling, China banned the importation of many waste categories and set strict contamination standards; China accounted for 60 % of the global demand for recyclables and received a third of U.S. exports in 2016 (Anderson, 2019). For example, paper waste from the United States averages 25 % contamination (e.g., with food, grease, glass), but China's standard requires contamination of less than 1 %. Prices for recycling or otherwise disposing of these materials rose dramatically as a result of China's policy, which may stimulate strategies for supplying less-contaminated materials and handling the noncompliant waste domestically. These strategies could include returning to separated recycling streams (Dolesh, 2019), increasing consumer compliance with recycling guidelines, and establishing smaller, more localized MRFs to reduce material transportation costs (Anderson, 2019).

Prices for recycled paper have fluctuated in response to recent trends. Mixed paper prices dropped from an average of $71/t in 2017 to negative in 2019 owing to China's import ban (Recycling Markets Inc., 2022). Subsequently, more U.S. paper mills have been upgrading their facilities to use mixed paper, which is helping mixed paper prices recover (Quinn, 2021). Cardboard prices have also been affected by China's ban, dropping from about $157/t in 2017 to $40/t in 2019 (Recycling Markets Inc., 2022). Those prices were recovering in 2021 owing to cardboard box demand associated with flourishing e-commerce sales, exports to India and other Asian countries, and China's production of brown recycled pulp (Quinn, 2021).

Various opportunities also exist for recovering energy from otherwise-landfilled paper and cardboard. Combustion is the primary method for recovering energy from these wastes today. Based on our analysis, about 6 % of these wastes were combusted in the United States in 2019. The percentage of these wastes combusted for energy recovery has remained relatively constant over the past 20 years (EPA, 2022g), and fewer than 100 U.S. facilities currently recover energy from MSW combustion (WBJ, 2020; EIA, 2022; EPA, 2022f). MSW combustion is less common in the United States than in countries with denser populations and greater land limitations—such as Japan and some European countries—because U.S. landfill space is relatively inexpensive, and the space-saving aspect of combustion is not as valuable relative to the high upfront costs of combustion facilities. In addition, U.S. communities sometimes oppose incinerator construction owing to the polluting reputation these facilities developed during the years before emissions-control equipment was required by the Clean Air Act.

Although not done at significant scales in the United States today, fuels and chemicals could be produced from otherwise-landfilled paper and cardboard via various biochemical and thermochemical conversion processes. Paper, composed mostly of cellulose, may be well suited to biochemical processes that employ pretreatment and enzymatic hydrolysis to saccharify carbohydrates into sugars and then convert the sugars into fuels or chemicals (AFDC, 2022). Another potential biochemical option is arrested anaerobic digestion, which produces volatile fatty acids that can be catalytically upgraded to hydrocarbon drop-in fuels (Atasoy et al., 2018; Bhatt et al., 2020). Thermochemical options for paper and cardboard wastes include gasification and pyrolysis. Gasification involves thermally converting waste into a synthesis gas that can then be converted catalytically into hydrocarbon fuels (AFDC, 2022; Seo et al., 2018). Pyrolysis involves heating waste in the absence of oxygen, which produces synthesis gas, biochar, and a liquid oil that can be upgraded to hydrocarbon drop-in fuels (AFDC, 2022; Sipra et al., 2018; Zafar, 2021). Some of these conversion pathways are still under development and others have been demonstrated, but commercial applications are lacking for economic, technological, and market reasons. The world's first commercial-scale biorefinery using gasification technology to convert MSW into transportation fuels began operating near Reno, Nevada, USA, in May 2022, and two other plants are under development in Texas and Indiana (Fulcrum BioEnergy Inc., 2022). The performance of these projects will help determine the commercial viability of this advanced process using MSW (including paper and cardboard waste). If successful, the projects may pave the way for future waste-to-fuel facilities and, ultimately, reductions in landfilled waste.

Federal, state, and local policies and programs play an important role in waste-management efforts. Recently, extended producer responsibility (EPR) legislation for packaging—designed to involve producers in waste reduction—has received increased attention in the United States. Four states (Oregon, Maine, Colorado, and California) passed EPR laws in 2021 and 2022, and EPR-related bills received consideration in 19 additional states (Felton, 2022). The EPR legislation is designed to shift the cost burden of recycling programs from governments and taxpayers to packaging producers, improve and expand recycling infrastructure, increase recovery rates, and support new technology development for resource recovery and/or sustainable product manufacturing. Additional state and local policies and programs complement EPR legislation, such as container deposit laws (commonly known as bottle bills), pay-as-you-throw programs, and recycled content standards to advance waste recycling and recovery systems.

### *Uncertainty and validation of assumptions*

There are uncertainties associated with assumptions made in this study; however, we were able to partially validate these assumptions as described below. The key uncertainties are associated with 1) assuming average waste composition between 2015 and 2020 applies to 2019, 2) using regional or national averages to fill the gaps for states with no detailed composition data, and 3) applying state-level composition values to all locations in that state.

1) We compared older and more recent waste composition studies where available (District of Columbia, Florida, Illinois, Massachusetts, Wisconsin, Washington, and California) and observed negligible or small (within 1 %–2%) differences in most subcategories and the overall share of paper/cardboard waste (Table S1). In addition, we compared our estimated total mass of paper and cardboard waste against that reported by several states with recent estimates and observed negligible differences. Those states are California (2018), Ohio (2019), Wisconsin (2020), and Washington (2020).

2) For the most part, states with reported values within a region have similar waste composition (Table S2). In addition, we compared total paper and cardboard waste as a percentage of total MSW when such state-level data were available but more detailed state-level data (percentages for newspapers, magazines, etc.) were not available. In all cases, our regional estimate of paper and cardboard waste as a percentage of MSW was within 5 % of the corresponding state-level

estimate. This comparison was conducted for District of Columbia (our regional estimate for paper and cardboard from total MSW in 2019 is about 22.1 % vs 27.5 % reported in 2021), Montana (22.3 % vs 25.9 % reported in 2018), Nevada (22.3 % vs 23.7 reported in 2018 for Washoe County), New Mexico (22.3 % vs 27.4 % reported in 2015), and South Carolina (24.8 % vs 23.4 % reported in 2013).

3) We compared waste composition studies when more than one was available for a state and observed negligible or small (within 1 %-2%) difference for most paper and cardboard waste categories and up to a 5 % difference for a few categories. This comparison was conducted for Arizona, Florida, Kansas, Minnesota, Tennessee, and Texas (Table S1). This observation helps justify extrapolating waste composition values across landfill locations in a given state. In addition, as noted above, for the most part, states (and thereby locations within a state) with reported values within a region have similar waste composition and differences could be minor or up to 5 %.

More broadly, our study is meant to be a starting point for analyzing the availability of paper and cardboard waste resources in the United States. Stakeholders who are considering investments or other decisions related to these resources should validate the results on-site. Similarly, although we include high-level estimates of the market and energy values of paper and cardboard waste along with our resource assessment, additional studies could characterize the economic, social, and environmental sustainability of various waste-management options.

## Conclusions

The aim of this study is to clarify *where* and *how much* paper and cardboard waste is available in the United States to inform decision making and technology deployment. We quantify and map landfilled paper and cardboard waste, and we estimate the market and energy value of these materials. Our study indicates that a large quantity of paper and cardboard waste is landfilled in the United States—more than is estimated in frequently cited sources—representing significant market and energy losses to the U.S. economy in 2019. In contrast to previous studies, we also provide a geographic analysis that quantifies waste types, amounts, and locations with high resolution, showing the correlation between population and landfilling.

Our results are meant to inform efforts to implement beneficial waste-management strategies by policy makers, researchers, businesses, and communities across the United States. In addition to the lost energy and economic value of paper and cardboard, landfilling these materials contributes to methane emissions, waste-disposal fees, deforestation, and local siting and environmental issues. Fortunately, paper and cardboard are amenable to improved management strategies—including source reduction and reuse, recycling and composting, and energy recovery—that can mitigate the drawbacks of landfilling.

## CRediT authorship contribution statement

**Anelia Milbrandt:** Project administration, Supervision, Methodology, Validation, Writing – original draft. **Jarett Zuboy:** Validation, Writing – original draft. **Kamyria Coney:** Data curation, Formal analysis. **Alex Badgett:** Data curation, Formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wmb.2023.12.002.

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