Making up for Lost Time (and Space): Quantifying Non-hazardous Industrial Waste Generation in the U.S.

Jonathan S. Krones,[1*] Marian R. Chertow[2], Xiao Li[2]

[1]*Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA 02467*
[2]*Center for Industrial Ecology, Yale School of the Environment, New Haven, CT 06511*
**Corresponding author: jonathan.krones@bc.edu, 301-788-4206*

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Executive Summary

Non-hazardous industrial waste (NHIW) is among the most significant unexamined waste streams in the country. While other waste categories are the subjects of regular study and accounting by the EPA, the NHIW stream has not been officially quantified since the mid-1980s. In this report, we present the first comprehensive and repeatable account of NHIW tonnage and composition in the United States in over three decades.

Using a combination of four independent methods, we estimate that NHIW generation totaled between 244-264 million metric tons (Tg) in 2015. The single largest component of this waste stream is an estimated 114 Tg of waste phosphogypsum generated in the manufacture of fertilizer. Wastes and byproducts from basic chemicals manufacturing totaled an additional 16–20 Tg. Food, beverage, and tobacco manufacturing was found to generate 44–46 Tg of NHIW, most of which are wastes from fruit and vegetable processing (24 Tg) and meat preparation and processing (13 Tg). Primary metals production, including foundries, generated 34–37 Tg of NHIW in total: 13 Tg of iron and steel slag, 7.8 Tg of ferrous and nonferrous foundry sands, and 4.9 Tg of red mud from alumina production. Paper mills and printing generated 13 Tg, mainly wastes from pulp, paper, and paperboard mills: wastewater sludge (4.5 Tg), ash (2.2 Tg), and other wastes (4.5 Tg). Nonmetallic minerals processing is responsible for an additional 9.4–15 Tg, a large fraction of which is cement kiln dust (4.7 Tg). The remaining industry sectors included in the analysis—petroleum and coal products; wood products; and textiles, apparel, and leather products—generated 6.4–7.4, 1.3–1.6, and 0.5–0.7 Tg, respectively. The complete account of results is presented in Table ES-1.

The four estimation methods that contribute to the construction of this account are: 1) historical forecasting using empirical results from past studies; 2) spatial up-scaling using data from the Pennsylvania Residual Waste program; 3) material balance using publicly available data on industry inputs and outputs; and 4) comparison with European waste accounts. Each of these estimation methods would be inadequate on its own, but when taken together, we find that they yield an account that is robust and of sufficient detail to be useful for environmental and industrial policy.

The scope of the study includes all materials generated as wastes, irrespective of their disposition, by primary materials processing and basic manufacturing activities in the United States, as identified by the North American Industry Classification System (NAICS). More advanced manufacturing and assembly activities (NAICS 333-339) are excluded. Other exclusions include materials processing activities included as part of the mining industry as well as byproducts with long-standing and economically mature beneficial uses, such as wood waste from sawmills. Other beneficially used wastes, like food processing scraps and iron and steel slag, are included in the account because of the potential for environmentally preferable uses over current practice.

The results from this study suggest that the quantity of NHIW generated in the United States is roughly equivalent with that of MSW. The methodology presented here is based on publicly available data and official statistical products. As such, it is intended to be repeated so that the account can be maintained and regularly updated. Such an account would be invaluable for the cultivation of eco-industrial policies like industrial symbiosis and other circular economy strategies.

Table ES-1. *Account of non-hazardous industrial waste generation in the United States, 2015*

NAICS Code	Industry sector/Waste material	NHIW (Tg)		% of Total
		Low	***High***	
311-312	***Food, Beverage & Tobacco—Total***	**43.78**	**45.83**	**18%**
3111	Animal Food Manufacturing	0.31	0.75	
3112	Grain and Oilseed Milling	0.8		
3113	Sugar and Confectionery Product Manufacturing	2.32		
3114	Fruit and Vegetable Preserving and Specialty Food Mfg	23.67		
3115	Dairy Product Manufacturing	0.92	1.6	
3116	Animal Slaughtering and Processing	12.85	12.89	
3117	Seafood Product Preparation and Packaging	0.74		
3118	Bakeries and Tortilla Manufacturing	0.61	0.87	
3119	Other Food Manufacturing	0.53	0.96	
3121	Beverage Manufacturing	0.84	0.98	
3122	Tobacco Manufacturing	0.19	0.24	
313-316	***Textiles, Apparel & Leather—Total***	**0.49**	**0.65**	**0.2%**
313-315	Textiles, Textile Product Mills, Apparel Manufacturing			
	Textile wastes	0.34	0.37	
	Other wastes	0.04	0.11	
316	Leather and leather products	0.11	0.17	
321	***Wood Products—Total***	**1.33**	**1.56**	**0.6%**
	Bark & wood wastes	1.03		
	Wood ash	0.16	0.32	
	Other wastes	0.14	0.21	
322-323	***Paper & Printing—Total***	***12.93***		**5.1%**
3221	Pulp, Paper, and Paperboard Mills			
	Wastewater residuals/sludges	4.49		
	Ash	2.23		
	Miscellaneous residues	4.5		
3222	Converted Paper Products	0.69		
323	Printing	1.02		

__Table ES-1 (Cont.).__ Account of non-hazardous industrial waste generation in the United States, 2015

NAICS Code	Industry sector/Waste material	NHIW (Tg)		% of Total
		Low	*High*	
324	***Petroleum & Coal Products—Total***	**6.4**	**7.4**	**2.7%**
32411	Petroleum refineries			
	Spent caustic	1.04	1.46	
	Spent catalyst	0.21	0.32	
	Contaminated soil	0.55	0.7	
	Sludges	0.77	1.06	
	Off-spec coke and fines	0.23		
	Ash	0.13		
	Other wastes	0.10		
32412	Asphalt paving, roofing, and saturated materials			
	Asphalt waste	0.39		
	Baghouse dust	2.49		
32419	Other petroleum and coal products			
	Sludge	*0.32*		
	Ash	*0.15*		
	Contaminated soil	*0.05*		
325-326	***Chemicals, Plastics & Rubber—Total***	**135.3**	**143.9**	**55%**
3251	Basic chemicals	15.73	20.1	
3252	Resins, etc.	2.2	2.84	
3253	Pesticide, fertilizer, and other agricultural chemicals			
	Phosphogypsum	113.7		
	Other wastes	1.01	2.49	
3254	Pharmaceuticals and medicine	0.64		
3255	Paint, coating, and adhesives	0.13	0.15	
3256	Soap, cleaning compound, and toilet preparation	0.48	0.56	
3259	Other chemical product and preparation	0.26	0.67	
3261	Plastics products	0.84	1.87	
3262	Rubber products	0.31	0.87	
327	***Nonmetallic Minerals—Total***	**9.4**	**14.5**	**4.7%**
3271	Clay products and refractories	0.1	0.57	
3272	Glass and glass products	1.1	3.15	
3273	Cement & Concrete			
	Cement kiln dust	4.68		
3274	Lime and gypsum products			
	Lime wastes	1.84		
	Gypsum wastes	1.47		
3279	Other nonmetallic mineral products	0.21	2.78	

Table ES-1 (Cont.). *Account of non-hazardous industrial waste generation in the United States, 2015*

NAICS Code	**Industry sector/Waste material**	**NHIW (Tg)**		**% of Total**
		Low	***High***	
331-332	***Primary Metal, Foundries & Fabricated Metal—Total***	**34.1**	**37.3**	**14%**
3311-3312	Iron & Steel			
	Blast furnace slag	5.74	5.98	
	Blast furnace dust & sludge	0.52		
	Steelmaking slag	7.14		
	Steelmaking dust & sludge	1.35		
	Mill scale	2.88		
	Rolling sludge	0.78		
	Grinding swarf	0.51		
	Other dusts	0.1		
3313	Alumina and Aluminum			
	Red mud	4.94		
	Skims and discarded drosses	0.21		
	Sludge	0.03		
	Secondary aluminum baghouse fines	0.11		
	Other wastes	0.25		
3314	Nonferrous Metals			
	Copper smelter slag & slag tailings	2.03		
	Converter and anode furnace slag	0.19		
	Calcium sulfate WWTP sludge	0.07		
	Zinc slag	0.08		
	Other wastes	0.05		
3315	Foundries			
	Ferrous foundry sand and other waste	4.49		
	Non-ferrous foundry sand and other waste	3.31		
332	Fabricated metal	*1.13*	*2.3*	
	TOTAL	**243.8**	**264.1**	**100%**

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1 Introduction

Solid waste is generated by nearly all activities in the economy, from mining and agriculture to materials processing, manufacturing, energy production, shipping, retail, consumption, and even waste treatment itself. Despite its ubiquity and environmental importance, knowledge about the quantity and composition of solid waste is notoriously inconsistent. In the United States, official waste statistics published annually by the EPA are limited to consumption wastes: municipal solid waste and related categories [1]. A few additional waste categories governed by specific regulations, such as industrial hazardous waste [2] and radioactive waste from nuclear power plants [3], are also closely monitored and regularly quantified. The rest of the world of waste goes largely unexamined and uncounted.

The lack of reliable, comprehensive, and timely knowledge about the quantity and composition of solid waste at the national scale is problematic. Industrial ecologists and other scholars have long argued the need for national material flow accounting to guide and inform environmental policy, analogous to the system of financial accounts that underpins economic policy [4]. As an essential material flow, solid waste is not exempt from this prescription. Efforts to characterize, to say nothing of reducing, the myriad environmental, social, and economic impacts of solid waste and its management are hamstrung by a lack of data. What activities generate the most waste? What wastes are the most environmentally impactful? How is waste generation, transport, and disposal distributed geographically? What effect does policy X or technology Y have on the waste stream and its impacts? As long as solid waste accounts remain inconsistent, incomplete, and out-of-date, these questions and others will remain fundamentally unanswerable and a world in which wastes are genuinely seen as resources rather than burdens will remain out of reach.

Potentially the most problematic waste stream vis-à-vis the disjuncture between the lack of data and the potential benefit that may come from maintaining regular accounts is non-hazardous industrial waste (NHIW). NHIW is a broad category of industrial byproducts and process residuals that "includes combustion residues, such as coal ash and scrubber sludges, foundry sand, inorganic chemical wastes, pulp and paper wastes, fuel-contaminated soil, asbestos-containing wastes, nonhazardous waste oil, industrial equipment and scrap, iron and steel slag, and many other types of waste" [5, pp. 10-11]. NHIW is most accurately defined in the negative, that is, industrial production residuals that are *not* regulated as hazardous under RCRA Subtitle C. Despite its legal definition, in practice NHIW is not necessarily non-hazardous. According to Dernbach, "some of this waste is close to legal limits for hazardous waste or would be considered legally hazardous if it were not excluded under RCRA (e.g. fuel-contaminated soil)" [5, p. 11]. Furthermore, NHIW is often stored or disposed in surface impoundments, which, when they fail, can have potentially calamitous outcomes [6]. If the impoundments are poorly designed or controlled, the waste can also seep out, contaminating surface- and groundwater.

On a positive note, NHIW includes many waste materials that have been identified and used for industrial symbiosis and beneficial reuse [7]. Repurposing these wastes can yield double environmental dividends. It avoids the impacts associated with disposal and, by substituting for raw materials, the impacts associated with raw materials extraction. The strategy is not environmentally faultless, as it may require intermediate processing (upgrading waste materials to raw material quality and controlling hazardous substances), as well as other ancillary activities like transportation. But on balance, at least theoretically, the practice is environmentally preferable to disposal [8-9]. While many NHIW materials are already widely beneficially reused, maintaining robust accounts of NHIW enables the strategic (i.e. not ad hoc) deployment of industrial ecology policies and practices, enabling wastes go to their highest and best uses rather than simply the most convenient [10].

Quantified estimates of NHIW generation are not completely absent from official publications. The EPA's *Guide to Industrial Waste Management*, a handbook for "the management of land-disposed, non-hazardous industrial wastes" updated most recently in 2016, opens with the statement, "each year, approximately 7.6 billion tons of industrial solid waste are generated and disposed of at a broad spectrum of American industrial facilities" [11, p. vii]. Although uncited in that publication, the figure "7.6 billion tons" originates in a 1988 EPA Report to Congress on *Solid Waste Disposal in the United States* [12] and even then was a misleading figure. A close look at that report reveals that far from being an estimate of NHIW generated each year, it is instead an estimate of the mass of dilute industrial wastewater disposed onsite in surface impoundments in 1985. Interestingly, this was not the only estimate of NHIW included in that report. As part of the same Congressionally-mandated review of solid waste regulations that led to the 7.6 billion tons figure, an EPA contractor, SAIC, also conducted an exhaustive literature review, concluding that 22 major manufacturing sectors in the U.S. generated an estimated 392 million metric tons of NHIW in 1985 [13].

These two figures—392 million metric tons and 7.6 billion (short) tons (6.9 billion metric tons) in 1985—turn out to be the most recent official estimates of NHIW in the U.S. Soon after publication, the gulf between the two values was quickly (if insufficiently) explained as the difference between dry and wet weight [14]. Nevertheless, the much larger, more spectacular number quickly became the only recognized estimate. In 1992, the Congressional Office of Technology Assessment utilized that figure—after trimming a billion tons or so to correct purported double counting—in their review of production waste generation in the United States [15]. Over the following decades, the number would be circulated and reproduced in various forms not only by the EPA but also by state policymakers [5], activists [16-18], and academics [19-21].

While the origins and implications of the continued use of this misleading historical quantity are interesting (and the subject of other papers, out of scope here), for the sake of this research, the number is irrelevant. Any claims made today based on a thirty-five-year-old number, however robust it may or may not have been at the time, must be dismissed out of hand. So much has changed over the past three decades to American industry and the material basis of the economy that, while some of the data underlying either or both of the 1985 estimates may still well be accurate, that accuracy cannot simply be assumed. Thankfully, researchers have stepped in where official statistics have lapsed. Mainly throughout the 1990s and early 2000s, efforts by industrial ecologists and allied scholars to establish comprehensive, national materials accounts have yielded a handful of estimates of NHIW generation that, while not able to replace 7.6 billion tons in common understanding of the topic, do set an order of magnitude on the actual value and point the way towards a method for reliable accounting.

Starting in the early 1990s, Robert and Leslie Ayres began developing material flow models of U.S. industry sectors in order to estimate “aggregate waste generation” by quantifying lost mass. Put simply, they used published statistics on industrial sector inputs and outputs, combined with insights about the transformation processes at work in those sectors, to determine the quantity and type of unaccounted outputs: emissions, moisture loss, and solid waste. Their research produced two estimates of NHIW: 146 million metric tons in 1988 [22] and 236 million metric tons in 1993 [23]. Other, related efforts in material flow modeling of the U.S. economy produced two more estimates: 136 million metric tons in 1990 [24] and 430 million metric tons in 1996 [25]. Although all four of these studies were built on the same general theoretical ground, they varied in scope and in detail, which makes comparing them to one another a fraught exercise. Even the two Ayres estimates should not suggest growth in NHIW generation from 1988 to 1993 since the models improved from one study to the next.

A subsequent estimate of NHIW generation departed from the material balance method, instead relying on data collected by the Pennsylvania Department of Environmental Protection under their Residual Waste Program. In 2009, a team of Yale University graduate students derived waste intensity factors from this data (kg/$) and applied them to national-scale industrial revenues, resulting in an estimate of 385 million metric tons of NHIW generated in 2002 [26].

Finally, the dearth of official NHIW statistics in the U.S. is not shared by many of its OECD peers. In fact, EU directives require all member states to report detailed waste accounts every other year. This data has been used to develop industrial waste generation profiles and waste intensity factors, although these have not been applied to the U.S. [27].

Three conclusions can be drawn from this brief literature review (more details can be found in [28]). First, all five estimates of NHIW generation in the U.S. that have been released since official recordkeeping ceased in the late 1980s are on the order of a few hundred million metric tons. This is far from the billion tons reported to Congress, but, interestingly, close to the

1985 SAIC figure: 392 million metric tons. Second, although these new estimates exist, they are not necessarily reliable (and the most recent still points to a year nearly twenty years past). Therefore, the need for new, robust waste accounts and accounting methods remains. Third, the estimates show that there exist both data and methods to develop new waste accounts.

In this research project, we construct the first reliable, detailed account of NHIW generation in the U.S. in over thirty years, focusing on the year 2015. Based on prior work, 15 industry sectors were selected for analysis, grouped into eight sectoral reports, as described in Table 1-1 [12-13]. We use a combination of multiple estimation methods to make best use of available data and to partially control for substantial data gaps and methodological uncertainties. We explain the estimation methodology at the end of the report. Results and discussion of the research and analysis is divided up into the next eight chapters of this report.

Table 1-1. *Industry sectors and groupings analyzed in this report*

Chapter	NAICS code	Industry sector description
2	311	Food Manufacturing
	312	Beverage and Tobacco Product Manufacturing
3	313	Textile Mills
	314	Textile Product Mills
	315	Apparel Manufacturing
	316	Leather and Allied Product Manufacturing
4	321	Wood Product Manufacturing
5	323	Paper Manufacturing
	323	Printing and Related Support Activities
6	324	Petroleum and Coal Products Manufacturing
7	325	Chemical Manufacturing
	326	Plastics and Rubber Products Manufacturing
8	327	Nonmetallic Mineral Product Manufacturing
9	331	Primary Metal Manufacturing
	332	Fabricated Metal Product Manufacturing

2 Results and Discussion

2.1 Food, Beverage & Tobacco Product Manufacturing (NAICS 311-312)

2.1.1 Summary

The food, beverage, and tobacco products sectors are estimated to have generated a total of 43.78 – 45.83 Tg of NHIW in 2015. The largest contributors to this total are fruit and vegetable processing wastes (23.67 Tg) and meat processing wastes (12.85 – 12.89 Tg), both estimates of which likely include large quantities of beneficially used materials and some moisture loss, suggesting a markedly smaller amount of material that must be actively managed as waste.

2.1.2 Industry structure

NAICS 311 and 312 include the firms that convert agricultural and animal products into food, beverage, and tobacco products for intermediate and final consumption. The 5-digit NAICS structure of these sectors is shown in Table 2.1-1.

Table 2.1-1. *NAICS 2017 structure of the food, beverage & tobacco product manufacturing sectors [1]*

311 Food Manufacturing	3118 Bakeries and Tortillas
3111 Animal Food*	31181 Bread and Bakery Products
3112 Grain and Oilseed Milling	31182 Cookie, Cracker, and Pasta
31121 Flour Milling and Malt	31183 Tortillas
31122 Starch and Vegetable Fats and Oils	3119 Other Foods
31123 Breakfast Cereal	31191 Snack Food
3113 Sugar and Confectionery Products	31192 Coffee and Tea
31131 Sugar	31193 Flavoring Syrup and Concentrate
31134 Non-chocolate Confectioneries	31194 Seasoning and Dressing
31135 Chocolate and Confectioneries	31199 All Other Food
3114 Fruit and Vegetable Preserving and Specialty Foods	
31141 Frozen Food	**312 Beverage and Tobacco Product Manufacturing**
31142 Fruit and Vegetable Canning, Pickling, and Drying	3121 Beverages
3115 Dairy Products	31211 Soft Drink and Ice
31151 Dairy Products (except Frozen)	31212 Breweries
31152 Ice Cream and Frozen Dessert	31213 Wineries
3116 Animal Slaughtering and Processing*	31214 Distilleries
3117 Seafood Product Preparation and Packaging*	3122 Tobacco*

* These sectors have a single 5-digit subsector

2.1.3 Solid wastes from NAICS 311-312

The solid waste generated by the food, beverage, and tobacco product industries is highly diverse, with each food product category having its own characteristic waste flows. Nearly all of these wastes are comprised of the inedible or unusable fraction of the agricultural products that are used as raw materials and as such are primarily organic in nature. Three main issues complicate NHIW accounting for this sector. First, many of the residuals from food processing are managed as wastewaters, so what may originally be generated as a solid is sometimes only recovered in wastewater treatment plant sludge. Second, because of the often-close relationship between the agriculture and food processing industries, allocating a waste between the two can prove challenging, particularly if packing, milling, canning, cleaning, slaughtering, etc. is co-located with primary production, i.e. cultivation. Finally, there is a long tradition of beneficial use of food processing residuals as animal feed, fertilizer, or other agricultural application. According to the accounting standard utilized here, all residuals, even those managed as by-products, should be enumerated, but in many cases solid wastes may be underreported in the raw data if they are not managed or even conceptualized as wastes onsite.

Tobacco manufacturing wastes are an exception. Since the 1950s, tobacco process wastes have been reconstituted as "tobacco sheet" and included as filler in cigarettes. Although primary tobacco leaf processing has a roughly 85% yield, the bulk of the lost material is recovered internally, and as such is not counted as a waste [2].

The size and complexity of the food, beverage, and tobacco industries makes a comprehensive listing of all possible industrial solid wastes impractical. As a representative list, Table 2.1-2 includes the wastes from these industries included in the European Waste Catalog [3].

Table 2.1-2. *Food, beverage & tobacco industry wastes as listed in the European Waste Catalog [3]*

Activity	**Waste category**
Preparation and processing of meat, fish and other foods of animal origin	- sludges from washing and cleaning - animal-tissue waste - materials unsuitable for consumption or processing - sludges from on-site effluent treatment
Fruit, vegetables, cereals, edible oils, cocoa, coffee, tea and tobacco preparation and processing; conserve production; yeast and yeast extract production, molasses preparation and fermentation	- sludges from washing, cleaning, peeling, centrifuging and separation - wastes from preserving agents - wastes from solvent extraction - materials unsuitable for consumption or processing - sludges from on-site effluent treatment
Sugar processing	- soil from cleaning and washing beets - off-specification calcium carbonate - sludges from on-site effluent treatment
Dairy products industry	- materials unsuitable for consumption or processing - sludges from on-site effluent treatment
Baking and confectionery industry	- materials unsuitable for consumption or processing - wastes from preserving agents - sludges from on-site effluent treatment
Production of alcoholic and non-alcoholic beverages (except coffee, tea and cocoa)	- wastes from washing, cleaning, mechanical reduction of raw materials - wastes from spirits distillation - wastes from chemical treatment - materials unsuitable for consumption or processing - sludges from on-site effluent treatment

2.1.4 NHIW estimation

2.1.4.1 Historical forecasting

The most recent in-depth, economy-wide assessment of NHIW from the food & beverage sectors (excluding tobacco) is the 1985 SAIC report to the EPA [4]. For these sectors, SAIC relied heavily on a 1980 EPA report prepared by ERCO, Inc. [5], which in turn utilized data from an even earlier report by the National Canners Association (also for the EPA) [6]. The most recent data on waste from the American tobacco products industry originate in a 1970 study by the Bureau of Solid Waste Management [7].

Based on this array of data, the historical forecasting method suggests that these sectors generated 11 Tg of NHIW in 2015, as shown in Table 2.1-3. The largest fractions are unusable food residuals from fruit and vegetable processing (20% of the total), soil and lime mud from sugar manufacturing (14% each), and paunch manure from meat processing (15%).

Weaknesses of this account are numerous. First, some of the data are a half-century old and industry practices and composition have changed considerably since then. Second, it is unclear if the historical account was comprehensive to start with. For example, the meat processing category only included wastes from cattle slaughter, excluding wastes from all other subsectors. Finally, because of the transition of industry statistics from SIC to NAICS in 1997, economic data needed for the extrapolation is only available at a high level of aggregation, masking any changes that occurred at the subsector-level.

Table 2.1-3. *NHIW from the food, beverage & tobacco industries estimated by historical forecasting, 2015*

Activity	Waste	Original (Tg)	Base year	2015 (Tg)	Source
Meat processing	Paunch manure	1.04	1976	1.63	[5], p. 7-44
	Sludge	0.32	1976	0.50	[5], p. 7-4
Dairy	Liquid whey	0.45	1976	0.67	[5], p. 7-4
Fruit & Vegetable processing	Unusable food residuals	1.50	1968	2.22	[6], p. 169
	Non-food waste	0.37	1968	0.55	[6], p. 169
Seafood	Unusable food residuals	0.19	1968	0.75	[6], p. 169
Sugar manufacturing	Soil & trash	1.34	1976	1.49	[5], p. 7-51
	Lime mud	1.34	1976	1.49	[5], p. 7-51
	Excess bagasse	0.30	1976	0.33	[5], p. 7-52
	Filter cake	0.57	1976	0.63	[5], p. 7-52
Grain milling	Sludge	0.07	1976	0.10	[5], p. 7-4
Beverage	Liquor stillage	0.09	1976	0.16	[5], p. 7-4
	Wine wastes	0.03	1976	0.05	[4], p. 4-78
Fat/oil	Filter cake	0.06	1984	0.13	[4], p. 4-76
	Fat/oil sludge	0.01	1984	0.02	[4], p. 4-76
	Plant trash	0.01	1984	0.03	[4], p. 4-77
Tobacco	Wastes	0.29	1995	0.22	[7], p. 78
TOTAL				**10.96**	

A second historical forecast based on the 1983 PACE survey data suggests a remarkably similar 10.7 Tg of NHIW (see Table 2.1-4). The contribution of each sector is roughly similar to the SAIC-based forecast in Table 2.1-3, with a few notable differences. Fruit and vegetable wastes remain the largest contributor, at 23% of the total. Sugarcane and sugar beet processing also contribute roughly 22% in this estimate. The 590,000 Mg of NHIW from grain and oilseed milling (7% of total) is notably higher than the SAIC estimate due to PACE's accounting for particulate air pollution control residues from that sector, a waste material that would be expected from milling processes. Meat processing wastes from the PACE estimate are somewhat lower than the SAIC estimate, likely due to the fact that most of those wastes are beneficially used or even considered as byproducts in the factory. In addition to putting waste numbers to the sectors that were absent in the earlier account (like pet food, bakeries, and "other"), the PACE data also provides an estimate for brewery waste and a confirmatory estimate of NHIW from tobacco product manufacturing.

Table 2.1-4. *NHIW from the food, beverage & tobacco industries estimated from 1983 PACE, 2015 [8]*

Sector	Subsector	1983 (Tg)	2015 (Tg)
Animal food manufacturing		0.18	0.31
Grain and oilseed milling		0.59	0.80
Sugar and confectionery product manufacturing	Cane sugar	2.20	1.38
	Beet sugar	0.76	0.84
	Other confectionery products	0.09	0.10
Fruit and vegetable	Canned	1.15	1.47
	Dried	0.09	0.19
	Frozen	0.63	0.78
Dairy product manufacturing		0.66	0.92
Animal slaughtering and processing	Red meat	0.42	0.55
	Poultry	0.13	0.35
	Eggs	0.04	0.10
	Fats & oils	0.01	0.01
Seafood products		0.05	0.05
Bakeries		0.40	0.61
Other food manufacturing		0.42	0.96
Beverage manufacturing	Malt beverages	0.49	0.62
	Wine & liquor	0.05	0.14
	Soft drinks & other beverages	0.17	0.23
Tobacco manufacturing		0.20	0.24
TOTAL			**10.66**

In recent years, the Food Waste Reduction Alliance has conducted regular surveys of food manufacturers to gauge disposal trends in the industry. The 2015 results have been published, but with no detailed information about waste composition and a limited response rate, their results are not useful for this accounting exercise [9].

2.1.4.2 Spatial up-scaling

Averaging the data reported in 2014 and 2016 to the Pennsylvania Residual Waste (PARW) program, 602 facilities in the Pennsylvania food, beverage, and tobacco product industries generated 838 Gg of NHIW in 2015 (excluding dilute wastewater). That year, Pennsylvania firms were responsible for 4.3% of the nationwide food manufacturing shipments and 3.7% of nationwide beverage and tobacco product manufacturing shipments. Within these sectors, sugar and confectionary products is notably overrepresented in the state, with 13.7% of national shipments, while grain & oilseed milling and tobacco manufacturing are underrepresented (1.0% and 1.6%, respectively). Using 5-digit scaling factors where they are available and 4-digit scaling factors elsewhere, the PARW data suggests that national NHIW generation in these sectors totaled 20.72 Tg in 2015 (Table 2.1-5). Dairy products manufacturing contributed the most to this total, with beverage manufacturing, fruit and vegetable freezing, canning, and processing third, and meat product manufacturing fourth.

By this up-scaling estimate, food waste makes up the largest fraction of the total generated by these sectors, 9.7 Tg, 81% of which comes from the dairy product manufacturing sector (Table 2.1-6). Wastewater treatment plant sludge and food processing sludge make up another 4.5 and 4.1 Tg, respectively. The beverage industry contributes 75% of the total WWTP sludge, while the sources of food processing sludge are well distributed across fruit & vegetable processing, dairy products, animal processing, animal food manufacturing, and bakeries. The balance of the waste account is comprised of agricultural wastes, filter media/aids—both of which are dominated by the beverage industry—and plant trash and other wastes.

Table 2.1-5. *NHIW by NAICS sector estimated by up-scaling from PARW data, 2015*

NAICS Code	Description	PA Waste (Gg)	US Waste (Tg)
3111	Animal food	55.0	0.86
3112	Grain & oilseed milling	0.8	0.07
3113	Sugar & confectionery product	36.9	0.25
3114	Fruit & vegetable product	75.6	2.35
3115	Dairy product	324.1	9.68
3116	Meat product	38.7	1.19
3118	Bakeries & tortilla	63.1	0.98
3119	Other food	43.9	0.64
3121	Beverage	194.7	4.39
3122	Tobacco	5.1	0.31
311-312	**TOTAL**	**837.8**	**20.72**

Table 2.1-6. *NHIW from the food, beverage & tobacco industries estimated by up-scaling from PARW data, 2015*

Waste Type	**Source**	**US Waste (Tg)**	**% of total**
Food Waste	Dairy	7.80	37.6%
	Fruit & Vegetable	0.57	2.8%
	Bakery	0.54	2.6%
	Beverage	0.32	1.6%
	Confection	0.21	1.0%
	Other	0.23	1.1%
	Total Food Waste	*9.68*	*46.7%*
Water & Wastewater Treatment Sludge	Beverage	3.38	16.3%
	Dairy	0.63	3.0%
	Tobacco	0.19	0.9%
	Animal food	0.15	0.7%
	Other	0.17	0.8%
	Total WWTP Sludge	*4.52*	*21.8%*
Food Processing Sludge	Fruit & Vegetable	1.13	5.4%
	Dairy	0.97	4.7%
	Meat	0.75	3.6%
	Animal food	0.45	2.2%
	Bakery	0.33	1.6%
	Other	0.43	2.1%
	Total Food Proc. Sludge	*4.06*	*19.6%*
Plant Trash		1.66	8.0%
Agricultural Wastes		0.45	2.2%
Filter Media/Aids		0.14	0.7%
Other Waste		0.21	1.0%
TOTAL		**20.72**	**100.0%**

The PARW data is internally inconsistent in its waste categories. What one firm may report as food waste another may report as food processing sludge or even a process wastewater (which would then be excluded from this analysis). Reported medium of disposal is also inconsistent. The data utilized here exclude waste volumes reported in four specific wastewater codes, but it is possible that what one reporter designates as liquid another may report as a sludge. This is especially likely in the case of dairy products, where the bulk of the waste is reported as liquid.

2.1.4.3 Material balance

The standard approach of balancing raw material inputs with intermediate and finished product outputs for the food & beverage industries (excluding tobacco) is enabled by the USDA Economic Research Service's *Food Availability Data System* [10], which includes information on "loss-adjusted food availability" for seven food categories: dairy; fats & oils; fruit; grains; meat, poultry, fish, eggs & nuts; sugar & sweeteners; and vegetables. This database includes per capita primary weight and retail weight for more than 200 distinct food items from 1970 to the present. Taking the difference between the two values and multiplying the result by the population (320.6 million people in 2015) yields an estimate of lost mass in food production that year. This is not strictly equivalent to solid waste, but like all material balance estimates, it is a physical upper bound on food processing residuals (while not commenting on any non-food wastes like filter materials or packaging.

This material balance suggests there was an estimated 37 Tg of lost mass in the food processing industry in 2015 (Table 2.1-7). Nearly 46% of this quantity comes from the processing, canning, and freezing of vegetables. Another 35% comes from meat processing, split between red meat and poultry, 18% is from fruit processing (mainly juicing), and a small amount from the dairy products and fats & oils sectors. This method reveals no losses from fish, nuts, grains, and sugar.

Table 2.1-7. *Lost mass in food processing, calculated using the USDA's* Food Availability Data System*, 2015 [10]*

Sector	Subsector	Loss (lbs/cap)	US Waste (Tg)
Meat	Red meat	43.09	6.27
	Poultry	44.71	6.50
	Total meat	*87.80*	*12.77*
Fruit	Fresh	6.69	0.97
	Canned	3.01	0.44
	Frozen	0.38	0.06
	Dried	8.20	1.19
	Juice	27.98	4.07
	Total fruit	*46.25*	*6.73*
Vegetables	Fresh	14.48	2.11
	Canned	42.09	6.12
	Frozen	33.94	4.94
	Processed and dehydrated	25.94	3.77
	Total vegetable	*116.46*	*16.94*
Dairy products		3.55	0.52
Eggs		0.5	0.07
Fats & oils		0.14	0.02
TOTAL		**254.70**	**37.04**

The main flaw of this estimate is the lack of information about the nature of the lost mass, whether it is a solid residual or simply moisture loss (as is likely the case of canning and dehydrating vegetables). It is also incomplete, as it does not account for any of the well-documented wastes from seafood [11] and nut processing [12]. Nevertheless, this is the same approach taken by an EPA contractor in a recent screening analysis of food processing waste data [13]. No relevant input and output data on tobacco product manufacturing was identified, and therefore no material balance was performed.

An alternate materials balance approach for estimating NHIW could be to use published waste intensities and production volumes. For these sectors, the most recent NHIW intensity factors identified were published in 2009 [14] but are in fact a reproduction from a 1993 World Health Organization report [15], which in turn point back to the same 1973 report utilized in the historical forecast above [6].

2.1.4.4 International comparison

Industrial waste data collected by the European Union provides the fourth independent estimate of NHIW used in the triangulation method. In 2014 (the most recent data available), 29 European countries reported a total of 36.6 Tg of NHIW generated by the food, beverage, and tobacco product sectors (NACE C10-12). Based on waste intensities from the seven countries responsible for 81% of the total (the Netherlands, France, Germany, Poland, Belgium, Italy, and the UK), it is estimated that 44.7 Tg of waste was produced by the U.S. food, beverage, and tobacco sectors in 2015 (see Table 2.1-8). The four waste categories most closely associated with food processing—animal and mixed food waste; vegetal wastes; animal feces, urine and manure; and common sludges—make up 72% of the total, with the balance made of waste categories less-commonly associated with food processing. For example, mineral and solidified wastes make up 11% of the total estimate, yet these waste materials usually originate from the production and use of minerals, not food wastes. It is possible that the European waste accounts from which this estimate is drawn are just as internally inconsistent as the PARW has proved to be.

One goal in limiting the number of source countries in this estimate is to minimize the inter-country variability in waste intensity factors, something that was not very successful here. Even just among the seven large economies listed above, the reported waste intensities vary wildly. For example, the intensity factors for vegetal wastes reported by Italy (2.71 Mg/$1,000) and the Netherlands (63.92 Mg/$1,000) differ by a factor of nearly 24.

Table 2.1-8. *NHIW from the food, beverage & tobacco industries estimated using European waste data*

Waste category	**Waste intensity (Mg/$1,000)**		**US Waste (Tg)**
	Low	*High*	
Chemical and medical wastes	0.07	1.96	0.65
Recyclable wastes	0.99	16.01	3.44
Waste equipment	0.00	0.02	0.01
Animal and mixed food waste	1.43	14.33	7.98
Vegetal wastes	2.71	63.92	21.56
Animal feces, urine and manure	0.19	2.09	0.78
Mixed ordinary wastes	1.68	8.92	3.41
Common sludges	0.35	8.35	1.80
Mineral and solidified wastes	0.22	15.23	5.08
TOTAL			**44.70**

2.1.4.5 Triangulation & Synthesis

The four methods yield total estimates of NHIW from the food, beverage, and tobacco industries in 2015 ranging from 10.66 Tg to 44.70 Tg. To rationalize these disparate estimates, they are compared at the lowest possible level, ideally the individual waste streams emanating from each subsector, although in many cases the heterogeneity of this sector and the coarse resolution of many of the estimates limit the triangulation to subsectoral totals. In each subsector, the PARW-based estimate excludes plant trash and other MSW-type materials.

2.1.4.5.1 NAICS 3111: Animal Food

Estimates of NHIW from the animal food manufacturing subsector are available from the PACE survey and the PARW data. In neither instance is there process-related information, nor is a material balance estimate available. Therefore, the best that can be achieved is the range of the two estimates: 0.31 – 0.75 Tg.

2.1.4.5.2 NAICS 3112: Grain & Oilseed Milling

Available estimates of NHIW from this subsector include 0.05 Tg from the PARW data, 0.27 Tg from the SAIC report, and 0.80 Tg from the PACE survey. Although only the SAIC account includes any specific waste composition information, the PACE estimate roughly equals the sum of filter cake and sludge from fat/oil production reported by SAIC (0.15 Tg), and air pollution control residuals reported in the PACE survey (0.59 Tg), indicating that the grain milling sludge estimate from SAIC is too low by an order of magnitude. The best estimate therefore is 0.80 Tg.

2.1.4.5.3 NAICS 3113: Sugar & Confectioneries

The three available estimates for NHIW from sugar and confectionery products include 0.22 Tg from PARW, 2.32 Tg from PACE, and 3.89 from SAIC. The PARW data clearly excludes key wastes from sugarcane and beet processing like bagasse and lime mud. The largest components of the SAIC estimate, 1.47 Tg each of soil & trash and lime mud, are based on rather crude and under-referenced sources. Therefore, the middle-of-the-road PACE estimate is the best bet for this subsector: 2.32 Tg.

2.1.4.5.4 NAICS 3114: Fruits & Vegetables

Estimates of NHIW from this subsector reveal the benefit of including a material balance method. While the PARW, PACE, and SAIC data yield estimates of 1.79, 2.44, and 2.77 Tg, respectively; the USDA data claims 23.66 Tg of food loss from fruit and vegetable packing, canning, freezing, drying, juicing, and other processing. It is logical to claim from the data that only approximately 2 Tg of NHIW from this subsector needed to be disposed in 2015, but the total waste generated was an order of magnitude larger; the difference was due to extensive and well-developed beneficial use and byproduct conversion in this subsector. As mentioned earlier, the waste accounting standard utilized here necessitates the inclusion of all residual materials, even those with long-standing beneficial uses. Therefore, the USDA estimate of 23.66 Tg is the most appropriate option, even though it is likely an overestimate, including moisture loss. The lower estimates of unutilized wastes should also be acknowledged in the final account.

2.1.4.5.5 NAICS 3115: Dairy

NHIW from the dairy subsector includes large quantities of waste milk, whey, and other liquid wastes. This contributes to the range in estimates available from the four available sources: 0.52 Tg from USDA, 0.67 from SAIC, 0.92 from PACE, and 9.40 Tg from PARW. The significant majority of each of the smaller estimates is whey or other cheesemaking waste; it is difficult to argue for the outlier PARW-based estimate, especially since 7.80 Tg of the total was reported as liquid food waste. The USDA documentation acknowledges that their dairy loss statistics are flawed. Combined with the fact that the SAIC value is exclusively whey, a realistic range for 2015 is between the 0.92 Tg from PACE and the remaining 1.60 Tg from PARW.

2.1.4.5.6 NAICS 3116: Meat/Animal Products

Like fruits & vegetables, unutilized meat processing NHIW estimates range between 0.84 Tg (PARW) – 2.12 Tg (SAIC), but the material balance reveals a much larger quantity of lost mass from meat processing: 12.86 Tg. Unlike the 0.55 Tg and 0.35 Tg reported by PACE for red meat and poultry wastes, respectively, the USDA material balance estimates 6.27 Tg and 6.50 Tg for those sectors. There is better agreement between the two sources for the other two sub-subsectors considered here: 0.07 – 0.10 Tg for egg processing waste and 0.01 – 0.02 Tg for fats & oils. The SAIC estimate (2.10 Tg) largely consists of 1.61 Tg of paunch manure, which is not explicitly acknowledged in any of the other estimates. Like fruits & vegetables, the final account for this subsector should be the lost-mass estimate, 12.86 Tg, while acknowledging 0.84 Tg (PARW) – 1.01 Tg (PACE) of unutilized waste.

2.1.4.5.7 NAICS 3117: Seafood

Only the SAIC data offers a realistic estimate of NHIW from this sector: 0.74 Tg. The difference between this value and the one reported in PACE (0.05 Tg) is likely due to seafood wastes being attributed to activity further up the value chain (fishing and aquaculture), well-established beneficial uses of waste (such as conversion into meal, pet food, or soil amendments), or accounting as wastewater.

2.1.4.5.8 NAICS 3118: Bakeries

The two available estimates for NHIW from this subsector (PACE and PARW) are close to each other and undifferentiated enough to simply report the range: 0.61 – 0.87 Tg.

2.1.4.5.9 NAICS 3119: Other Food

Different estimates for any miscellaneous category are difficult to rationalize because it is unclear if the same miscellaneous activities, and associated wastes, would be included in both estimates. Nonetheless, the PARW and PACE estimates are again comparable to one another: 0.53 – 0.96 Tg.

2.1.4.5.10 NAICS 3121: Beverages

Malt and other brewery wastes should make up the bulk of this category, yet the SAIC data attributes just 2.5 Gg of the total estimated 0.22 Tg to those wastes. The PARW estimates includes 3.38 Tg of WWTP sludge, but this is reported as a liquid waste, suggesting it is largely wastewater. Excluding this data point, the remaining PARW wastes and the PACE estimate yield a reasonable range: 0.84 – 0.98 Tg.

2.1.4.5.11 Tobacco NAICS 3122: Products

Even though the source of the tobacco product wastes used in the historical forecasting is a half-century old, the resulting estimate from PACE is reinforced by contemporary results from PARW: 0.19 – 0.24 Tg.

2.1.4.5.12 Summary

The NHIW estimates triangulated above are summarized in Table 2.1-9. In total, the food, beverage, and tobacco products sectors generated an estimated 43.78 – 45.83 Tg of NHIW in 2015. The largest contributors to this total are fruit and vegetable processing wastes (23.67 Tg), meat processing wastes (12.85 – 12.89 Tg), and sugar processing wastes (2.32 Tg).

Interestingly, this triangulated estimate closely straddles the 44.70 Tg of NHIW estimated using EU statistics. It is possible that this is merely a coincidence, since when limited to just the four waste categories associated with food, beverage, and tobacco product industries, the EU data yields a smaller estimate of 32.12 Tg. On the other hand, if the total quantities rather than the material categorization are to be trusted, then this final estimate strongly corroborates the triangulated estimate.

Table 2.1-9. *Triangulated estimate of NHIW from the food, beverage & tobacco product sectors, 2015*

NAICS	Subsector/Activity	NHIW (Tg) *Low*	*High*	Notes
3111	Animal food manufacturing	0.31	0.75	
3112	Grain and oilseed milling	0.80		Mainly APC residue
3113	Sugar and confectionery products			
	Cane sugar	1.38		Mainly bagasse
	Beet sugar	0.84		
	Other	0.10		
	Total	***2.32***		
3114	Fruit & vegetable			
	Fruit	6.73		
	Vegetable	16.94		
	Total	***23.67***		1.71 – 2.77 Tg unutilized
3115	Dairy product manufacturing	0.92	1.60	Mainly cheese mfg waste
3116	Animal slaughtering and processing			
	Red meat	6.27		
	Poultry	6.50		
	Eggs	0.07	0.10	
	Fats & oils	0.01	0.02	
	Total	***12.85***	***12.89***	0.84 – 1.01 Tg unutilized
3117	Seafood product preparation and packaging	0.74		
3118	Bakeries and tortilla manufacturing	0.61	0.87	
3119	Other food manufacturing	0.53	0.96	
3121	Beverage manufacturing	0.84	0.98	
3122	Tobacco manufacturing	0.19	0.24	
	Grand Total	**43.78**	**45.83**	

2.2 Textiles, Apparel & Leather Product Manufacturing (NAICS 313-316)

2.2.1 Summary

The textiles, apparel, and leather product manufacturing sectors are estimated to have generated roughly 0.57 Tg of NHIW in 2015. Textile manufacturing generated between 0.38 – 0.48 Tg, 0.34 – 0.37 Tg of which is composed of textile and fiber wastes. Leather and leather products generated 0.11 – 0.17 Tg. No wastes were estimated from the apparel manufacturing subsector.

2.2.2 Industry structure

NAICS 313-316 consist of those firms primarily involved with the production of yarns and threads, fabrics, textiles, apparel and other textile products, and leather products. The 5-digit NAICS structure of these sectors is shown in Table 2.2-1.

Table 2.2-1. *NAICS 2017 structure of the textiles, apparel & leather product manufacturing sectors [1]*

313 Textile Mills
- 3131 Fiber, Yarn, and Thread Mills*
- 3132 Fabric Mills
  - 31321 Broadwoven Fabric Mills
  - 31322 Narrow Fabric Mills and Schiffli Machine Embroidery
  - 31323 Nonwoven Fabric Mills
  - 31324 Knit Fabric Mills
- 3133 Textile and Fabric Finishing; Fabric Coating Mills
  - 31331 Textile and Fabric Finishing Mills
  - 31332 Fabric Coating Mills

314 Textile Product Mills
- 3141 Textile Furnishings Mills
  - 31411 Carpet and Rug Mills
  - 31412 Curtain and Linen Mills
- 3149 Other Textile Product Mills
  - 31491 Textile Bag and Canvas Mills
  - 31499 All Other Textile Product Mills

315 Apparel Manufacturing
- 3151 Apparel Knitting Mills
  - 31511 Hosiery and Sock Mills
  - 31519 Other Apparel Knitting Mills
- 3152 Cut and Sew Apparel
  - 31521 Cut and Sew Apparel Contractors
  - 31522 Men's and Boys' Cut and Sew Apparel
  - 31524 Women's, Girls', and Infants' Cut and Sew Apparel
  - 31528 Other Cut and Sew Apparel
- 3159 Apparel Accessories and Other Apparel*

316 Leather and Allied Product Manufacturing
- 3161 Leather and Hide Tanning and Finishing*
- 3162 Footwear*
- 3169 Other Leather and Allied Products*

* These sectors have a single 5-digit subsector

Overall, this is a small sector, representing less than 2% of the total value added of U.S. manufacturing (NAICS 31-33) each year since 2007 (Figure 2.2-1) [2]. In 2015, textile mills (313) and textile product mills (314) were roughly equal in size (value add about $11b) while apparel manufacturing (315) was about half that. The leather and leather products industry (316) had a value added of less than $2b. These quantities have been stable for much of the previous decade, following a rapid decline by nearly a third from 2007-2009.

2.2.3 Solid wastes from NAICS 311-312

Wastes from textile, textile product, and apparel manufacturing are substantially composed of the fiber and textile materials themselves. Today, textiles are made from natural materials like cotton and wool, synthetic materials like polyester and nylon, and combinations thereof. At each stage in the manufacturing process, some of this material is lost as waste. Pigments and dyes as well as other treatment chemicals are also present in textile wastes, in some cases causing those wastes to be classified as hazardous. Detailed characterizations of solid wastes from textile manufacturing are presented in a report from the EPA, *Best Management Practices for Pollution Prevention in the Textile Industry* [3].

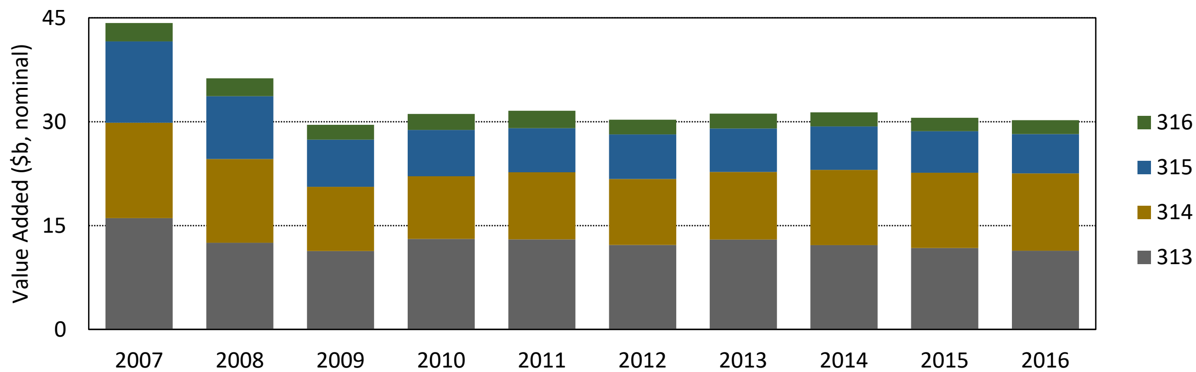

Figure 2.2-1. *Value added (billion $, nominal) from industry subsectors 313-316, 2007-2016 [2]*

Leather industry wastes are a mix of animal-derived materials generated in the cleaning and preparation of hides (e.g. hair, blood, flesh) and the chemicals used in converting these hides to finished leather. Many of these wastes end up in wastewater treatment sludge. Leather product manufacturing also results in waste leather from cutting, etc. Wastes categories from these industries included in the European Waste Catalog are listed in Table 2.2-2 [4].

Table 2.2-2. *Textiles, apparel & leather product industry wastes as listed in the European Waste Catalog [4]*

Activity	**Waste category**
Textile industry	- wastes from composite materials (impregnated textile, elastomer, plastomer) - organic matter from natural products (for example grease, wax) - non-hazardous wastes from finishing - non-hazardous dyestuffs and pigments - non-hazardous sludges from on-site effluent treatment - wastes from unprocessed textile fibres - wastes from processed textile fibres
Leather and fur industry	- fleshings and lime split wastes - liming waste - tanning liquor - sludges, in particular from on-site effluent treatment - waste tanned leather (blue sheetings, shavings, cuttings, buffing dust) - wastes from dressing and finishing

2.2.4 NHIW estimation

2.2.4.1 Historical forecasting

The most recent comprehensive data on solid waste from textile and leather product manufacturing come from a series of studies conducted by contractors for the EPA in the mid-1970s, the "Assessments of Industrial Hazardous Waste Practices." Reports in this series focused on characterizing the types, quantities, treatment and disposal options, and potential hazard of industrial wastes from select industries, including the textiles industry (SIC 22) [5] and the leather tanning and finishing industry (SIC 31) [6]. In both reports, contractors collected empirical data on industrial process residuals primarily via site visits to a representative sample of factories in 1975. These data were combined with information from academic and industrial reports and expert input from trade associations to develop mass-balanced process models of industry sub-sectors and extrapolate waste production to the national scale.

In both reports, contractors developed their own industry sub-classification schemes that best reflected contemporary industry structure and patterns of waste generation. For textiles, instead of using the SIC codes, which were acknowledged to be an obsolete scheme for this industry sector, the contractor identified seven processes that better represented the structure of the industry as it was in 1975: wool scouring, wool fabric dyeing and finishing, greige goods, woven fabric dyeing and finishing, knit fabric dyeing and finishing, carpet dyeing and finishing, and yarn and stock dyeing and finishing. For each of these industry processes, the contractor identified quantities of: non-hazardous process wastes, potentially hazardous dye and chemical containers, and potentially hazardous wastewater treatment sludge.

There is just a single SIC (and equivalent NAICS) code for leather tanning and finishing, so the contractors for that report structured their inquiry through seven characteristic tannery types: complete chrome tannery, vegetable tannery, sheepskin tannery, split tannery, leather finishers, beamhouse/tanhouse facilities, and retan/finishers. The industry process models developed in this report characterize and quantify non-hazardous and potentially hazardous residuals to air, water, and land, as well as materials sold or re-used as byproducts.

The reports included forecasted values for 1977 and 1983 for all industry subsectors, incorporating expected changes to production output as well as environmental regulations. Those forecasted values are not used here because they were not based predominantly on empirical observation.

There is a poor correspondence between SIC and NAICS codes for these sectors, making it challenging to gain insight on NHIW from the various subsectors listed in Table 2.2-1 above. Therefore, results are reported at a higher level of aggregation: textile mills and textile products (NAICS 313-314) and leather and leather products (NAICS 316). No satisfactory historical data were identified for NHIW from the apparel manufacturing industry (NAICS 315).

The historical data suggest that textiles and leather manufacturing generated 514 Gg of NHIW in 2015 (see Table 2.2-3). The majority of the waste from these sectors is waste textiles and textile constituents (373 Gg), followed by leather wastes from hide preparation (78 Gg). Much of the leather waste was flagged as "potentially hazardous" but is included here because the overwhelming fraction of the waste stream is made of non-hazardous material—only a small fraction is the hazardous component. Other potentially hazardous waste streams include dirt, grease & sludge from textile manufacturing, leather wastewater sludge and screening, empty chemical and dye containers, and leather finishing wastes. Miscellaneous process solid wastes from leather production is strictly non-hazardous.

Table 2.2-3. *NHIW from the textiles, apparel & leather product industries estimated by historical forecasting, 2015*

Sector	Waste	Original (Tg)	Base year	2015 (Tg)	Source
Textiles	Fiber, yarn, thread, cloth, fabric, flock & wool waste	0.53	1974	0.37	[5]
Textiles	Chemical & dye containers	0.01	1974	0.01	[5]
Textiles	Dirt, grease & sludge	0.05	1974	0.03	[5]
Leather	Fleshings, splits, hair, trimmings & shavings	0.11	1974	0.08	[6]
Leather	Unfinished & finished leather trim, buffing dust, finishing residue	0.01	1974	0.01	[6]
Leather	Miscellaneous process solid wastes	0.01	1974	0.01	[6]
Leather	Wastewater screenings & sludge	0.01	1974	0.01	[6]
	TOTAL			**0.52**	

Other later, official EPA publications also present accounts of NHIW from both textiles [7] and leather production [8], but offer no new empirical observations. All data in these subsequent reports are drawn ultimately from the two 1976 studies referenced above. In addition, the American Textile Manufacturers Institute (ATMI) conducted surveys of textile mills in the late 1980s and early 1990s, but results are not comprehensive enough to draw conclusions about waste volumes generated from the entire sector [9-10].

As for apparel manufacturing, no reliable, empirical data were identified that could enable historical forecasting. A 1998 trade journal article quotes a report from the erstwhile American Apparel Manufacturers Association (AAMA, now part of the American Apparel & Footwear Association) that "as much as 1.85 billion pounds of fiber and fabric waste are produced annually in the United States…at all three levels of production: fiber production, textile manufacturing, apparel and other end-product manufacturing" [11]. The article continues, "the AAMA estimates that 75% to 85%, or up to 1.2 billion to 1.5 billion pounds of total waste produced by mills and cutting plants is currently recycled." Of the total 1.85 billion lbs. (0.84 Tg), apparel manufacturing was thought to contribute between 450 – 600 million lbs. (0.20 – 0.27 Tg), 100 – 150 million lbs. of which (0.05 – 0.07 Tg) was sent to landfill. It must be noted that these numbers are explicitly referred to as "wild guesses" in the trade publication [12].

Results from the 1983 PACE survey suggest solid waste from these sectors totaled 656 Gg in 2015: 622 Gg of NHIW and 34 Gg of air pollution control (APC) residues (Table 2.2-4). The largest fraction was generated by fabric mills, followed by textile finishing, leather tanning and finishing, and textile furnishings. Again, wastes apparel manufacturing (NAICS 315) was not present in the raw data.

Table 2.2-4. *NHIW from the textiles, apparel & leather product industries estimated from PACE, 2015 [13]*

NAICS	Description	1983 (Gg)		2015 (Tg)
		NHIW	*APC*	*Total*
3131	Fiber, yarn, and thread mills	31.66	0.54	0.02
3132	Fabric mills	279.50	32.21	0.20
3133	Textile and fabric finishing and fabric coating mills	132.09	28.67	0.14
3141	Textile furnishings mills	91.99	4.63	0.08
3149	Other textile product mills	60.69	1.63	0.04
3161	Leather and hide tanning and finishing	72.03	2.00	0.10
3162	Footwear manufacturing	116.30	0.91	0.06
3169	Other leather and allied product manufacturing	14.51	0.27	0.01
313-316	**TOTAL**			**0.66**

2.2.4.2 Spatial up-scaling

Averaging the data reported in 2014 and 2016 to the Pennsylvania Residual Waste Database (PARW), 65 facilities in the Pennsylvania textiles, apparel, and leather products industries generated 17.1 Gg of NHIW in 2015. That year, these firms were responsible for 3.9% of nationwide textile mill shipments, 2.6% of textile products, 3.6% of apparel manufacturing, and 3.6% of leather and leather product manufacturing. This data suggests that national NHIW generation in these sectors totaled 0.58 Tg in 2015 (Table 2.2-5). The manufacturing of textile furnishings contributed the most to this total, followed by textile and fabric finishing and coating and leather manufacturing.

By this estimate, textile wastes make up the largest fraction of the total generated by these sectors, 0.34 Tg (Table 2.2-6). Leather wastes, on the other hand, only total 0.02 Tg, with the rest of the waste from the leather products industry being plant trash and sludges and scales.

Table 2.2-5. *NHIW by NAICS sector estimated by up-scaling from PARW data, 2015*

NAICS Code	Description	PA Waste (Gg)	US Waste (Tg)
3131	Fiber, yarn, and thread mills	0.2	0.01
3132	Fabric mills	0.2	0.00
3133	Textile and fabric finishing and fabric coating mills	2.3	0.12
3141	Textile furnishings mills	10.6	0.30
3149	Other textile product mills	1.7	0.08
3159	Apparel accessories and other apparel	0.0	0.00
3161	Leather and hide tanning and finishing	1.4	0.04
3162	Footwear	0.6	0.01
3169	Other leather and allied product	0.1	0.00
313-316	**TOTAL**	**17.1**	**0.58**

Table 2.2-6. *NHIW from the textiles, apparel & leather industries estimated by up-scaling from PARW data, 2015*

Waste Type	Source	US Waste (Tg)	% of total
Textile Wastes (Yarn, Fabric, Fiber, Elastic)	Fiber, yarn, and thread	0.01	1.0%
	Fabric	0.00	0.7%
	Textile and fabric finishing and fabric coating	0.03	4.7%
	Textile furnishings	0.30	52.3%
	Other textile product	0.00	0.2%
	Apparel accessories and other apparel	0.00	0.4%
	Total Textile Wastes	*0.34*	*59.2%*
Leather Wastes	Leather and hide tanning and finishing	0.02	3.1%
	Footwear	0.01	1.1%
	Total Leather Wastes	*0.02*	*4.2%*
Waste Tires		0.07	12.7%
Plant Trash		0.06	10.7%
Sludges & Scales		0.04	7.4%
Other Wastes		0.03	5.7%
TOTAL		**0.58**	**100.0%**

2.2.4.3 Material balance

No data exist to perform an economy-wide material balance analysis for these sectors. However, leather production process models from the United Nations Industrial Development Organization (UNIDO) do allow for a crude assessment of leather waste and scraps using leather production data from the Food and Agriculture Organization (Table 2.2-7) [14]. Two models were identified. The first quantifies the material flow in a representative tannery processing cattle hide into finished leather [14]. In this model, 1,000 kg of raw material (called "wet, salted hide") yield just 255 kg of finished product and 637 kg of solid wastes and by-products (the balance discharged to air and water). According to FAO data, U.S. tanneries processed 108.6 Gg of bovine hides and skins in 2014 (the most recent data available). Based on these values, cattle hide tanneries generated 0.07 Tg of solid waste in 2014. See Table 2.2-8 for more detail.

Table 2.2-7. *U.S. production of raw hides, leather, and shoes, 2014 [14]*

Product	Amount	Unit
Bovine hides and skins (apparent avail.)	108.6	Gg (wet salted weight)
Heavy leather from bovine animals	18.3	Gg
Light leather from bovine animals	55.3	Million m^2
Light leather from sheep and goats	6.4	Million m^2
Leather shoes, all types	86.6	Million pairs

Table 2.2-8. *Waste from leather production in idealized tanneries by material balance, 2014 [15]*

Waste type	Waste intensity *(kg/Mg wet salted cattle hide)*	2014 waste *(Gg)*
Fleshings	300	32.58
Trimmings	100	10.86
Unused Cr-split	107	11.62
Cr-shavings	99	10.75
Cr-off cuts	20	2.17
Buffing dust	1	0.11
Leather off cut	5	0.54
Crust leather waste	5	0.54
Total	**637**	**69.18**

The second model builds on the results from the first, characterizing waste intensity factors for process wastes “having a chemical composition comparable to finished leather” [16]. It includes data for three types of finished leather: heavy bovine, light bovine, and sheep and goat leathers. The report also includes waste generation factors for shoes, leather goods, leather garments, gloves, and furniture and upholstery. Production data to enable the use of these factors was only identified for shoes. This model suggests that the leather and leather products industry in 2014, including shoe manufacturing, generated 0.06 Tg of solid waste (Table 2.2-9).

That both material balance-based estimates produced results so close together (0.06 Tg and 0.07 Tg) is partially a coincidence. Some of the waste intensity factors from the second model are based on data in the first, although it is not exactly clear how. There is some but not complete overlap between the scopes of analysis of the two models; the first includes raw hide cleaning and processing while the second includes leather product manufacturing. With an unclear system scope, results from the two models cannot be combined. However, we can say with confidence that NHIW from these industries exceeded 0.07 Tg in 2015.

Table 2.2-9. *Waste from finished leather and shoe manufacturing by material balance, 2014 [16]*

Waste type	Waste intensity		2014 waste *(Gg)*
Unusable wet blue splits, shavings and trimmings			
Heavy bovine leather	171.0	Mg / Gg finished leather	3.13
Light bovine leather	513.0	Mg / million m^2 finished leather	28.37
Sheep and goat leather	180.0	Mg / million m^2 finished leather	1.15
Subtotal			***32.65***
Dry leather wastes (trimmings, dust…)			
Heavy bovine leather	27.7	Mg /Gg finished leather	0.51
Light bovine leather	83.2	Mg / million m^2 finished leather	4.60
Sheep and goat leather	151.3	Mg / million m^2 finished leather	0.97
Subtotal			***6.08***
Shoe manufacturing wastes	266.0	Mg / million pairs	23.04
TOTAL			**61.76**

There is some confusion about the units of waste generation for heavy bovine leather. In the report, the table of waste ratios is labeled “t / t finished leather” but the table of calculations assume ratios per thousand tons. Here, we follow the calculation model.

2.2.4.4 International comparison

European industrial waste data suggests that the U.S. textile, apparel, and leather products industries generated 1.01 ± 0.70 Tg of NHIW in 2015 (see Table 2.2-10). This is equivalent to 11.61 ± 8.01 Mg of NHIW per $1,000 industrial economic output. When non-process wastes are excluded (recyclable wastes, waste equipment, mixed ordinary wastes, and mineral and solidified waste), the total is reduced to 0.65 ± 0.57 Tg of NHIW, most of which is textile waste.

Table 2.2-10. *NHIW from the textiles, apparel & leather industries estimated using European waste data*

	Waste intensity (Mg/$1,000)		**US Waste 2015 (Tg)**	
	Average	*Std. Dev.*	*Average*	*Std. Dev.*
Chemical wastes	1.40	1.01	0.12	0.09
Industrial effluent sludges	1.05	0.86	0.09	0.08
Other chemical wastes	0.00	0.00	0.00	0.00
Textile wastes	4.89	6.29	0.43	0.55
Recyclable waste	1.95	1.48	0.17	0.13
Waste equipment	0.02	0.03	0.00	0.00
Animal and vegetal wastes	0.08	0.15	0.01	0.01
Mixed ordinary wastes	1.82	1.38	0.16	0.12
Common sludges	0.08	0.06	0.01	0.01
Mineral and solidified wastes	0.18	0.20	0.02	0.02
Total Waste	**11.61**	**8.01**	**1.01**	**0.70**

Sum of individual wastes may not equal “total waste” due to rounding errors and because of inconsistencies in the raw data.

2.2.4.5 Triangulation & Synthesis

The three available methods yield total estimates of NHIW from the textile, apparel, and leather products industries ranging from 0.52 Tg to 0.66 Tg. Without a materials balance, it is difficult to say on which side of this range the actual value lies. Nevertheless, the four available estimates are well-clustered, making it not unreasonable to simply report this range. However, it is possible to compare results at a slightly lower level of aggregation.

2.2.4.5.1 NAICS 313-314: Textiles and textile products

All estimates agree that textile wastes make up the bulk of the waste stream from these subsectors (NAICS 313-314). Historical data from the 1970s put this figure at 0.37 Tg (with an additional 0.04 Tg of non-textile NHIW from these sectors). PACE data from the early 1980s suggest the value of all wastes from these subsectors is 0.48 Tg (0.46 Tg of solid waste, with the balance air pollution control residuals). PARW data put textile wastes at 0.34 Tg with 0.04 Tg of other wastes from these subsectors. Finally, the European data, which cannot be disaggregated into subsectors, nonetheless yields an estimate of textile waste of 0.43 ± 0.55 Tg. The large variability of this estimate is driven mainly by the data from one country, Poland, which contributed 12.5% of the total sectoral wastes and had a calculated intensity of textile wastes a full order of magnitude larger than the largest generator (Italy): 20.92 vs. 2.27 Mg/million USD. Therefore, a more accurate estimate of textile waste is likely somewhat lower than the average value of 0.43 Tg.

Based on this data, we can claim that textile wastes were generated at a rate of 0.34 – 0.37 Tg in 2015. Other wastes (wastewater treatment sludges, air pollution control residues, non-hazardous chemical wastes) were generated somewhere between 0.04 – 0.11 Tg.

2.2.4.5.2 NAICS 315-316: Apparel, leather and leather products

Leather and leather products were estimated to generate 0.11 Tg from the 1974 data, 0.17 Tg from the 1983 PACE data, and 0.05 Tg from PARW data. The European data obscures subsectoral information; it is possible that much of the chemical waste (0.12 ± 0.09 Tg) and industrial effluent sludges (0.09 ± 0.08 Tg) originate in the leather goods industry, but it cannot be said with any certainty. The composition of this waste stream is uncertain. Results from the highly constrained material balance models suggest that the sector generates somewhat more than 0.07 Tg of leather wastes.

Given the high degree of uncertainty, it is nevertheless reasonable to claim that the amount of NHIW from the leather and leather products subsectors is between 0.11 – 0.17 Tg. No NHIW was estimated from the apparel industry.

2.2.4.5.3 Summary

The NHIW values triangulated here are presented in Table 2.2-11. The grand total suggests a range of NHIW generation between 0.43 – 0.65, a greater spread than the range of pre-triangulated estimates: 0.52 – 0.66 Tg. The likely value is the average of the grand total range: 0.57 Tg.

Table 2.2-11. *Triangulated estimate of NHIW from the textiles, apparel & leather sectors, 2015*

NAICS	Subsector/Waste material	NHIW (Tg) *Low*	*High*	Notes
313-314	Textile, textile product mills			
	Textile wastes	0.34	0.37	
	Other wastes	0.04	0.11	Sludge, grease, APC residuals & chemicals
	Total	***0.38***	***0.48***	
315	Apparel manufacturing	0.00		
316	Leather and leather products	0.11	0.17	Hide preparation, leather scraps & chemicals
	Grand Total	**0.49**	**0.65**	

2.2.5 More resources

2.2.5.1 Textiles

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2.2.5.2 Leather

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2.3 Wood Product Manufacturing (NAICS 321)

2.3.1 Summary

The wood product manufacturing industry is estimated to have generated between 1.33 – 1.56 Tg of NHIW in 2015. This includes 1.03 Tg of wood wastes: 42% from sawmills, 53% from veneer, plywood, and engineered wood products manufacturing, and 5% from other wood products manufacturing. Combustion residues, mainly wood ash, made up 0.16 – 0.32 Tg of NHIW, and other waste materials between 0.14 – 0.21 Tg. There remains a relatively small but important flow of hazardous wastes from wood preservation activities.

2.3.2 Industry structure

Firms in the wood product manufacturing sector (NAICS 321) convert logs harvested in forests into lumber, plywood, engineered wood, wood containers, wood windows and doors, prefabricated wood buildings, and many other wood products (excluding furniture). The 5-digit NAICS structure of this sector is shown in Table 2.3-1. Much of the diversity of this sector is contained within NAICS 3219 and in particular NAICS 32199.

Table 2.3-1. *NAICS 2017 structure of the wood product manufacturing sector [1]*

321 Wood Product Manufacturing
3211 Sawmills and Wood Preservation*
3212 Veneer, Plywood, and Engineered Wood Products*
3219 Other Wood Products
32191 Millwork
32192 Wood Containers and Pallets
32199 All Other Wood Products

* These sectors have a single 5-digit subsector

This sector contributed less than 2% of the total value added of U.S. manufacturing each year from 2007 to 2016 [2]. It was strongly affected by the 2008 financial crisis, with value added declining nearly 40% between 2007 and 2008, although it has since rebounded (Figure 2.3-1). Of the three four-digit subsectors, NAICS 3219, "Other Wood Products" contributes roughly twice as much value added as the other two. This is not an indication of physical throughput, however, merely the comparative market value of the products from those, appropriately, higher value added products compared with lumber (3211) and plywood (3212).

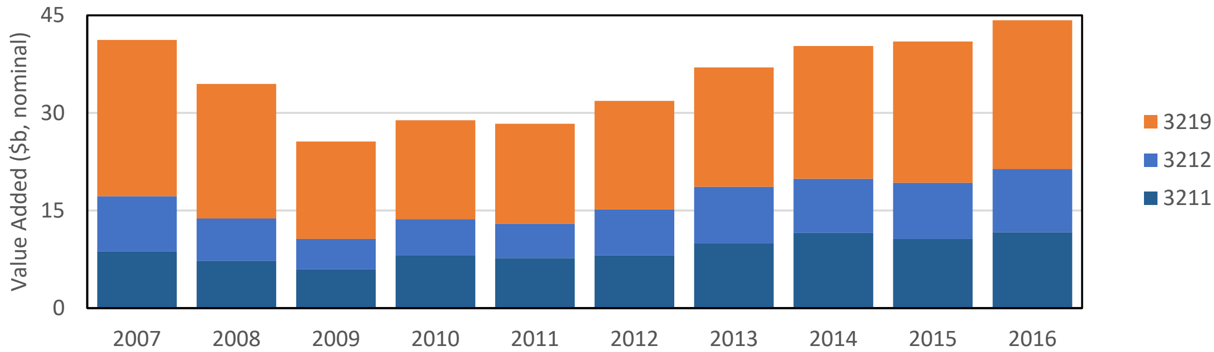

Figure 2.3-1. *Value added (billion $, nominal) from industry subsector 321, 2007-2016 [2]*

2.3.3 Solid wastes from NAICS 311-312

Waste from sawmills and wood product manufacturing facilities is mainly wood waste in various forms: sawdust, bark, shavings, cuttings, etc. A substantial amount of this material is utilized as a byproduct within the sector, converted into particleboard and other engineered wood products. Another fraction of mill residue is used as animal bedding and mulch. Much of the rest is burned for energy, producing ash as a waste product. Only a small fraction of the total amount of wood waste originally generated is ultimately managed as waste.

Wastes from wood preservation are almost all managed as hazardous waste, since the chemicals used in that industry sector are still largely toxic [3]. Wastes from these industries included in the European Waste Catalog are listed in Table 2.3-2 [4].

Table 2.3-2. *Wood product industry wastes as listed in the European Waste Catalog [4]*

Activity	Waste category
Wood processing, production of panels	- waste bark and cork - sawdust, shavings, cuttings, wood, particle board and veneer
Wood preservation	- non-hazardous wood preservatives

2.3.4 NHIW estimation

2.3.4.1 Historical forecasting

There is no comprehensive, reliable, historical account of NHIW from the wood product manufacturing sectors. The only historical data identified is of wood preservation sludges generated in 1978 (84 Gg) and 1980 (86.7 Gg) [5, p. 4-144]. These quantities refer to wastes that are almost surely hazardous, however. The wood preserving industry uses three major pesticides for treating wood, creosote, pentachlorophenol, and waterborne inorganic arsenicals, all of which produce hazardous wastes [6].

Data from the 1983 PACE survey suggest that these sectors generate a total of 5.81 Tg of solid waste: 4.85 Tg of NHIW and 0.96 Tg of air pollution control residues (Table 2.3-3). Sawmills were responsible for the plurality of the tonnage (2.51 Tg), followed by particleboard manufacturing (0.93 Tg), and plywood (0.73 Tg). More than half of the wastes attributed to NAICS 3219 "Other wood product manufacturing" are from activities that are "not elsewhere classified."

Table 2.3-3. *NHIW from the wood product manufacturing industries estimated from PACE, 2015 [7]*

NAICS	Description	1983 (Gg) *NHIW*	1983 (Gg) *APC*	2015 (Tg) *Total*
3211	Sawmills and wood preservation	1667.7	215.6	2.57
3212	Veneer, plywood, and engineered wood product mfg	856.4	231.0	1.84
3219	Other wood product manufacturing	730.6	207.3	1.41
321	**TOTAL**			**5.81**

2.3.4.2 Spatial up-scaling

Pennsylvania Residual Waste Program data suggest that NHIW from wood products manufacturing totaled just 1.17 Tg, most of which coming from veneer, plywood, and engineered wood product manufacturing (NAICS 3212) (Table 2.3-4). In this accounting, sawmills are responsible for just 0.06 Tg of NHIW, while the varied rest of the sector (NAICS 3219) generated 0.18 Tg of NHIW. Of the total 1.17 Tg, 0.63 Tg is wood waste, most of which coming from NAICS 3212. This sector also generates the most combustion ash (0.27 Tg). See Table 2.3-5 for more composition details.

Table 2.3-4. *NHIW by NAICS sector estimated by up-scaling from PARW data, 2015*

NAICS Code	Description	PA Waste (Gg)	US Waste (Tg)
3211	Sawmills and wood preservation	1.9	0.06
3212	Veneer, plywood, and engineered wood product manufacturing	19.0	0.93
3219	Other wood product manufacturing	12.3	0.18
321	**TOTAL: Wood product manufacturing**	**33.2**	**1.17**

Table 2.3-5. *NHIW from the wood product manufacturing industry estimated by up-scaling from PARW data, 2015*

Waste Type	**Source**	**US Waste (Tg)**	**% of total**
Wood wastes and sawdust	Sawmills and wood preservation	0.03	2.7%
	Veneer, plywood, and engineered wood product mfg	0.55	47.4%
	Other wood product manufacturing	0.05	4.2%
	Total Wood Wastes	*0.63*	*54.3%*
Ash	Sawmills and wood preservation	0.01	1.0%
	Veneer, plywood, and engineered wood product mfg	0.27	22.7%
	Total Ash Wastes	*0.28*	*23.7%*
Other wastes	Sawmills and wood preservation	0.01	0.6%
	Veneer, plywood, and engineered wood product mfg	0.06	5.3%
	Other wood product manufacturing	0.07	6.0%
	Total Other Wastes	*0.14*	*11.8%*
Plant trash		0.12	10.2%
TOTAL		**1.17**	**100.0%**

2.3.4.3 Material balance

Wood products manufacturing lends itself reasonably well to a materials balance estimate. The main sawmill transformation activity is straightforward: logs are converted to lumber and wood waste. Bark and wood residue is then converted to board and other products, fuel, and mulch. Energy generation converts fuel to ash. Further conversion activities (e.g. millwork, pallet manufacturing, etc.), while also waste producing, quickly become ill-suited to this estimation method for reasons of industry complexity and material double-counting.

Ayres & Ayres [8, pp. 55-58] present an approach to this material balance calculation that utilizes a variety of publicly available data sources. However, it requires many simplifying assumptions that, while acceptable for the purposes of an economy-wide material balance, are to be avoided if possible. Each decade, the U.S. Forest Service publishes detailed data on forest resources and activities in support of the Resources Planning Act (RPA) Assessment, including data on bark and wood residues generated at "primary wood-using mills" in the United States. These figures seem to be model outputs rather than bottom-up, empirical observations, which is why this source is analyzed as part of a material balance estimate of NHIW rather than historical forecasting.

The most recent compendium of forest data is in support of the upcoming 2020 RPA Assessment, and includes estimates of mill residues for the year 2016 [9, pp. 198-199]. Mill residue generation and utilization can be estimated for the year 2015 using production data for sawnwood and logs (a decrease of just 0.24%) [10, p. 4]. This method estimates that 58 Tg of bark and other mill residues was generated in 2015, of which 26.7 Tg was used to generate energy, 21.7 Tg was used in the manufacture of particleboard and other fiber products, and 8.9

Tg went to mulch, animal bedding, and other uses. Only 0.43 Tg of mill residue was left over as wood waste.

It is unclear how much of the mill residue that is reportedly used for energy production is consumed within the wood products manufacturing sector. The 2014 Manufacturing Energy Consumption Survey [11] reports that the wood products manufacturing sector consumed 243 trillion BTU of wood and wood-related fuel in that year, of which 216 trillion BTU came from mill residues. Sawmill production changed only 0.01% between 2014 and 2015, so this energy consumption value can be used for our target year as well. According to the Forest Product Laboratory, wood has a net heating value of 13.8 million BTU/ton (dry basis), or 15.2 trillion BTU/Tg [12]. Following Ayres & Ayres, mill residues have an ash content between 1-2% (dry basis) [8, p. 58]. This means that ash production in NAICS 321 in 2015 was between 0.16-0.32 Tg. A summary of the results from this material balance estimate is in Table 2.3-6.

Table 2.3-6. *NHIW from the wood product manufacturing industry estimated by materials balance, 2015*

Waste Type	US Waste (Tg)
Unused wood waste and mill residues	0.43
Ash	0.16 – 0.32

The EPA has developed their own model of wood material flows in the U.S. [13]. The focus of this model is to estimate wood product waste for their municipal solid waste accounting efforts, rather than on production wastes (for which they use a crude residual rate of 5%). A similar, albeit simpler, model has been published in *BioCycle Magazine* [14].

2.3.4.4 International comparison

European waste data indicates that the wood product manufacturing sector generated 17.97 ± 12.28 Tg of NHIW in 2015 (Table 2.3-7). The overwhelming quantity of this waste was in the form of wood wastes: 16.49 ± 11.76 Tg. The second largest waste stream was combustion wastes: 0.79 ± 1.18 Tg. The extremely high degree of variability in both of these waste streams is due to what seems to be vastly different industry practices and environmental policies across the continent, even with EU harmonization. For example, Germany, which generated 2.8 Tg of sectoral NHIW, did so with a waste intensity of just 72 Mg/$; while Romania, with its 1.9 Tg of NHIW, had a waste intensity greater than 400 Mg/$. Combustion products have an even wide spread, with Belgium reporting a waste intensity of 44 Mg/$, more than seven times that of Germany's.

Table 2.3-7. *NHIW from the wood product manufacturing industries estimated using European waste data*

	Waste intensity (Mg/$1,000)		US Waste 2015 (Tg)	
	Average	*Std. Dev.*	*Average*	*Std. Dev.*
Chemical and medical wastes	0.45	0.60	0.04	0.06
Wood wastes	166.76	118.94	16.49	11.76
Other recyclable waste	1.96	0.90	0.19	0.09
Equipment	0.01	0.01	0.00	0.00
Animal and vegetal wastes	0.88	2.97	0.09	0.29
Mixed ordinary wastes	2.54	1.66	0.25	0.16
Common sludges	0.04	0.15	0.00	0.02
Combustion wastes	8.03	11.96	0.79	1.18
Other mineral and solidified wastes	0.79	0.95	0.08	0.09
Total Waste	**181.70**	**124.17**	**17.97**	**12.28**

Sum of individual wastes may not equal "total waste" due to rounding errors and because of inconsistencies in the raw data.

2.3.4.5 Triangulation & Synthesis

There is not enough data to triangulate NHIW completely by both subsector and waste material. The PACE estimate is broken down by subsector; PARW by both subsector and waste material; the materials balance estimate is primarily by material, yet offering some insight into subsector; and the international estimate is by material.

2.3.4.5.1 Waste wood

Estimates for wood waste generated by these sectors range from 0.43 Tg to 18 Tg. It is reasonable to exclude the European-derived estimate here, as practices in contributing countries do not resemble those in the United States. Similarly, the historical PACE estimates do not account for the large increase in internal use of mill residues as the market for fiberboard and other engineered woods has developed since 1983. The PARW estimate shows 0.55 Tg of wood waste from NAICS 3212 but just 0.03 Tg from NAICS 3211. This is in contrast with the 0.43 Tg of wood waste from Forest Service data which almost certainly includes just sawmills and related activities (NAICS 3211). We can combine these data to arrive at a complete estimate of production wood wastes: 0.43 (3211) + 0.55 (3212) + 0.05 (3219) = 1.03 Tg.

2.3.4.5.2 Combustion residues

Estimates of ash and other combustion residues are between 0.16 – 0.32 Tg from the materials balance and 0.79 ± 1.18 Tg from the European data. Again, the European data is not reliable, especially because the standard deviation of national waste intensities is larger than the mean value. That the materials balance estimate range nicely straddles the PARW scale-up estimate (0.28 Tg), we can reliably report that range as the triangulated value: 0.16 – 0.32 Tg

2.3.4.5.3 Other wastes

Other wastes, like non-hazardous preservation sludges and non-wood production wastes from higher value-added activities (NAICS 3219) are a bit challenging to nail down. PARW data suggests these are 0.14 Tg; international data puts them at 0.21 Tg; while the PACE estimate retains upwards of 4 Tg of unaccounted-for wastes, after taking out our estimates of wood and ash generation. With no composition detail provided by the PACE survey, it cannot be reliably included. The triangulated estimate for other wastes must be 0.14 – 0.21 Tg.

2.3.4.5.4 Summary

The total NHIW generated by this sector in 2015 is estimated to be 1.33 – 1.56 Tg, most of which is wood waste. Table 2.3-8 presents the final triangulated values.

Table 2.3-8. *Triangulated estimate of NHIW from the wood product manufacturing sectors, 2015*

Waste material/Subsector		NHIW (Tg) *Low*	*High*	Notes
Wood waste				
3211	*Sawmills and wood preservation*	*0.43*		
3212	*Veneer, plywood, and engineered wood product mfg*	*0.55*		
3219	*Other wood product mfg*	*0.05*		
	Total	***1.03***		
Ash		0.16	0.32	
Other waste		0.14	0.21	Chemical sludges & non-wood wastes
	Grand Total	**1.33**	**1.56**	

2.4 Paper Manufacturing & Printing (NAICS 322-323)

2.4.1 Summary

The paper manufacturing and printing industry sectors are estimated to have generated 12.93 Tg of NHW in 2015. Most (87%) of this comes from pulp, paper, and paperboard mills, which are estimated to generate 4.49 Tg of sludge, 2.23 Tg of ash, and 4.50 Tg of other waste. Converted paper production and printing are estimated to generate 0.69 Tg and 1.02 Tg of NHIW, respectively.

2.4.2 Industry structure

The paper manufacturing industry is comprised of firms that manufacture pulp from wood, recovered paper and paper products, and other fibrous materials; manufacture that pulp into paper and paperboard; and convert paper and paperboard into products. Although there are distinct NAICS codes for each of these activities (see Table 2.4-1), many facilities are vertically integrated, with wood entering in one side and converted paper products coming out the other. This is certainly the case for NAICS 3221, in which most pulp manufacturing occurs in an integrated paper or paperboard mill. Paper and paperboard mills are further categorized by product: printing & writing, tissue, boxboard, cardboard, etc.

Firms in the printing industry print text and images onto products made from paper, textiles, metal, glass, plastic, and other materials. This includes books, clothing, advertising items, and screen printing.

Table 2.4-1. *NAICS 2017 structure of the paper manufacturing and printing sectors [1]*

322 Paper Manufacturing	**323 Printing and Related Support Activities**
3221 Pulp, Paper, and Paperboard Mills	3231 Printing and Related Support Activities
32211 Pulp Mills	32311 Printing
32212 Paper Mills	32312 Support Activities for Printing
32213 Paperboard Mills	
3222 Converted Paper Products	
32221 Paperboard Containers	
32222 Paper Bag and Coated and Treated Paper	
32223 Stationery Products	
32229 Other Converted Paper Products	

These two industry sectors contributed 5.5% of total U.S. manufacturing value added in 2015, a slight decrease in both absolute and relative terms from pre-2009 (Figure 2.4-1) [2]. In 2015, pulp, paper, and paperboard mills added $43.5 billion in value. Of this quantity, just 7.2% came from dedicated pulp mills (NAICS 32211), while 52.2% came from paper mills (NAICS 32212) and 40.6% from paperboard mills (NAICS 32213). Converted paper products added $42.3 billion, slightly more than half of which (53.2%) came from paperboard container manufacturing (NAICS 32221). Paper bag manufacturing (NAICS 32222) represented an additional 22.5%, with stationery and other converted paper products contributing the rest. The printing industry (NAICS 323) added $47.4 billion in 2015.

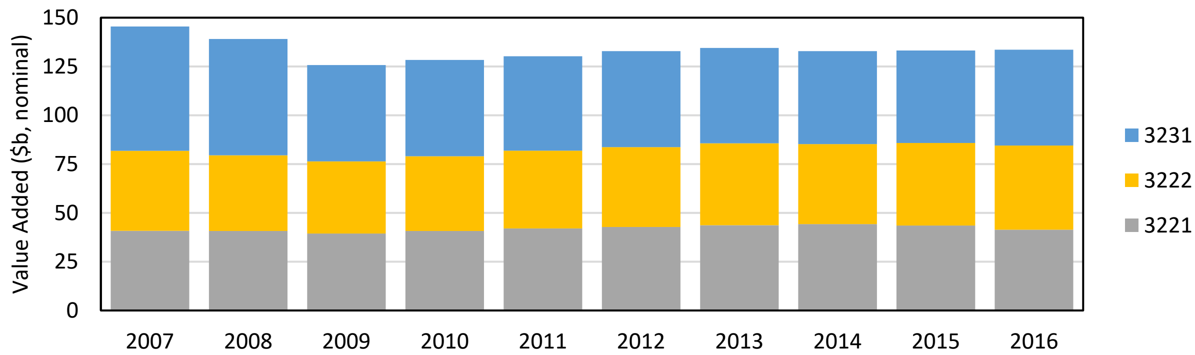

Figure 2.4-1. *Value added (billion $, nominal) from industry subsectors 322-323, 2007-2016 [2]*

2.4.3 Solid wastes from NAICS 311-312

Papermaking generates non-hazardous waste residuals throughout the manufacturing process. Wood preparation generates bark and wood waste; pulping generates a variety of chemical wastes (e.g. lime mud, green liquor sludge), depending on the pulping process utilized; paper recycling generates de-inking wastes; papermaking generates fiber rejects and wastewater sludge; and power production generates wood and coal ash. A detailed catalog of pulp and papermaking wastes can be found in the relevant chapter of the 1995 *Pollution Prevention Handbook* [3, pp. 513-528].

Paper converting and printing wastes are almost entirely off-cut or rejected media, paper or otherwise. Chemical printing wastes are generally hazardous [4].

Wastes from these industries included in the European Waste Catalog are listed in Table 2.4-2 [5].

Table 2.4-2. *Paper manufacturing & printing industry wastes as listed in the European Waste Catalog [5]*

Activity	Waste category
Pulp, paper, and cardboard industry	- waste bark and wood - green liquor sludge (from recovery of cooking liquor) - de-inking sludges from paper recycling - mechanically separated rejects from pulping of waste paper and cardboard - wastes from sorting of paper and cardboard destined for recycling - lime mud waste - fibre rejects, fibre-, filler- and coating-sludges from mechanical separation - sludges from on-site effluent treatment
Printing industry	- sludges containing ink - non-hazardous waste inks - non-hazardous waste printing toner

2.4.4 NHIW estimation

2.4.4.1 Historical forecasting

The most recent, bottom-up, empirical data on NHIW generation by pulp, paper, and paperboard mills comes from an industrial organization rather than a government source. The National Council for Air and Stream Improvement (NCASI) conducts scientific and environmental research for the forest products industry. Periodically, it surveys industry group members about key environmental performance metrics, solid waste included. A technical report published in 1999 presents data on “solid residue generation and management for 1995 from 285 U.S. pulp and paper facilities representing approximately 70% of that year’s U.S. pulp and paper production” [6]. Data were collected for 15 waste types, grouped into three categories: industry wastewater treatment residuals, ash, and miscellaneous solid residues. NCASI extrapolated survey values to the entire industry via 17 product categories. Based on these same product categories, we can forecast 1995 values to 2015 using production statistics published in the *Statistical Abstract of the United States* [7] and the *FAO Yearbook of Forest Products Statistics* [8-9].

The results from the forecast are presented in Table 2.4-3. The total estimated NHIW from the pulp, paper, and paperboard manufacturing sector in 2015 was 11.22 Tg. Wastewater treatment residuals and miscellaneous residues were generated at 4.5 Tg each, while ash quantities were half that tonnage. The first two categories can be broken down by industry subsector because the original data were reported at the product level. Paper production generated the most wastewater treatment residuals, while paperboard yielded the most miscellaneous residues. Ash, on the other hand, was estimated in the original study based on reported quantities and ash content of each fuel consumed.

In the NCASI report, “miscellaneous residues” include 11 waste materials: broke not recovered internally; virgin fiber pulping rejects; secondary fiber pulping rejects; paper mill rejects; lime mud not recycled internally; lime slaker grit; green liquor dregs; solid waste from the wood yard not burned; raw water treatment residuals; general mill refuse; and other waste. The estimates of these waste streams included in the report come from a subset of respondents and are not necessarily representative of the sector as a whole. The report does not provide the product breakdown of each of the wastes, making it imprudent to forecast to 2015. After all, some of these wastes are tied to particular products, e.g. pulp manufacturing will not yield “paper mill rejects;” similarly, recycled paper production will not have “solid waste from the wood yard.” There has not been consistent change in industry output over the past decades, with market pulp declining as paperboard increasing, for instance. As a result, using whole-industry scaling factors is not appropriate, and these miscellaneous residues are excluded.

No eligible historical data were identified for the converted paper products and printing industries.

Table 2.4-3. *NHIW from pulp, paper, and paperboard manufacturing estimated by historical forecasting, 2015*

Waste/Activity	Original (Tg)	Base year	2015 (Tg)	Source
Industry wastewater treatment residuals				
Market pulp (bleached kraft, sulfite)	0.26	1995	0.23	[6, p. 4]
Paper (newsprint, printing & writing, tissue & toweling)	3.79	1995	2.97	[6, p. 4]
Paperboard (corrugating medium, container, box)	1.24	1995	1.30	[6, p. 4]
Subtotal	***5.29***	***1995***	***4.49***	
Miscellaneous residues				
Market pulp (bleached kraft, sulfite)	0.72	1995	0.59	[6, p. 16]
Paper (newsprint, printing & writing, tissue & toweling)	2.45	1995	1.53	[6, p. 16]
Paperboard (corrugating medium, container, box)	2.20	1995	2.38	[6, p. 16]
Subtotal	***5.37***	***1995***	***4.50***	
Ash				
Coal ash	1.28	1995	1.02	[6, p. 12]
Wood/bark ash	1.05	1995	0.83	[6, p. 12]
Wastewater treatment residuals ash	0.48	1995	0.38	[6, p. 12]
Subtotal	***2.81***	***1995***	***2.23***	
TOTAL			**11.22**	

Data from the 1983 PACE survey are forecasted to 2015 in the conventional way, yielding an estimate for total NHIW from these sectors of 24.88 Tg (Table 2.4-4). Most of this comes from mills (17.82 Tg), with an additional 5.85 Tg of NHIW from the printing industry and 1.21 Tg from converted paper production.

Table 2.4-4. *NHIW from the paper manufacturing & printing industries estimated from PACE, 2015 [10]*

NAICS	Description	1983 (Gg)		2015 (Tg)
		NHIW	*APC*	*Total*
3221	Pulp, paper, and paperboard mills			
32211	*Pulp mills*	*1,290.3*	*573.0*	*1.64*
32212	*Paper mills*	*6,112.0*	*2,138.6*	*7.62*
32213	*Paperboard mills*	*3,543.5*	*2,715.9*	*8.56*
	Subtotal	10,945.7	5,427.5	17.82
3222	Converted paper product manufacturing	1,328.3	83.4	1.21
3231	Printing and related support activities	2,615.6	5.7	5.85
313-316	**TOTAL**			**24.88**

2.4.4.2 Spatial Up-Scaling

Scaling up scaling from the Pennsylvania Residual Waste database to the entire nation yields an estimate of 6.19 Tg of NHIW from the paper manufacturing and printing industries (Table 2.4-5). Paper manufacturing is overrepresented in Pennsylvania, with paper mills in that state generating 12% of the output of paper mills nationally. Paperboard is much less prevalent (1% of national output) and there are no dedicated pulp mills that report to the database.

Pennsylvania also has 7% of the total output of both converted paper products and printing industries.

Of the 6.19 Tg total NHIW, 4.48 Tg are generated by paper (3.10 Tg) and paperboard mills (1.38 Tg). An additional 0.69 Tg comes from converted paper product manufacturing and 1.02 Tg from printing.

Table 2.4-5. *NHIW by NAICS sector estimated by up-scaling from PARW data, 2015*

NAICS Code	Description	PA Waste (Gg)	US Waste (Tg)
3221	Pulp, paper, and paperboard mills		
32211	*Pulp mills*	*0.00*	*0.00*
32212	*Paper mills*	*372.8*	*3.10*
32213	*Paperboard mills*	*15.2*	*1.38*
	Subtotal	***388.0***	***4.48***
3222	Converted paper product manufacturing	36.5	0.69
3231	Printing and related support activities	67.0	1.02
322-323	**TOTAL**	**491.4**	**6.19**

Waste composition information for this estimate is shown in Table 2.4-6. The largest material fraction is ash (1.95 Tg), which comes entirely from paper mills. The next largest fraction is paper waste (1.73 Tg), which comes mainly from paperboard mills, converted product manufacturing, and printing, with only a small quantity generated at paper mills. Sludges (0.91 Tg), on the other hand, are generated mainly at paper mills, as are wood wastes (0.20 Tg). The rest of the waste is made of plastic waste (0.54 Tg), plant trash (0.70 Tg), and other wastes (0.15 Tg).

Table 2.4-6. *NHIW from the paper mfg & printing industries estimated by up-scaling from PARW data, 2015*

Waste Type	Source	US Waste (Tg)	% of total
Paper Wastes	Paper mills	0.03	0.5%
	Paperboard mills	0.61	9.9%
	Converted products	0.34	5.4%
	Printing	0.75	12.2%
	Total Paper Wastes	*1.73*	*28.0%*
Wood Wastes	Paper mills	0.18	3.0%
	Converted products	0.01	0.1%
	Printing	0.01	0.1%
	Total Wood Wastes	*0.20*	*3.2%*
Sludges	Paper mills	0.86	13.9%
	Converted products	0.06	0.9%
	Total Sludges	*0.91*	*14.8%*
Ash	Paper mills	1.95	31.5%
Plastic Waste		0.54	8.7%
Plant Trash		0.70	11.3%
Other Waste		0.15	2.4%
TOTAL		**6.19**	**100.0%**

2.4.4.3 Material balance

The material balance estimate of NHIW from the papermaking industry follows the method developed by Ayres & Ayres [11, pp. 58-65] and refined by Krones [12, pp. 107-143]. It is populated by production and consumption data primarily compiled by the Forest Products Laboratory (FPL) of the U.S. Forest Service, the US Geological Survey, and other official bodies. Data on wood, pulp, and paper fiber flows has been published by the FPL through 2013. Here, the material balance is constructed for that year and adjusted based on changes in industry production to 2015 [7].

2.4.4.3.1 Pulping and energy recovery

The FPL reports that 91.25 million cords of pulpwood were consumed in the manufacture of wood pulp in 2013 [13, p. 81]. Based on an average density of 1.36 Mg/cord of pulpwood (air dried) [14, p. 262], this is equivalent to 124.1 Tg of pulpwood input. The FPL also reports that 48.17 Tg of wood pulp was produced in 2013 [13, p. 81], leaving 75.93 Tg of material generated as pulping waste. “Air dried” refers to 15% H_2O content, so this is equivalent to 64.54 Tg of pulping wastes, bone dry.

To determine the fraction of this waste that does not get burned for energy, we turn to the U.S. Energy Information Administration Manufacturing Energy Consumption Survey (MECS), which reports data for 2014. In that year, the paper industry (NAICS 322) produced 859 trillion BTU of heat from pulping liquor and 311 trillion BTU from wood residues [15]. The MECS survey form offers conversion factors for pulping liquor (11 million BTU/short ton) and roundwood (17.2 million BTU/short ton). Converting energy units to mass using these factors, we find the consumption of 70.84 Tg of black liquor and 16.40 Tg of wood residues. Black liquor fuel has a moisture content between 25-35% [16], making the dry content of the consumed black liquor fuel 46.04-53.13 Tg. The wood residue has a moisture content of 15%, giving it a bone-dry equivalent of 13.94 Tg. Taking these figures together, it is clear that effectively all of the input pulpwood is converted either to wood pulp or fuel, with no material left to be disposed of as wood waste. It is possible that the FPL statistics do not include debarking wastes, which may or may not be generated on-site at the mills. For our purposes, however, the material balance does not show a distinct wood waste stream.

The combustion of black liquor and wood, as well as coal, produces ash and other combustion residues. As we have argued, the industry consumed all of the residual pulpwood as fuel in 2013, 64.54 Tg (bone-dry). The MECS also reports the production of 67 trillion BTU from non-process wood [15], the equivalent of an additional 6.75 Tg of wood (bone-dry). With a wood ash content of 5% (dry weight) [6], this total yields a quantity of 3.56 Tg of wood ash. MECS also reported that the paper industry consumed 6.35 Tg of coal in 2014 [17]. With an ash content of 9.5% [6], this is an additional 0.60 Tg of coal ash.

The last component of the pulping material balance involves the input of replacement chemicals. According to Ayres's model, any inputs of chemicals are there to replace chemicals that have been lost (after adjusting for changes in production volume from year to year). The USGS reports the consumption of a variety of pulping and bleaching chemicals (all 2015 values): 943 Gg of lime [18, p. 9]; 59 Gg of soda ash [19, p. 6]; 69 Gg of salt [20, p. 13]; and 124 Gg of sulfuric acid [21, p. 10]. Other chemical inputs to pulping are not included here.

2.4.4.3.2 Papermaking

The FPL publishes data on fiber inputs and outputs in papermaking. In the past, these data have been useful in estimating fiber and chemical wastes from this step in the manufacturing process. However, for 2013, the mass of reported paper production exceeds that of reported fiber consumption: 73.01 Tg out vs. 68.82 Tg in [13, p. 77]. It is unclear how this would be possible. Nevertheless, we can still glean some information about NHIW from these (albeit suspect) data. FPL reports that 27.15 Tg of recovered paper was used in papermaking in 2013. There is a loss of about 10% of recovered paper in the de-inking process [22, p. 21], which would result in 2.72 Tg of deinking sludge being generated in the process.

Papermaking chemicals include various fillers and coatings. Replacement chemicals can also be proxies for waste. The USGS reports the consumption of three coating/filler materials (all 2015 values): 944 Gg of kaolin clay [23, p. 17]; 83 Gg of talc [24, p. 4]; and 35.7 Gg of titanium dioxide [25, pp. 9-10].

A summary of the pulp and paper manufacturing waste flows estimated using material balance is presented in Table 2.4-7. No similar data was identified for the converted paper production or printing sectors.

Table 2.4-7. *NHIW from the pulp and paper manufacturing sectors estimated by material balance, 2015*

Waste type	Waste	Original (Tg)	Base Year	2015 (Tg)
Sludge	Pulping sludge	1.20	2015	1.20
	De-inking sludge	2.72	2013	2.67
	Papermaking sludge	1.06	2015	1.06
	Subtotal			***4.93***
Ash	Pulping liquor ash	3.23	2013	3.17
	Wood ash	0.34	2014	0.34
	Coal ash	0.60	2014	0.59
	Subtotal			***4.10***
TOTAL				**9.03**

2.4.4.4 International comparison

European waste data suggest that US paper manufacturing and printing industries generated 24.40 ± 14.49 Tg of NHIW in 2015 (see Table 2.4-8). The two largest fractions are wood wastes and paper wastes, estimated to be 7.92 ± 12.98 Tg and 4.91 ± 4.92, respectively. Sludges and chemical wastes total 4.66 ± 5.06 Tg and ash (combustion wastes) 1.58 ± 1.16 Tg. The balance of the account is made up of non-process wastes.

It is clear from these figures that there is quite a bit of variability among the 28 countries reporting waste from this sector. Even among the largest sectoral waste producers in Europe—Finland, France, and Germany—the distribution is broad. For example, the Finnish industry generates nearly 130 Mg of wood waste per million USD output, while German industry generates just 1.98 Mg/million USD. This likely has to do with policies that encourage or discourage burning wood for energy. In any event, these large uncertainties limit the usefulness of the international comparison estimate for this sector beyond an order of magnitude assessment.

Table 2.4-8. *NHIW from the paper manufacturing and printing industries estimated using European waste data*

	Waste intensity (Mg/$1,000)		**US Waste 2015 (Tg)**	
	Average	*Std. Dev.*	*Average*	*Std. Dev.*
Acid, alkaline or saline wastes	2.05	3.83	0.55	1.03
Chemical wastes	3.36	3.55	0.91	0.96
Industrial effluent sludges	6.91	4.80	1.87	1.30
Common sludges	4.94	6.54	1.33	1.77
Paper and cardboard wastes	18.19	18.23	4.91	4.92
Wood wastes	29.32	48.07	7.92	12.98
Combustion wastes	5.86	4.31	1.58	1.16
Recyclable wastes	2.07	1.08	0.56	0.29
Mixed ordinary wastes	15.00	7.88	4.05	2.13
Other wastes	1.81	2.24	0.49	0.60
Total Waste	**90.36**	**53.66**	**24.40**	**14.49**

Sum of individual wastes may not equal "total waste" due to rounding errors and because of inconsistencies in the raw data.

2.4.4.5 Triangulation & Synthesis

2.4.4.5.1 NAICS 3221: Pulp, paper, and paperboard mills

The total estimated quantity of NHIW from pulp, paper, and paperboard manufacturing ranges from 4.48 to 17.82, depending on the estimation method. There is reasonable agreement among the estimates for sludge generation: 4.49 Tg from the NCASI survey forecast, 4.66 Tg from international comparison, and 4.93 Tg from the material balance. The latter two estimates are useful only in that they point to the likely accuracy of the NCASI results. The outlier is the 0.86 Tg estimated from the PARW scale-up. It is not clear why this value is so much smaller than the others. It is possible that it is due to a particular bias in the type of paper mill that happens to be in Pennsylvania. More likely it is an artifact of how industry codes are assigned in the database, with the wastewater treatment residuals allocated to some downstream wastewater facility rather than the generating mill.

Estimates of ash generation at pulp, paper, and paperboard mills are: 1.16 Tg (international), 1.95 Tg (PARW), 2.23 (NCASI), and 4.10 (material balance). Again, the NCASI-based value is likely the most accurate one here. The international statistics have been shown to be highly variable while the PARW-based estimate only includes ash generated at paper mills (with nothing reported for either pulp or paperboard mills). That the material balance estimate is nearly twice that of the NCASI-based estimate suggests that either the underlying data or the model logic is flawed, and not all the pulping liquor or pulpwood residue is burned for energy recovery. This is further validated by the 4.50 Tg of "miscellaneous waste" estimated with the NCASI data that does not appear anywhere else. Some of this could be made up of uncombusted wood waste in a different version of the material balance. The 7.92 Tg of wood waste from the European data is too uncertain to be useful while the 0.18 Tg of wood waste from the PARW-based estimate cannot be reconciled with the reported NCASI data.

Ultimately, the results from the NCASI-based forecast prevail: 11.22 Tg from pulp, paper, and paperboard mills. Interestingly, this is very close to the quantity of NHIW forecast from the 1983 PACE survey data for these subsectors (excluding the APC tonnage): 11.62 Tg.

2.4.4.5.2 NAICS 3222, 323: Converted paper products & Printing

There are fewer data points from which to triangulate estimates of NHIW from converted paper products and printing. The PACE-based estimate offers 1.21 Tg and 5.85 Tg, respectively, while the PARW-based estimate is 0.69 Tg and 1.02 Tg, respectively. How to close the wide gulf between these two estimates is not immediately clear. Roughly half of the tonnage from the PARW-based estimate is classified as paper waste, while the balance is some form of generic factory and MSW-type waste. There is no composition information from PACE, but those values are of the same order as the paper and cardboard waste value from the international comparison (4.91 Tg). In the U.S., a lot of converting and printing scrap is returned to paper and paperboard mills as “pulp substitute” or “high grade deinking” recovered fiber. In this case, the larger PACE numbers may not be fully accurate (seeing as how they are 36 years old), and we can more reliably use the figures from the upscaling estimate.

2.4.4.5.3 Summary

The NHIW values triangulated above are presented in Table 2.4-9. The grand total is 12.93 Tg of NHIW from the paper manufacturing and printing sectors, most of which comes from pulp, paper, and paperboard mills.

Table 2.4-9. *Triangulated estimate of NHIW from the paper manufacturing and printing sectors, 2015*

NAICS	Subsector/Waste material	NHIW (Tg)	Notes
3221	Pulp, Paper, and Paperboard Mills		
	Wastewater residuals/sludges	4.49	Incl. pulping, bleaching, papermaking, and deinking sludges
	Ash	2.23	Incl. coal ash, wood/bark ash, and pulping liquor ash
	Miscellaneous residues	4.50	Incl. wood waste, chemical wastes, and product rejects
	Total	***11.22***	
3222	Converted Paper Products	0.69	
323	Printing and Related Support Activities	1.02	
	Grand Total	**12.93**	

2.5 Petroleum & Coal Products Manufacturing (NAICS 324)

2.5.1 Summary

The petroleum and coal products manufacturing sector is estimated to have generated 6.76 Tg (6.43-7.40 Tg) of NHIW in 2015. Half of this quantity (3.36 Tg; 3.03-4.00 Tg) is estimated to come from petroleum refineries, including 1.04-1.46 Tg of spent caustic, 0.77-1.06 Tg of sludges, and 0.55-0.70 Tg of contaminated soil, with smaller quantities of spent catalyst, off-spec coke and fines, ash, and other wastes. Asphalt manufacturing is estimated to have generated 2.88 Tg of NHIW, 86% of which is air pollution control dust. Other petroleum and coal products generated 0.52 Tg, made up of sludge, ash, and contaminated soil.

2.5.2 Industry structure

Firms in the petroleum and coal products manufacturing industry are involved primarily with the conversion of crude oil to petroleum products like gasoline, asphalt, and lubricating oils; and the conversion of coal to coke and related products in merchant facilities (i.e. not integrated with steel mills). Although the number of products from this industry is quite large, most petroleum products are produced in large, integrated refineries, which is why, despite the diversity of products, the NAICS structure has just three subsectors (see Table 2.5-1).

Table 2.5-1. NAICS 2017 structure of the petroleum & coal products manufacturing sectors [1]

324	**Petroleum and Coal Products Manufacturing**
3241	Petroleum and Coal Products
32411	Petroleum Refineries
32412	Asphalt Paving, Roofing, and Saturated Materials
32419	Other Petroleum and Coal Products

The value added by this sector over the period 2007-2016 fluctuated between $80 billion and $132 billion and between 3.6% and 5.7% of total contribution of manufacturing to GDP (Figure 2.5-1) [2]. The overwhelming fraction of value added from this sector comes from petroleum refining, with the balance split roughly evenly between asphalt and coal products manufacturing.

The high volatility in the economic output from this sector illustrated in Figure 2.5-1 is the result of the special role that petroleum plays in the economy. This volatility is not reflected in the physical throughput of the industry. While value added by petroleum refineries decreased by 31.7% from 2007 to 2016, gross inputs of crude oil to U.S. refineries increased by 6.9% over the same period [3].

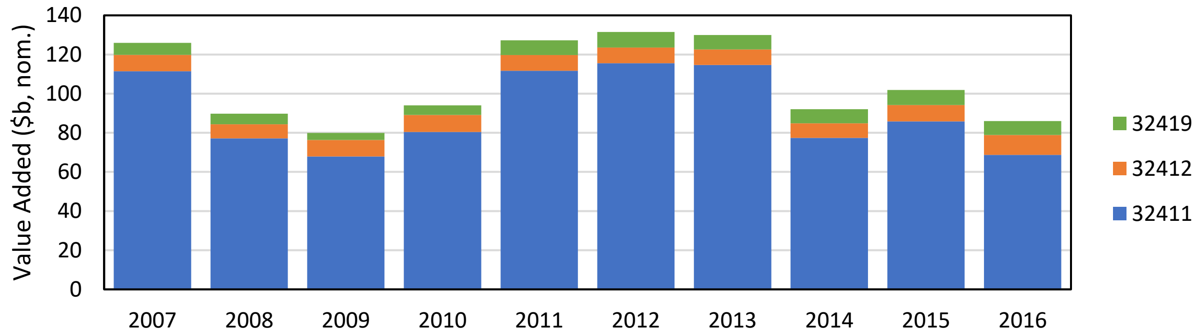

Figure 2.5-1. *Value added (billion $, nominal) from industry sector 324, 2007-2016 [2]*

2.5.3 Solid wastes from NAICS 324

Wastes from petroleum refining and coal products manufacturing include process residuals (i.e. fractions of input raw materials that are not desired in saleable outputs); pollution control residuals; wastewater and other sludges; and spent catalysts, caustics, filters, and other process residues [4]. These activities also often result in soil and other materials contaminated with petroleum and other chemicals.

Many of the waste categories from these sectors have been deemed hazardous under RCRA. There are nine K-listed wastes associated with petroleum refining (K048-K052 and K169-K172) and nine K-listed wastes associated with coal product manufacturing (K060, K087, K141-K145, and K147-K148). In addition, there are two F-list wastes for petroleum refineries (F037-F038). On top of these listed wastes, many more wastes are hazardous by virtue of their hazardous characteristics.

Wastes from these industries included in the European Waste Catalog are listed in Table 2.5-2 [5].

Table 2.5-2. *Petroleum refining & coal products manufacturing wastes as listed in the European Waste Catalog [5]*

Activity	**Waste category** ***Hazardous***	 ***Non-hazardous***
Petroleum refining	- desalter sludges - tank bottom sludges - acid alkyl sludges - oil spills - oily sludges from maintenance - acid & other tars - wastewater sludge - wastes from cleaning of fuels with bases - oil containing acids - spent filter clays	- wastewater sludge - boiler feedwater sludges - wastes from cooling columns - sulfur-containing wastes from petroleum desulfurization - bitumen
Coal product manufacturing	- acid & other tars	- waste from cooling columns

Estimating NHIW from these sectors is particularly challenging for four reasons. First, petroleum refining occurs in the liquid and gas phases, which means the process residuals are largely liquid or sludge, with varying quantities of water from facility to facility. Second, even though it is estimated that the majority of wastes from petroleum refining is non-hazardous, a substantial quantity is still either hazardous or could be deemed hazardous, depending on handling practices. Third, there is considerable release to air of volatiles from hydrocarbon contaminated soils and other wastes, so over time, the same waste materials could be classified in different waste categories. Finally, because of the dominance of petroleum refining to this industry, most of the focus is on that subsector at the expense of asphalt and coal products manufacturing. Even though these other subsectors are small relative to petroleum refining, they still produce wastes that should be included in this account.

2.5.4 NHIW estimation

2.5.4.1 Historical forecasting

Two distinct sources (in addition to the 1983 PACE survey) were identified for use in historical forecasting for wastes from the petroleum refining industry: industry data collected by the American Petroleum Institute and survey data collected by the U.S. EPA. Forecasts of each of these sources are conducted based on annual gross inputs to U.S. refineries published by the U.S. EIA, rather than economic data published by the U.S. Census Bureau. The latter remains the forecasting method for the 1983 PACE data.

2.5.4.1.1 Forecast from 1997 API survey

The American Petroleum Institute (API) is an industry group for the petroleum refining industry. For many years it has conducted periodic studies on generation and management practices of residuals from refining. A recent study with publicly available data is the 1997 *Management of Residual Materials: 1995 – Petroleum Refining Performance* (API Publication 339). This study collated data from a subset of U.S. refineries extrapolated to the entire industry for both 1994 and 1995. The data are reproduced in a report released by the U.S. Department of Energy [4, p. 32]. Both years are used here because the data show nearly 40% more waste generated in 1994 than in 1995. Comparing these values and waste categories to previous API surveys (e.g. [6]), there are a number of waste types excluded in the more recent survey data, including spent acids and other inorganic wastes, waste coke/carbon/charcoal, and aqueous wastes.

Results from this forecast show a total of 4.50 Tg of residuals generated in 2015 based on the 1994 data and 3.22 Tg of residuals based on the 1995 data (both wet-basis). Excluding the listed hazardous wastes, the totals are 3.56 Tg and 2.57 Tg, respectively The largest fractions of these estimates are spent caustics, biomass, and contaminated soil/solids, which together make up roughly 85% of the non-listed totals for both years. See Table 2.5-3 for complete estimate.

Table 2.5-3. *Wastes from petroleum refining estimated by historical forecasting from 1997 API survey [4]*

Waste Type (with RCRA code)	**Original ('000 tons, wet)**		**2015 (Tg)**		**Source**
	1994	1995	1994	1995	
API Separator Sludge (K051)	101	37	0.11	0.04	[4, p. 32]
DAF Float (K048)	355	164	0.38	0.17	[4, p. 32]
Slop Oil Emulsion Solids (K049)	49	225	0.05	0.24	[4, p. 32]
Tank Bottoms	87	83	0.09	0.09	[4, p. 32]
Primary Sludges (F037-8)	328	128	0.35	0.14	[4, p. 32]
Pond Sediments	143	65	0.15	0.07	[4, p. 32]
Contaminated Soil/Solids	661	525	0.70	0.55	[4, p. 32]
FCC Catalyst or Equivalent	286	173	0.30	0.18	[4, p. 32]
Hydroprocessing Catalysts (K171-2)	53	63	0.06	0.07	[4, p. 32]
Other Spent Catalysts	18	15	0.02	0.02	[4, p. 32]
Biomass	773	582	0.82	0.61	[4, p. 32]
Spent Caustics	1,379	988	1.46	1.04	[4, p. 32]
TOTAL			**4.50**	**3.22**	
TOTAL, excluding RCRA-listed wastes			***3.56***	***2.57***	

It is possible to perform the same forecast using data from earlier API surveys. The most recent data is used here because it presumably reflects industry practice most similar to how today's refineries operate. However, given the wide gulf between the 1994- and 1995-basis estimates from the 1997 survey, it is useful to look briefly at another, previous, survey. The 1991 API survey presents data from 1987 and 1988 [6]. This forecast suggests 2015 totals of 5.59 Tg (1987 basis) and 5.54 Tg (1988 basis), or excluding listed wastes, 4.09 Tg (1987) and 4.12 Tg (1988). Much of the difference between this estimate and the one presented in Table 2.5-3 is due to the waste categories that are not included in the later account. If the earlier account is limited to the same waste categories as listed in Table 2.5-3, however, the totals become 2.70 Tg and 2.56 Tg of non-listed wastes, respectively.

2.5.4.1.2 Forecast from 1996 EPA study

The other source for a bottom-up historical forecast comes from the EPA. In 1992, the EPA issued a survey to all petroleum refineries operating in the U.S. as authorized by RCRA §3007, requesting information on, among many other things, quantity generated of each of 29 petroleum refining residuals [7]. Responses were received from 172 of the 185 refineries.

Results from this forecast are presented in Table 2.5-4. It estimates that petroleum refineries generated 3.65 Tg of non-listed waste in 2015 (wet basis). The majority of this waste is in the form of sulfuric acid alkylation catalysts (2.13 Tg), with much of the rest of the tonnage spent caustic (1.11 Tg). FCC catalyst and fines and off-spec coke and fines each make up an additional 0.23 Tg. The remaining 25 waste categories together make up the balance.

Table 2.5-4. *Wastes from petroleum refining estimated by historical forecasting from 1996 EPA study [7]*

Waste Type	Original (Gg)	Base year	2015 (Tg)	Source
Sludges/Sediments				
Clarified slurry oil (CSO) sludge from catalytic cracking (K170)	24.0	1992	0.03	[7, p. 41]
Unleaded gasoline storage tank sludge	3.6	1992	0.00	[7, p. 41]
Crude oil storage tank sludge (K169)	22.0	1992	0.03	[7, p. 41]
Process sludge from sulfur complex and H_2S removal facilities	8.5	1992	0.01	[7, p. 42]
Sludge from HF alkylation	11.3	1992	0.01	[7, p. 42]
Sludge from H_2SO_4 alkylation	0.6	1992	0.00	[7, p. 41]
Desalting sludge from crude desalting	4.8	1992	0.01	[7, p. 41]
Residual oil storage tank sludge	9.1	1992	0.01	[7, p. 41]
Process sludge from residual upgrading	0.2	1992	0.00	[7, p. 42]
Catalysts				
Catalyst from catalytic hydrotreating (K171)	5.6	1992	0.01	[7, p. 41]
Catalyst from catalytic reforming	3.6	1992	0.00	[7, p. 41]
Catalyst from catalytic cracking (FCC catalyst)	124.1	1992	0.15	[7, p. 41]
Fines from catalytic cracking (FCC fines)	67.8	1992	0.08	[7, p. 41]
Catalyst from catalytic hydrorefining (K172)	18.6	1992	0.02	[7, p. 41]
Catalyst from H2SO4 alkylation	1,760.1	1992	2.13	[7, p. 41]
Catalyst from sulfur complex and H_2S removal facilities	4.2	1992	0.00	[7, p. 42]
Catalyst from extraction/isomerization processes	0.3	1992	0.00	[7, p. 41]
Catalyst from catalytic hydrocracking	18.0	1992	0.02	[7, p. 41]
Catalyst from polymerization	4.1	1992	0.00	[7, p. 41]
Catalyst from HF alkylation	0.2	1992	0.00	[7, p. 42]
Off-Spec Products				
Off-spec coke and fines	194.3	1992	0.23	[7, p. 42]
Off-spec product and fines from residual upgrading	0.8	1992	0.00	[7, p. 42]
Off-spec sulfur	9.6	1992	0.01	[7, p. 42]
Treating Clays				
Treating clay from clay filtering	9.0	1992	0.01	[7, p. 42]
Treating clay from lube oil processing	0.7	1992	0.00	[7, p. 42]
Treating clay from the extraction/isomerization process	2.5	1992	0.00	[7, p. 41]
Treating clay from alkylation	2.9	1992	0.00	[7, p. 42]
Miscellaneous Residuals				
Spent caustic from liquid treating	917.7	1992	1.11	[7, p. 42]
Spent amine and spent Stretford solution	23.9	1992	0.03	[7, p. 42]
Acid-soluble oil from HF alkylation (ASO)	33.5	1992	0.04	[7, p. 42]
TOTAL			**3.97**	
TOTAL, excluding K-listed wastes			**3.65**	

2.5.4.1.3 Forecast from 1983 PACE survey

The PACE survey is the only one that offers a historical forecast estimate of non-refinery components of this industry sector. Results shown in Table 2.5-5 suggest a total NHIW generation of 3.41 Tg in 2015. It is unclear if this is a dry or wet mass basis. NHIW from petroleum refineries make up 60% of the total (2.04 Tg), asphalt production makes up 28% (0.97 Tg), and coal products make up the rest (0.41 Tg). Asphalt and coal products manufacturing shows a much higher proportion of air pollution control residues than the petroleum refining subsector.

Table 2.5-5. *NHIW from the petroleum and coal products manufacturing industry estimated from PACE, 2015 [8]*

NAICS	Description	1983 (Gg) *NHIW*	*APC*	2015 (Tg) *Total*
3241	Petroleum and coal products			
32411	*Petroleum refineries*	*1,384.3*	*339.5*	*2.04*
32412	*Asphalt paving, roofing, and saturated materials*	*222.4*	*194.7*	*0.97*
32419	*Other petroleum and coal products*	*32.0*	*114.1*	*0.41*
324	**TOTAL**			**3.41**

2.5.4.2 Spatial Up-Scaling

Up-scaling from Pennsylvania Residual Waste data yields an estimate of 7.65 Tg of NHIW for petroleum refining and coal products manufacturing in 2015. Even though the U.S. petroleum industry had its origins in Pennsylvania, today that state's industry (187 facilities) makes up just 2% of national shipments.

As shown in Table 2.5-6, petroleum refineries contribute 52% of the total NHIW estimated by up-scaling, or 4.00 Tg. Asphalt manufacturers contribute 39%, 2.99 Tg, and coal products manufacturers contribute the balance, 0.66 Tg.

Table 2.5-6. *NHIW by NAICS sector estimated by up-scaling from PARW data, 2015*

NAICS Code	Description	PA Waste (Gg)	US Waste (Tg)
3241	Petroleum and coal products		
32411	*Petroleum refineries*	*80.2*	*4.00*
32412	*Asphalt paving, roofing, and saturated materials*	*88.8*	*2.99*
32419	*Other petroleum and coal products*	*19.4*	*0.66*
324	**TOTAL**	**188.4**	**7.65**

Analysis of the waste composition (Table 2.5-7) shows that petroleum refining waste are mainly contaminated soil/debris (2.38 Tg), wastewater sludges (0.89 Tg), spent catalysts (0.21 Tg), and ash (0.13 Tg). Asphalt manufacturing wastes are primarily air pollution control (baghouse) dust (2.49 Tg) and asphalt wastes (0.39 Tg). Coal products manufacturing wastes are mainly wastewater sludges (0.32 Tg) and ash (0.15 Tg).

2.5.4.3 Material balance

A material balance model was constructed for petroleum refining in the United States. It relies on data published by the Energy Information Administration and the U.S. Geological Survey. The structure of the industry subsector and the data itself enable a single material balance point, where all inputs and converted into all outputs.

Table 2.5-7. *NHIW from petroleum and coal products mfg estimated by up-scaling from PARW data, 2015*

Waste Type	**Source**	**US Waste (Tg)**	**% of total**
Baghouse Dust	Asphalt materials	2.49	32.6%
Contaminated Soil/Debris	Petroleum refining	2.38	31.2%
	Other petroleum & coal products	0.05	0.7%
	Total Contaminated Soil/Debris	*2.44*	*31.9%*
Sludge	Petroleum refining	0.89	11.7%
	Other petroleum & coal products	0.32	4.1%
	Total Sludges	*1.21*	*15.8%*
Asphalt Wastes	Petroleum refining	0.01	0.2%
	Asphalt materials	0.39	5.1%
	Total Asphalt Wastes	*0.40*	*5.3%*
Ash	Petroleum refining	0.13	1.6%
	Other petroleum & coal products	0.15	2.0%
	Total Ash	*0.28*	*3.6%*
Spent Catalysts	Petroleum refining	0.21	2.8%
Other Waste		0.30	3.9%
Plant Trash		0.32	4.2%
TOTAL		**7.65**	**100.0%**

The bulk of the material balance data comes from two EIA data products: “Refinery & Blender Net Input” and “Refinery & Blender Net Production” [9-10]. EIA publishes all data related to petroleum refining in terms of “thousand barrels,” a volumetric unit that does not obey a conservation law. Using a table of density factors from the U.S. EPA [11], these volumes are converted to masses and reported in Table 2.5-8, along with data on sulfur flows from the USGS [12].

Overall, in 2015, I calculated that petroleum refineries input 926.32 Tg of material, 88% of which was crude oil. Outputs totaled 922.95 Tg, leaving 3.37 Tg unaccounted for. This is equivalent to an estimate of process residuals in petroleum refining.

Table 2.5-8. *Lost mass from petroleum refining estimated by material balance, 2015*

Input Material flow	**2015 (Tg)**	**Source**	**Output Material flow**	**2015 (Tg)**	**Source**
Crude Oil	815.74	[9]	Liquefied Refinery Gases	18.03	[10]
Hydrocarbon Gas Liquids	17.71	[9]	Gasoline	413.18	[10]
Fuel Ethanol	41.29	[9]	Aviation Fuel	76.35	[10]
Other Liquids	48.90	[9]	Distillate Fuel Oil	244.44	[10]
Sulfur	2.68	[12, p. 10]	Residual Fuel Oil	20.78	[10]
			Petrochemical Feedstocks	13.17	[10]
			Petroleum Coke	57.96	[10]
			Asphalt and Road Oil	20.33	[10]
			Still Gas	35.01	[10]
			Other Petroleum Products	15.78	[10]
			Recovered Sulfur	7.91	[12, p. 8]
Total In	***926.32***		***Total Out***	***922.95***	
		Lost Mass 3.37 Tg			

2.5.4.4 International comparison

European waste data suggest that petroleum and coal products manufacturing industries in the U.S. generated 15.92 ± 38.37 Tg of NHIW in 2015 (Table 2.5-9). The largest component of this account by far, and the source of the greatest variability (where the standard deviation is more than three times the magnitude of the average value) is in mineral wastes. Excluding the single outlier value from Estonia in this material category, the total becomes 4.48 ± 3.20 Tg. Further restricting the estimate to eliminate ordinary plant trash and metallic wastes, the total becomes 3.76 ± 3.49 Tg. The majority of this tonnage is in the form of chemical and medical wastes, specifically acid, alkaline, or saline wastes. Contaminated soils also make up a good sized fraction of the total.

The Netherlands contributes a full 51% of the total waste in this sector. This is due to that country's significant petroleum refining capacity (cf. Royal Dutch Shell). Germany and France also contribute to the total.

Table 2.5-9. *NHIW from petroleum and coal products manufacturing estimated using European waste data*

	Waste intensity (Mg/$1,000)		**US Waste 2015 (Tg)**	
	Average	*Std. Dev.*	*Average*	*Std. Dev.*
Chemical and medical wastes	5.70	5.59	2.80	2.75
Metallic wastes	0.67	1.40	0.33	0.69
Mixed ordinary waste	0.78	1.46	0.38	0.72
Soils	1.36	1.23	0.67	0.61
Mineral wastes	23.49	77.06	11.55	37.89
Other wastes	0.37	0.27	0.18	0.13
Total Waste	**32.38**	**78.04**	**15.92**	**38.37**

Sum of individual wastes may not equal "total waste" due to rounding errors and because of inconsistencies in the raw data.

2.5.4.5 Triangulation & Synthesis

2.5.4.5.1 Petroleum refineries

Estimates for NHIW from petroleum refineries range include 2.04 Tg (from PACE), 2.57-3.56 Tg (from the API survey), 3.37 Tg (from material balance), 3.65 Tg (from the 1992 EPA survey) and 3.61 Tg (from the PARW data, excluding plant trash and other non-process waste). It is highly likely that the "real" value of NHIW from petroleum refineries in 2015 falls somewhere in this range: 2-4 Tg. However, as the scope of each of the estimates varies slightly, it is prudent to compare results material-by-material, where possible.

Three estimates have composition data: historical forecasts from the API and EPA surveys and up-scaling from the PARW data. The other estimates (PACE forecast and material balance) are simply the totals.

2.5.4.5.1.1 Spent caustic

Both API- and EPA-derived accounts include estimates of spent caustic solution: 1.04-1.46 Tg and 1.11 Tg, respectively. This is a wastewater containing a caustic chemical (e.g. NaOH) that is used to remove sulfur compounds from crude oil [13, p. 826]. There is no standardization around the water content of this stream, so we use the entire estimate range: 1.04-1.46 Tg. (A forecast of a previous API survey estimates a lower quantity of spent caustic, 0.73-0.77 Tg, but also includes other categories of chemical waste that may overlap with spent caustic.)

2.5.4.5.1.2 Spent catalyst

Spent catalyst quantities are estimated in all three accounts, although each represents this waste stream slightly differently. API and EPA both include estimates of spent fluid catalytic cracking (FCC) catalysts: 0.18-0.30 Tg and 0.23 Tg, respectively. The EPA-derived account also includes 2.13 Tg of spent sulfuric acid alkylation catalyst and 0.04 Tg of other catalysts. The API-derived account includes 0.02 Tg of other spent catalysts and the account upscaled from PARW data refers to 0.21 Tg of generic spent catalyst. The variability in this waste category is explained in part by the different approaches to recycling and regenerating these catalysts. Some catalysts can be regenerated (i.e. cleaned so they can be reused) inside the refinery itself, while others must be sent to third party facilities for this process [13]. The degree to which one approach is used over another is determined largely by the technology available and industry best practice. The PARW data presents the most recent look at spent catalyst generation, and suggests that the 2.13 Tg of spent sulfuric acid alkylation catalyst reported in the EPA-derived account is an outlier. We can confidently claim an estimate of 0.21-0.32 Tg of spent catalyst, most of which is FCC catalyst. (Hydroprocessing catalysts are listed hazardous wastes, and are therefore excluded from this account.)

2.5.4.5.1.3 Contaminated soils/solids

Contaminated soil is included in both the API-based forecast and the PARW upscaled estimate. Soil contamination is not a fundamental part of petroleum refining (even if it is quite common). It is therefore difficult to say if one estimate is more "correct" than another, as any point estimates will be based on specific practices and instances of contamination in the base year. Pennsylvania, with its old refineries, may simply have more contaminated soil due to age and, perhaps, construction activities. Nevertheless, there is an apparent trend of increasing quantities of soil contamination over time: the earlier API survey yields an estimate of just 0.28-0.34 Tg of contaminated soil in 2015; the later API survey yields 0.55-0.70 Tg, and the contemporary PARW data shows 2.38 Tg. The latter value seems like an outlier, so with prudence, the middle values are used here.

2.5.4.5.1.4 Sludges

Sludges come in many types in petroleum refineries. The API survey includes specific categories of sludge: tank bottoms (0.09 Tg), pond sediments (0.07-0.15 Tg) and biomass (0.61-0.82). Both the EPA-derived estimate and the PARW-derived estimate offer generic values for non-hazardous sludges: 0.05 Tg and 0.89 Tg, respectively. We can discount the EPA value and then the total API estimate and the PARW estimate roughly align: 0.77-1.06 Tg.

2.5.4.5.1.5 Other wastes

There remain a few waste categories that are each only presented in one account estimate. These include 0.23 Tg of off-spec coke and fines, 0.07 Tg of chemical wastes, and 0.02 Tg of treating clays from the EPA-based forecast; and 0.13 Tg of ash and 0.01 Tg of asphalt waste from the PARW upscaled estimate. With no reason to exclude these wastes, they are all included.

2.5.4.5.1.6 Summary

In total, the material-by-material estimate constructed above yields a range of 3.03-4.00 Tg of NHIW generated by refineries in 2015. This is somewhat above the gross estimate from the PACE data (2.04 Tg) but squarely in line with the material balance estimate (3.37 Tg).

2.5.4.5.2 Asphalt paving, roofing, and saturated materials

NHIW from asphalt paving, roofing, and saturated materials manufacturing is estimated from just two sources: the 1983 PACE survey (0.97 Tg) and the PARW data (2.88 Tg). The PACE-derived estimate is considerably lower than that from PARW, but as the majority of the PARW-based account is air pollution control dust (2.49 Tg), a quantity that would inevitably increase as air pollution standards tightened over the decades between PACE (1983) and PARW (2014-2016), the latter estimate is the more believable one.

2.5.4.5.3 Other petroleum and coal products

NHIW from other petroleum and coal products manufacturing is estimated from just two sources: the 1983 PACE survey (0.41 Tg) and the PARW data (0.52 Tg). The PARW account includes a composition breakdown, and given its contemporary provenance, it is likely more accurate than the 1983 PACE data.

2.5.4.5.4 Summary

In total, NHIW from the petroleum and coal products manufacturing sectors is estimated to be 6.43-7.40 Tg in 2015, with a mid-range value of 6.76 Tg (Table 2.5-10). This is roughly twice the magnitude of the estimate from European data, once outliers have been excluded. The latter value is not of great utility for this sectoral triangulation in large part due to different hazard determination criteria in the U.S. and EU.

Table 2.5-10. *Triangulated estimate of NHIW from the petroleum and coal products manufacturing sectors, 2015*

NAICS	Subsector/Waste material	NHIW (Tg) *L*	*M*	*H*	Notes
32411	Petroleum refineries				
	Spent caustic	1.04	1.11	1.46	
	Spent catalyst	0.21	0.27	0.32	Excludes hazardous hydroprocessing catalyst and uncertain quantities of H_2SO_4 alkylation catalyst
	Contaminated soil	0.55	--	0.70	
	Sludges	0.77	0.89	1.06	Includes tank bottoms, pond sediments, and bio-sludge
	Off-spec coke and fines		0.23		
	Ash		0.13		
	Other chemical wastes		0.07		Includes spent amine, Stretford solution, and acid-soluble oil from HF alkylation
	Treating clays		0.02		
	Asphalt waste		0.01		
	Subtotal	***3.03***	***3.36***	***4.00***	
32412	Asphalt paving, roofing, and saturated materials				
	Asphalt waste		0.39		
	Baghouse dust		2.49		
	Subtotal		***2.88***		
32419	Other petroleum and coal products				
	Sludge		*0.32*		
	Ash		*0.15*		
	Contaminated soil		*0.05*		
	Subtotal		***0.52***		
324	**Grand Total**	**6.43**	**6.76**	**7.40**	

2.6 Chemical, Plastics & Rubber Products Mfg (NAICS 325-326)

2.6.1 Summary

The chemical, plastics, and rubber products manufacturing sectors are estimated to have generated 135.30-143.89 Tg of NHIW in 2015. The vast majority of this tonnage (79-84%) is composed of phosphogypsum from the manufacturing of phosphatic fertilizers. An additional 12-14% arises from organic chemicals manufacturing, although that sector is also known to generate much larger quantities of aqueous and hazardous wastes that are not accounted for here. The other subsectors contribute much smaller quantities of NHIW, such as the 1.15-2.74 Tg from plastics and rubber products manufacturing.

2.6.2 Industry structure

The chemical, plastics, and rubber products manufacturing sectors span two NAICS sector codes: 325 and 326. Firms in the chemical manufacturing sector (NAICS 325) convert petroleum and minerals and their derivatives into a vast catalogue of organic and inorganic chemical products, both intermediate and final. Intermediate products from the chemicals industry are then used as feedstocks for plastic and rubber products manufacturers (NAICS 326). Although generally linked by types of manufacturing processes and in some cases by continuous value chains, these are large, diverse sectors for which generalization can be difficult. Together, the two sector codes comprise nine individual four-digit subsectors and many more at lower levels of aggregation (Table 2.6-1) [1]. There are historical reasons for this diversity, as the size, complexity, and economic importance of the chemicals industries have grown dramatically in the time horizon that the federal government has been maintaining national economic accounts. As a result, the three-digit level of aggregation for NAICS 325 in particular is rarely a practical object of analysis. Nevertheless, this is the level at which many data products are published, and provides a degree of comparison in this study with the other sectors covered.

The chemical manufacturing sector is the largest manufacturing industrial sector in the country: in 2016 it produced 16.6% of the total value added from manufacturers to the U.S. economy (plastics and rubber products produced an additional 4.9%) [2]. From 2007-2016, these sectors together grew by 11.6%, in 2016 exceeding half a trillion dollars in value added terms (Figure 2.6-1). The largest subsectors are pharmaceuticals, basic chemicals, and plastics, each contributing more than 4% of total manufacturing GDP. This measure is a poor indicator of physical throughput, however, especially in an industry that combines both extremely high value-add products (e.g. pharmaceuticals) and commodity products.

Table 2.6-1. NAICS 2017 structure of the chemical, plastic & rubber product manufacturing sectors [1]

325 Chemical Manufacturing	
3251 Basic Chemicals	
32511 Petrochemicals	
32512 Industrial Gas	
32513 Synthetic Dyes and Pigments	
32518 Other Basic Inorganic Chemicals	
32519 Other Basic Organic Chemicals	
3252 Resins, Synthetic Rubbers, Fibers and Filaments	
32521 Resins and Synthetic Rubbers	
32522 Artificial and Synthetic Fibers and Filaments	
3253 Pesticide, Fertilizer, and Other Agricultural Chemicals	
32531 Fertilizer	
32532 Pesticide and Other Agricultural Chemicals	
3254 Pharmaceuticals and Medicine*	
3255 Paints, Coatings, and Adhesives	
32551 Paints and Coatings	
32552 Adhesives	
3256 Soaps, Cleaning Compounds, and Toilet Preparations	
32561 Soaps and Cleaning Compounds	
32562 Toilet Preparations	
3259 Other Chemical Products and Preparations	
32591 Printing Ink	
32592 Explosives	
32599 All Other Chemical Products and Preparations	
326 Plastics and Rubber Products Manufacturing	
3261 Plastics Products	
32611 Plastics Packaging Materials etc.	
32612 Plastics Pipe, Pipe Fitting, etc.	
32613 Laminated Plastics Plate, etc.	
32614 Polystyrene Foam Products	
32615 Urethane and Other Foam Products	
32616 Plastics Bottles	
32619 Other Plastics Products	
3262 Rubber Products	
32621 Tires	
32622 Rubber and Plastics Hoses and Belting	
32629 Other Rubber Products	

* These sectors have a single 5-digit subsector

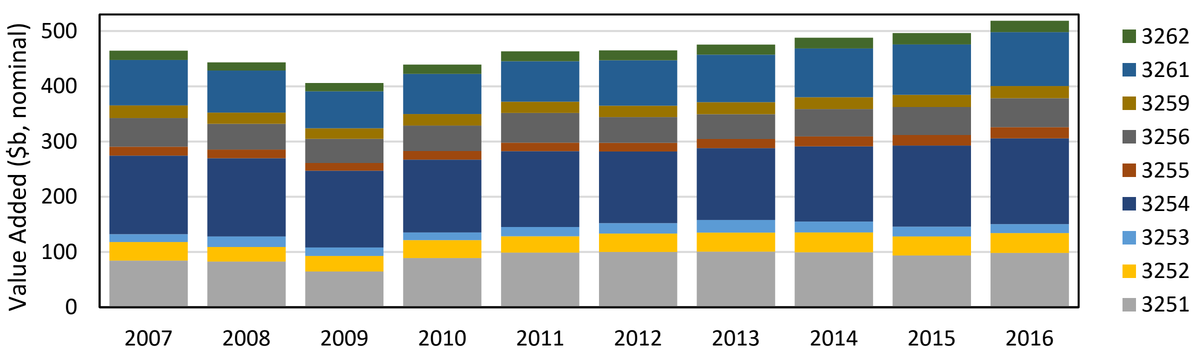

Figure 2.6-1. *Value added (billion $, nominal) from industry subsectors 325-326, 2007-2016 [2]*

2.6.3 Solid wastes from NAICS 325-326

Wastes from the chemical, plastic, and rubber manufacturing industries include wastes and byproducts from raw materials (e.g. phosphorus slag), process residuals (e.g. decantates, filtrates, solvents), pollution control residuals (treatment sludges), and waste products and spent reagents (e.g. acids, bases, solvents, paint, plastics).

Many of the materials, products, and wastes from these sectors can be classified as hazardous. The majority of listed hazardous wastes under RCRA apply to these sectors: inorganic pigments (K002-K008), organic chemicals (K009-K011, K013-K030, K083, K085, K093-K096, K103-K105, K107-K118, K136, K149-K151, K156-K159, K161, K174-K175, and K181), inorganic chemicals (K071, K073, K106, and K176-K178), pesticides (K031-K043, K097-K099, K123-K126, and K131-K132), explosives (K044-K047), veterinary pharmaceuticals (K084 and

K101-K102), and ink (K086). Non-specific source wastes occur very often in the chemicals industry sectors as well (F001-F005, F024-F025). Many more wastes are classified as hazardous by virtue of their specific characteristics.

Wastes from these industries included in the European Waste Catalog are listed in Table 2.6-2 [3]. The European Waste Catalog classifies industrial activities differently from NAICS, but the waste category list is still a good representation of the types of wastes generated in NAICS 325-326.

Challenges in estimating NHIW from these sectors arise from three sources: 1) the boundary between hazardous and non-hazardous can vary across time, firm, and geography, so while it may be possible to estimate a total waste burden, determining the specific non-hazardous fraction is fraught; 2) much of the raw material inputs, products, and residuals are in aqueous, liquid, or even gaseous states, complicating efforts to ascertain accurate, consistent, and meaning measures of mass; and 3) as mentioned above, the great diversity and recent evolution of these sectors means that system boundaries often differ from source to source and across time.

Table 2.6-2. *Chemical, plastic, & rubber products manufacturing wastes as listed in the European Waste Catalog [3]*

Activity	**Waste category**	
Inorganic chemical manufacturing	- waste acids - waste bases - waste salts & oxides - sulfur wastes - spent activated carbon	- phosphorus slag - calcium-based reaction wastes - pesticide and herbicide wastes - carbon black - wastewater treatment sludges
Organic chemical product manufacturing, including plastic and rubber	- aqueous washing liquids - waste mother liquors - organic solvents - still bottoms and reaction residues	- filter cakes and spent absorbents - wastewater treatment sludges - waste plastic and rubber
Coatings, adhesives, sealants, and printing inks manufacturing	- waste paint - sludges from paint or varnish - waste coating powders - waste ink	- ink sludges - waste printing toner - waste adhesives and sealants - wastewater treatment sludges

2.6.4 NHIW estimation

2.6.4.1 Historical forecasting

Numerous historical sources were identified for use in forecasting NHIW types and quantities from the chemical, plastics, and rubber sectors. All three of the challenges in accounting for wastes from these sectors listed above are present in this estimation activity, particularly due to the accounting standards conversion from SIC to NAICS codes in 1997. While this changeover disrupted accounting in all manufacturing sectors, the effects are more significant than normal in the chemicals and related industries. Before 1997, the SIC scheme defined Major Groups 28 (Chemicals and Allied Products) and 30 (Rubber and Miscellaneous Plastics Products). The

NAICS scheme after 1997 reclassified these activities into NAICS 325 and 326, as defined above. Most of the activities within SIC 28 remained within NAICS 325, with the exception of alumina refining (included in SIC 2819), which was relocated to NAICS 331311. The same cannot be said for SIC 30, which found its activities scattered among six high-level NAICS codes in addition to NAICS 326. The reorganization at the subsectoral level compounds the difficulty of accurately corresponding between SIC-coded data and contemporary, NAICS sectors.

To assemble as comprehensive a historical account of NHIW as possible, we relied on seven independent sources published over a time period spanning the years 1976-1998. Few of these sources provided data on both SIC (or later NAICS) codes, instead focusing on particular industry segments, specific minerals and materials, or individual environmental hazards. The distinctions between mineral extraction and beneficiation, materials processing, and chemical manufacturing steps can get murky in these sectors, exacerbated by the SIC/NAICS reclassification. Here we err on the side of inclusion, trusting past analysts to have made judgment calls about which activities and environmental exchanges are meaningfully part of the chemical, plastics, and rubber industries. However, as many of the raw data were published before the RCRA hazardous waste regulation was fully in effect, some of the wastes included in this estimate may now be seen as hazardous.

The earliest sources of data on NHIW for these sectors are a series of industry-specific studies commissioned by the EPA in the late 1970s in support of then-new solid and hazardous waste regulation. They focus on pharmaceuticals [4], rubber products [5], inorganic chemicals [6], and fertilizers [7]. These studies report on deep dives into each sector, synthesizing data from site visits to facilities with process and material flow models. Data on NHIW from organic chemicals, fertilizers, and plastics and resins come from the Industry Studies Database, maintained by SAIC for the EPA [8]. SAIC also estimated NHIW from the soaps and detergents sector [8]. Finally, data on NHIW from materials processing activities that fall within the sectoral bounds of NAICS 325-326 are available from two more contemporary EPA reports [9-10].

Results from this historical forecasting method suggest that 146.2 Tg of NHIW was generated by the chemical, plastic, and rubber manufacturing sectors in 2015 (Table 2.6-3). Nearly half of this quantity (70.79 Tg) is shown to come from organic chemicals manufacturing (NAICS 32511, 32519), followed by 32.87 Tg from fertilizer manufacturing (NAICS 325312), 21.22 Tg from plastics and resins (NAICS 325211), and 16.71 Tg from inorganic chemicals (NAICS 32518). The rest of the sector combined to generate the remaining 4.65 Tg of NHIW.

Table 2.6-3. *NHIW from the chemical, plastics, and rubber industries estimated by historical forecasting, 2015*

Subsector	Waste Type	Gg (Base year)	Base year	Tg (2015)	Source
32511 & 32519: Organic chemicals	Light ends	20,446.00	1981	**40.00**	[8, p. 4-126]
	Heavy ends	4,782.40	1981	**9.36**	[8, p. 4-126]
	Decantate/filtrate	3,630.70	1981	**7.10**	[8, p. 4-126]
	Precipitates/filtration residues	3,067.90	1981	**6.00**	[8, p. 4-126]
	By-products	2,788.30	1981	**5.45**	[8, p. 4-126]
	Other	1,470.20	1981	**2.88**	[8, p. 4-126]
	Subtotal			***70.79***	
32513: Synthetic dyes/pigments	Chlorine process waste solids	414.00	1988	**0.48**	[9, p. 13-3]
	Other	53.00	1979	**0.08**	[6, p. 7]
	Subtotal			***0.56***	
32518: Inorganic chemicals	Ore residues (soda ash, bauxite, silica, etc.)	1,613.91	1979	**1.43**	[6, pp. 6-9]
	Salt tailings, brine muds	12,960.46	1979	**11.50**	[6, pp. 5-8]
	Lime	450.00	1979	**0.40**	[6, p. 9]
	Other	169.01	1979	**0.15**	[6, pp. 5,8]
	Phosphorus slag	2,600.00	1988	**2.32**	[9, p. 7-3]
	Fluorogypsum	894.00	1988	**0.80**	[9, p. 9-3]
	Treated roast/leach residue	102.00	1991	**0.08**	[10, p. 216]
	Furnace offgas solids, dust	28.40	1994	**0.03**	[10, p. 288]
	Subtotal			***16.71***	
325211: Plastics & resins	Decantates/filtrates	7,265.14	1982	**17.83**	[8, p. 4-189]
	Sludges	434.86	1982	**1.07**	[8, p. 4-189]
	Off-specification products	293.82	1982	**0.72**	[8, p. 4-189]
	Spent solvents	286.64	1982	**0.70**	[8, p. 4-189]
	Light ends	195.67	1982	**0.48**	[8, p. 4-189]
	Other	168.79	1982	**0.41**	[8, p. 4-189]
	Subtotal			***21.22***	
325312: Phosphatic fertilizer	Phosphogypsum	47,600.00	1988	**31.87**	[9, p. 12-4]
	Fluoride scrubber effluent	678.12	1979	**0.93**	[7, p. 15-35]
	Waste scale	125.00	1990	**0.08**	[10, p. 509]
	Subtotal			***32.87***	
32532: Pesticides	Decantates/Filtrates	1,524.83	1981	**1.73**	[8, p. 4-87]
	Light Ends	858.16	1981	**0.97**	[8, p. 4-87]
	Other	338.14	1981	**0.38**	[8, p. 4-87]
	Subtotal			***3.08***	
3254: Pharmaceuticals	Biological sludge	82.60	1973	**0.27**	[4, p. 6]
	Mycelium (plus filter aid and sawdust)	75.00	1973	**0.24**	[4, p. 6]
	Other	24.25	1973	**0.08**	[4, pp. 6-7]
	Subtotal			***0.59***	
325611: Soaps and detergents		31.27	1981	**0.03**	[8, p. 4-253]
3262: Rubber products	Fabricated rubber products waste	181.54	1974	**0.15**	[5, p. III-180]
	Tire & inner tube waste	192.78	1974	**0.13**	[5, p. III-62]
	Rubber and plastics hose and belting waste	49.30	1974	**0.06**	[5, p. III-137]
	Reclaimed rubber waste	38.75	1974	**0.03**	[5, p. III-106]
	Subtotal			***0.37***	
TOTAL				**146.23**	

Examining the composition of this estimate, most of the NHIW from organic chemicals and plastics & resins manufacturing are generated in aqueous or liquid form. Light and heavy ends, in particular, are liquid wastes from distillation and other refining processes. They are accounted for as solid wastes because they are historically disposed to land (rather than to water), but it is misleading to suggest that the estimated 40 Tg of light ends is equivalent to the estimated 32 Tg of phosphogypsum from phosphitic fertilizer manufacturing. Furthermore, as mentioned above, many of these wastes (albeit an unquantifiable amount) are now classified as hazardous wastes, meaning this estimate should be considered an upper bound; on the other hand, segments of the industry that have changed considerably from the base year data (e.g. pharmaceuticals, plastics), likely have waste profiles that differ from that estimated here.

Data from the 1983 PACE survey yields an estimate of NHIW from this sector at just 27.38 Tg: 15.73 Tg from basic chemical manufacturing (including both organic and inorganic chemicals), between 2-3 Tg each from resins, agricultural chemicals, pharmaceuticals, and plastic and rubber products (Table 2.6-4). The other subsectors are estimated to generate less than 1 Tg of NHIW each. Air pollution control residuals are estimated to comprise more than 20% of the total.

Table 2.6-4. *NHIW from the chemicals, plastics & rubber manufacturing industry estimated from PACE, 2015 [11]*

NAICS	Description	1983 (Gg)		2015 (Tg)
		NHIW	***APC***	***Total***
3251	Basic chemical	8,135.2	1,821.4	15.73
3252	Resin, synthetic rubber, and artificial synthetic fibers and filaments	1,703.4	1,043.6	2.84
3253	Pesticide, fertilizer, and other agricultural chemicals	2,519.4	628.3	2.49
3254	Pharmaceutical and medicine	770.8	42.8	2.28
3255	Paint, coating, and adhesive	112.9	2.8	0.15
3256	Soap, cleaning compound, and toilet preparation	281.1	91.1	0.48
3259	Other chemical product and preparation	255.9	144.2	0.67
325	***Subtotal: Chemical manufacturing***	***13,778.9***	***3,774.3***	***24.63***
3261	Plastics product	697.0	85.0	1.87
3262	Rubber product	546.0	57.5	0.87
326	***Subtotal: Plastics and rubber products manufacturing***	***1,243.0***	***142.5***	***2.74***
325-326	**TOTAL**			**27.38**

2.6.4.2 Spatial Up-Scaling

Scaling up data from the Pennsylvania Residual Waste Program suggests that the chemicals, plastics, and rubber products manufacturing sectors generated 5.35 Tg of NHIW in 2015 (Table 2.6-5). Pennsylvania produces 3.2% of the national chemical industry economic output and 5% of plastics and rubber products. Of the 5.35 Tg estimated total, basic chemicals are responsible for 27.7%, plastics and rubber 21.5%, resins 20.4%, pharmaceuticals 12.0%, soaps and detergents 10.5%, and the rest 7.9%. Notably, the agricultural chemicals sector, of which Pennsylvania provides only 1.32% of national output, is shown to generate just 0.04 Tg of NHIW—there is no phosphatic fertilizer production occurring in the state.

Table 2.6-5. *NHIW by NAICS sector estimated by up-scaling from PARW data, 2015*

NAICS Code	Description	PA Waste (Gg)	US Waste (Tg)
3251	Basic chemical manufacturing	30.3	1.48
3252	Resin, synthetic rubber, and artificial synthetic fibers and filaments mfg	26.3	1.09
3253	Pesticide, fertilizer, and other agricultural chemical manufacturing	0.5	0.04
3254	Pharmaceutical and medicine manufacturing	25.0	0.64
3255	Paint, coating, and adhesive manufacturing	8.7	0.13
3256	Soap, cleaning compound, and toilet preparation manufacturing	12.4	0.56
3259	Other chemical product and preparation manufacturing	14.1	0.26
325	***Subtotal: Chemical manufacturing***	***117.3***	***4.20***
3261	Plastics product manufacturing	40.8	0.84
3262	Rubber product manufacturing	7.4	0.31
326	***Subtotal: Plastics and rubber products manufacturing***	***48.3***	***1.15***
325-326	**TOTAL**	**165.6**	**5.35**

Composition of the NHIW estimate from the Pennsylvania Residual Waste program is well distributed (Table 2.6-6). It includes: various sludges and scales (27% of the total), including wastewater treatment sludge and process sludges, arising largely from basic chemicals and resins production; waste plastic and rubber (20.3%), including both packaging materials as well as process wastes; waste chemicals (14.6%) of all sorts, including acids, bases, salts, alcohols, detergents, and others; pharmaceutical wastes (4.0%) arising virtually entirely from the pharmaceuticals sector; and smaller amounts of off-spec products (3.9%), filter media (3.4%), and other wastes. Plant trash makes up 12.7% of the total.

2.6.4.3 Material balance

The data necessary to conduct a robust material balance analysis of the chemical, plastics, and rubber products industries are only available for phosphatic fertilizer manufacturing (NAICS 325312). In the past, more data had been published, which Ayres & Ayres used to great effect to assess material flows and NHIW generation from the entire industry sector [12]. The publication of key references has since ceased, so this estimation method will be restricted to just a small subset of the overall sector of interest. Conveniently, this subsector is thought to generate the single largest quantity of NHIW: phosphogypsum.

Table 2.6-6. NHIW from chemicals, plastics & rubber mfg estimated by up-scaling from PARW data, 2015

Waste Type	Source	US Waste (Tg)	% of total
Sludge & Scale	Basic chemicals	0.61	11.4%
	Resins, synthetic fibers, etc.	0.58	10.7%
	Other subsectors	0.26	4.9%
	Total Sludge & Scale	*1.44*	*27.0%*
Plastic & Rubber	Soaps, cleaning compounds, etc.	0.32	5.9%
	Plastics products	0.32	6.0%
	Rubber products	0.22	4.2%
	Resins, synthetic fibers, etc.	0.16	2.9%
	Other subsectors	0.07	1.3%
	Total Plastic & Rubber	*1.09*	*20.3%*
Waste Chemicals	Basic chemicals	0.46	8.7%
	Other subsectors	0.32	5.9%
	Total Waste Chemicals	*0.78*	*14.6%*
Pharmaceutical Wastes	Pharmaceuticals	0.22	4.0%
Off-Spec Products		0.21	3.9%
Filter Media/Aids	Basic chemicals	0.13	2.5%
	Other subsectors	0.05	0.9%
	Total Filter Media/Aids	*0.18*	*3.4%*
Other Waste		0.75	14.0%
Plant Trash		0.68	12.7%
TOTAL		**5.35**	**100.0%**

In 2015, U.S. phosphate mines produced 127 Tg of crude phosphate rock [13, p. 56.4]. Phosphate rock is combined with sulfuric acid to produce superphosphate; according to USGS statistics, 14.1 Tg of 100% H_2SO_4 was consumed by the phosphatic fertilizer sector in 2015 [14, p. 74.9], producing 27.4 Tg of superphosphate [13, p. 56.4] and resulting in 113.7 Tg of phosphogypsum waste. This derived tonnage is validated by a published value of phosphogypsum generation: 4.5 tons per ton of phosphoric acid production [15, p. 24]. With a generation of 27.4 Tg of phosphoric acid, this intensity factor suggests the generation of 123.3 Tg of phosphogypsum, very close to the material balance-derived value. The 4.5 tons/ton generation rate is considerably higher than a previous EPA-published intensity of 2.65 tons phosphogypsum/ton phosphoric acid [7, p. 15-34]. However, the ore grade of phosphate rock has been declining, and the 25 years between the two published factors may be explained by this fact.

2.6.4.4 International comparison

European waste data suggests that the chemicals, plastics, and rubber manufacturing sectors generated 106.85 ± 104.10 Tg of NHIW in 2015 (Table 2.6-7). The vast majority of this waste is classified as mineral waste, which includes wastes from naturally occurring minerals, artificial mineral wastes, and waste refractory materials. The data could suggest that 88.61 ± 103.32 Tg of phosphogypsum was generated that year. There are additional, modest quantities of acid, alkaline, and saline wastes; and chemical wastes (1.52 ± 7.37 Tg and 2.55 ± 7.10 Tg, respectively), sludges (2.51 ± 10.81 Tg), and plastic and rubber wastes (1.67 ± 1.83 Tg and 0.36 ± 0.23 Tg, respectively). The rest of the waste tonnage is ordinary or other waste.

Table 2.6-7. *NHIW from chemicals, plastics & rubber manufacturing estimated using European waste data*

	Waste intensity (Mg/$1,000)		**US Waste 2015 (Tg)**	
	Average	*Std. Dev.*	*Average*	*Std. Dev.*
Acid, alkaline or saline wastes	1.49	7.21	1.52	7.37
Chemical wastes	2.50	6.94	2.55	7.10
Sludges	2.46	10.56	2.51	10.81
Rubber wastes	0.35	0.22	0.36	0.23
Plastic wastes	1.64	1.79	1.67	1.83
Mineral wastes	86.61	100.99	88.61	103.32
Mixed ordinary wastes	3.94	4.86	4.03	4.98
Combustion wastes	2.15	4.59	2.20	4.69
Other wastes	3.16	2.52	3.24	2.58
Total Waste	**104.43**	**101.75**	**106.85**	**104.10**

Sum of individual wastes may not equal "total waste" due to rounding errors and because of inconsistencies in the raw data.

2.6.4.5 Triangulation & Synthesis

2.6.4.5.1 Basic chemical manufacturing

Three wildly divergent estimates of NHIW from basic chemical manufacturing have been presented: 1.48 Tg (PARW), 15.73 Tg (PACE), and 88.06 Tg (forecast). It is likely that the PARW results are too low, as not all of the waste-producing activities in this sector occur in Pennsylvania. On the other hand, the historical data includes many waste types that may neither be considered solid waste nor non-hazardous today. Removing some of the more-obvious waste types (light ends, heavy ends, decantate/filtrate, brine muds), the estimate from the historical data comes closer to that from PACE: 20.1 Tg.

2.6.4.5.2 Resin, synthetic rubber, and artificial synthetic fibers and filaments manufacturing

The three estimates for NHIW from this subsector follow the patterns from basic chemicals: 1.09 Tg (PARW), 2.84 Tg (PACE), and 21.22 Tg (forecast). The same logic applies to the triangulation of these three estimates. The composition of the estimated account based on historical data is almost entirely materials that would be excluded from NHIW accounts today: decantates/filtrates, spent solvents, and light ends. This leaves 2.20 Tg of sludge, off-spec product, and other wastes. It is likely that the NHIW from this sector lies somewhere between 2.20 Tg and the 2.84 Tg estimate from the PACE data.

2.6.4.5.3 *Pesticide, fertilizer, and other agricultural chemical manufacturing*

Estimates from this sector as a whole range include 0.04 Tg (PARW), 2.49 Tg (PACE), and 35.95 (forecast). Subtracting phosphogypsum (which is superseded by the material balance estimate) and the likely-hazardous wastes from pesticide manufacturing, the historical forecast value becomes just 1.01 Tg. The materials balance estimate of phosphogypsum (113.7 Tg) completes the triangulation for this subsector.

2.6.4.5.4 *Pharmaceutical and medicine manufacturing*

Estimates of NHIW from pharmaceutical manufacturing include 0.59 Tg (forecast), 0.64 Tg (PARW), and 2.28 Tg (PACE). None of these is a convincing value. The historical forecast is based on an industry wholly unfamiliar to today's pharmaceutical sector. The PARW data only includes 0.22 Tg of actual pharmaceutical wastes, the rest being packaging, plant trash, and other waste. Finally, it is impossible to know what materials are included in the PACE estimate, but it is also representative of a different era in pharmaceutical manufacturing. These weaknesses notwithstanding, the contemporary origins of the PARW data trump all else, so 0.64 Tg is the triangulated result.

2.6.4.5.5 *Paint, coating, and adhesive manufacturing*

Two estimates are provided for NHIW from the paints subsector: 0.13 Tg (PARW) and 0.15 Tg (PACE). Their proximity makes them both reasonable estimates.

2.6.4.5.6 *Soap, cleaning compound, and toilet preparation manufacturing*

The three estimates for NHIW form the soaps subsector are 0.03 Tg (forecast), 0.48 Tg (PACE), and 0.56 Tg (PARW). The historical forecast data comes from an expert industry assessment rather than empirical observation, so it can be discarded. The PARW estimate includes a significant quantity of materials that would likely be considered packaging waste rather than process residual; nevertheless, the PARW data seems to be biased low overall, so the range between the PACE and PARW estimates is not unreasonable.

2.6.4.5.7 *Other chemical product and preparation manufacturing*

The other chemical product subsector has two estimates above: 0.26 Tg (PARW) and 0.67 Tg (PACE). With such a varied composition (including printing ink, explosives, photographic film, and other chemical products), it is not possible to close the gap between these two estimates any further.

2.6.4.5.8 *Plastics & rubber products manufacturing*

There are four available estimates of NHIW from the plastics and rubber products sector. For rubber, the historical forecast yields 0.37 Tg, PACE 0.87 Tg, PARW 0.31 Tg and the international comparison shows 0.36 Tg of rubber across the entire industry sector. For plastic, there is one fewer estimate: 0.84 Tg (PARW), 1.87 Tg (PACE), and 1.67 Tg (international comparison). The estimates in both cases are clustered close enough for the triangulation to accommodate the ranges.

2.6.4.5.9 Summary

In total, the triangulated estimate of NHIW from the chemicals, plastics & rubber products manufacturing sector in 2015 is 135.30 – 143.89 Tg (Table 2.6-8). This notably excludes large quantities of wastes from organic chemicals, resins, and pesticide manufacturing that today would most likely either not be managed as solid waste or not be considered non-hazardous. The estimate is also somewhat above, but not wholly dissimilar from, the sector-wide estimate yielded by the international comparison method: 106.85 Tg vs. 139.69 Tg. By far the largest component of both estimates is mineral waste, specifically phosphogypsum, which comprises more than 80% of the total from this sector. Beyond this waste material, however, the methods and data employed in this triangulation preclude reliable estimates of waste composition from this sector.

Table 2.6-8. *Triangulated estimate of NHIW from the chemicals, plastics & rubber manufacturing sectors, 2015*

NAICS	Subsector/Waste material	NHIW (Tg)			Notes
		L	*M*	*H*	
3251	Basic chemicals	15.73		20.1	*
3252	Resin, synthetic rubber, and artificial synthetic fibers and filaments	2.2		2.84	*
3253	Pesticide, fertilizer, and other agricultural chemicals				
	Phosphogypsum		113.7		
	Other wastes	1.01		2.49	*
3254	Pharmaceuticals and medicine		0.64		
3255	Paint, coating, and adhesives	0.13		0.15	
3256	Soap, cleaning compound, and toilet preparation	0.48		0.56	
3259	Other chemical product and preparation	0.26		0.67	
325	***Subtotal: Chemical manufacturing***	***134.15***		***141.15***	
3261	Plastics products	0.84	1.67	1.87	
3262	Rubber products	0.31	0.37	0.87	
326	***Subtotal: Plastics and rubber products manufacturing***	***1.15***	***2.04***	***2.74***	
	Grand Total	**135.30**	**139.69**	**143.89**	

* Excludes most aqueous and likely hazardous wastes chemicals processing (e.g. light ends, heavy ends, decantate/filtrate, brine muds, pesticide manufacturing wastes)

2.7 Nonmetallic Mineral Product Manufacturing (NAICS 327)

2.7.1 Summary

The nonmetallic mineral product manufacturing sector is estimated to have generated 9.40-14.49 Tg of NHIW in 2015. Cement kiln dust is the largest waste stream from this sector at 4.68 Tg, a value that also is one of the more reliable estimates in the account. Wastes from glass, lime, and gypsum manufacturing are also estimated to be notable components of the waste account: 3.15 Tg, 1.84 Tg, and 1.47 Tg respectively in the high estimate case, which is the end of the range that has stronger corroboration from international waste data.

2.7.2 Industry structure

Firms in the nonmetallic mineral product manufacturing sector (NAICS 327) produce clay products, ceramics, glass, cements and cement products, lime, gypsum, and other similar products. These activities comprise five distinct NAICS industry subsectors (Table 2.7-1). Within the Other Nonmetallic Mineral Products subsector (NAICS 3279) firms produce abrasives, cut stone and stone products, ground and treated earth products, mineral wool, and other minor mineral products. Material inputs to this sector are largely basic minerals and rocks like sand, clay, gravel aggregate, and limestone.

Table 2.7-1. NAICS 2017 structure of the nonmetallic mineral product manufacturing sector [1]

327 Nonmetallic Mineral Product Manufacturing	3274 Lime and Gypsum Products
3271 Clay Products and Refractories	32741 Lime
32711 Pottery, Ceramics, and Plumbing Fixtures	32742 Gypsum Products
32712 Clay Building Materials and Refractories	3279 Other Nonmetallic Mineral Products
3272 Glass and Glass Products*	32791 Abrasive Products
3273 Cement and Concrete Products	32799 All Other Nonmetallic Mineral Products
32731 Cement	
32732 Ready-Mix Concrete	
32733 Concrete Pipe, Brick, and Block	
32739 Other Concrete Products	

* These sectors have a single 5-digit subsector

In total, this sector contributes approximately 3% of the country's manufacturing GDP, up from closer to the 2% that it was in the aftermath of the 2008 recession as growth in the construction sector, a major customer for these products, lagged (Figure 2.7-1). Cement and concrete products (NAICS 3273) is the largest of the five subsectors by value added, contributing nearly 44% of the sector total in 2016. Glass and glass products (NAICS 3272) and other nonmetallic mineral products (NAICS 3279) contributed a bit over one fifth of the total each while clay products and refractories (NAICS 3271) and lime and gypsum products (NAICS 3274) contributed just 6-7% each.

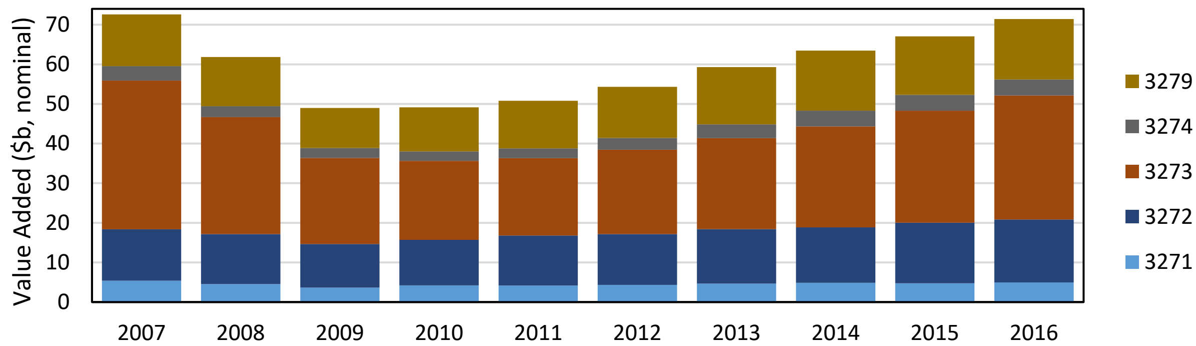

Figure 2.7-1. *Value added (billion $, nominal) from industry subsector 327, 2007-2016 [2]*

2.7.3 Solid wastes from NAICS 327

Solid wastes from the nonmetallic mineral product sector fall generally into two categories: waste products and pollution control wastes (air and water). Unlike other basic manufacturing sectors (e.g. chemicals, metals, paper), the processes involved in nonmetallic mineral product manufacturing largely do not yield many solid process residuals. Some are purely mechanical processing (e.g. grinding), some are thermal treatments that evolve gases (e.g. cement manufacturing), and others are thermal treatments that involve a change in form (e.g. glassblowing). None involve the significant separation or refinement of a raw material. In all of these processes, however, there are the inevitabilities of waste product, that is, non-spec or excess product. Additionally, the processes produce dust and sludge that are captured and disposed as solid waste.

Wastes from these industries included in the European Waste Catalog are listed in Table 2.7-2 [3].

2.7.4 NHIW estimation

2.7.4.1 Historical forecasting

No sector-wide historical assessments of NHIW from the non-metallic mineral product sector were identified. In 1985, SAIC had limited success identifying reliable estimates of NHIW from the sector [4]; we have been similarly unsuccessful in a review of the literature published since 1985. The SAIC report does however detail the types of wastes that would be generated by this industrial sector: silica particulates, spent diatomaceous earth, soda ash, lime, brine residues, lubricants, pottery sludge, waste cullet, fiber resin masses, and air pollution control sludge from cement, clay, concrete, gypsum, and plaster manufacturing. The limited quantitative data reported by SAIC for this sector comes mainly from the 1981 PACE survey. We use a subsequent (1983) PACE survey below, so these earlier values are excluded from analysis here.

Table 2.7-2. *Nonmetallic mineral product manufacturing wastes as listed in the European Waste Catalog [3]*

Activity	Waste type
Glass and glass products	- waste glass-based fibrous materials - particulates and dust - waste glass - glass-polishing and -grinding sludge - solid wastes from flue-gas treatment - sludges and filter cakes from flue-gas treatment
Ceramic goods, bricks, tiles, and construction products	- particulates and dust - sludges and filter cakes from gas treatment - discarded molds - waste ceramics, bricks, tiles and construction products - gas treatment wastes - glazing wastes - sludge from on-site effluent treatment
Cement, lime, and plaster and articles and products made from them	- wastes from calcination and hydration of lime - particulates and dust - sludges and filter cakes from gas treatment - wastes from asbestos-cement manufacture - gas treatment wastes - waste concrete and concrete sludge

Nevertheless, historical data on two individual waste flows from this sector were identified: waste lime and limestone particulates from lime manufacturing and cement kiln wastes from clinker manufacturing. Lime manufacturing wastes were reported in a 1979 EPA study of wastes from inorganic chemicals manufacturing [5]. Cement kiln dust (CKD) waste data came from a 1998 EPA report on the costs of disposing this waste material, which is classified as a "special waste" by the EPA under RCRA [6]. The CKD values came originally from surveys conducted by the American Portland Cement Association.

Both of these waste materials were forecast using physical production values (tons of lime and clinker manufactured, respectively), rather than the economic output values that are commonly used in this estimation method. The results show that 4.44 Tg of CKD and 1.83 Tg of lime and limestone particulates were generated in 2015 (Table 2.7-3).

Table 2.7-3. *NHIW from the nonmetallic mineral product industries estimated by historical forecasting, 2015*

Activity	Waste	Original (Tg)	Base year	2015 (Tg)	Source
Lime manufacturing	Lime and limestone particulates	1.90	1979	1.83	[5], p. 6
Clinker manufacturing	Cement kiln dust	4.08	1995	4.44	[6], p. 7
TOTAL (incomplete)				**6.27**	

The lack of historical sector-wide data for the nonmetallic mineral product industry may be due to three factors. First, most of the historical data used in forecasting wastes from other sectors was originally published in service of hazardous waste regulation. Since most of the materials used and wastes generated in the non-metallic mineral product manufacturing sector are non-hazardous, this sector was rarely a focus of EPA resources in the 1970s and 1980s. Second, as we will show below, a very substantial fraction of the waste from this sector is pollution control residue. As such, these wastes are only generated if and when plants are required to scrub their exhausts and effluents, and quantities generated are influenced both by the scrubbing technology employed and the regulatory requirements for removal. In early years, these requirements may have been such that there simply was not very much pollution control residue to quantify. Finally, there is no overarching industry association for the nonmetallic minerals sector as there is for, for instance, the pulp and paper industry. Lacking this central coordination, there is limited opportunity for sector-wide surveys and other data collection instruments.

The 1983 PACE data do offer a sector-wide look, albeit one with limited compositional information [7]. Forecasting this data to 2015 yields an estimate of 22.32 Tg (Table 2.7-4). Air pollution control (APC) residues are estimated to be more than twice the tonnage of NHIW: 15.17 Tg to 7.14 Tg, respectively. The largest contributing subsector is the cement industry, estimated to generate 3.47 Tg of NHIW and 11.40 Tg of APC residue. Lime and gypsum manufacturing is estimated to generate 3.31 Tg of NHIW, including 1.41 Tg of solid waste and 1.90 Tg of APC residue. Of the total from this subsector, lime manufacturing generates 1.84 Tg while gypsum is responsible for the remaining 1.47 Tg.

The other nonmetallic mineral product manufacturing subsector (NAICS 3279) is estimated to generate 2.78 Tg of NHIW, most of which (1.53 Tg) comes from ground or treated mineral and earth manufacturing. The remaining two subsectors, clay products and glass products, are estimated to generate just 0.57 and 0.78 Tg, respectively. Most of the waste from these two subsectors is process solid waste rather than APC residue, the reverse from the other three subsectors.

Table 2.7-4. *NHIW from the nonmetallic mineral product manufacturing industry estimated from PACE, 2015 [7]*

NAICS	Description	1983 (Gg) NHIW	1983 (Gg) APC	2015 (Tg) Total
3271	Clay product and refractory manufacturing	428.1	51.8	0.57
3272	Glass and glass product manufacturing	691.7	89.9	0.78
3273	Cement and concrete product manufacturing	2,696.7	9,476.2	14.87
3274	Lime and gypsum product manufacturing	724.4	1,022.5	3.31
3279	Other nonmetallic mineral product manufacturing	847.9	1,217.3	2.78
327	**TOTAL**			**22.32**

2.7.4.2 Spatial Up-Scaling

Data from the Pennsylvania Residual Waste Program suggests the nonmetallic mineral products manufacturing sector generates 3.94 Tg of NHIW in 2015 (Table 2.7-5). Pennsylvania has approximately 5% of this sector's national economic output, with subsector fractions ranging from 3.3% (NAICS 3274) to 11% (NAICS 3271). Of the total, 86% (3.4 Tg) is estimated to come from the glass and glass product manufacturing subsector. The rest of the subsectors are shown to generate significantly less waste, none exceeding the 0.21 Tg generated by the other nonmetallic mineral product manufacturing subsector.

Table 2.7-5. *NHIW by NAICS sector estimated by up-scaling from PARW data, 2015*

NAICS Code	Description	PA Waste (Gg)	US Waste (Tg)
3271	Clay product and refractory manufacturing	11.5	0.10
3272	Glass and glass product manufacturing	182.2	3.40
3273	Cement and concrete product manufacturing	7.6	0.12
3274	Lime and gypsum product manufacturing	3.1	0.09
3279	Other nonmetallic mineral product manufacturing	8.8	0.21
327	**TOTAL:**	**213.2**	**3.94**

Nearly all of the NHIW reported from the glass and glass product manufacturing sector is glass waste, or cullet (3.15 Tg) (Table 2.7-6). Ceramic waste, gypsum waste, and refractory wastes comprise an additional 0.02 Tg, 0.06 Tg, and 0.14 Tg, respectively. Air pollution control wastes are 0.16 Tg, with the balance of the account (0.41 Tg) a variety of other factory wastes and plant trash.

Table 2.7-6. *NHIW from nonmetallic mineral product mfg estimated by up-scaling from PARW data, 2015*

Waste Type	Source	US Waste (Tg)	% of total
Glass Waste (Cullet)	Glass products	3.15	80.0%
Ceramic Waste	Clay products & refractories	0.01	0.3%
	Cement & concrete	0.01	0.3%
	Total Ceramic Waste	*0.02*	*0.5%*
Gypsum Waste	Lime & gypsum products	0.06	1.5%
Refractory Material	Clay products & refractories	0.06	1.5%
	Glass products	0.02	0.5%
	Other nonmetallic mineral products	0.06	1.5%
	Total Refractory Material	*0.14*	*3.6%*
APC Waste	Clay products & refractories	0.02	0.4%
	Glass products	0.05	1.2%
	Other nonmetallic mineral products	0.10	2.5%
	Total APC Waste	*0.16*	*4.1%*
Other Waste		0.22	5.5%
Plant Trash		0.19	4.8%
TOTAL		**3.94**	**100.0%**

2.7.4.3 Material balance

No data were identified to perform a sector-wide material balance for the nonmetallic mineral product manufacturing sector. Ayres & Ayres, who conducted comprehensive, economy-wide material balance assessments of the U.S. economy for 1988 and 1993, confirm this data limitation [8]. However, they also state "it appears that the major waste emissions from the stone, clay and glass sector (exclusive of losses in quarrying and concentration) are primarily related to combustion of fossil fuels" [8, p. 95].

The one industry sector for which material balance data is available is cement, specifically, the generation of cement kiln dust (CKD) from clinker manufacturing. Total CKD generation, captured in air pollution control systems, is accounted for as the sum of that which is recycled into cement kilns as a raw material; beneficially used as a soil amendment, ballast for roadway construction, wastewater treatment, solid waste remediation, and landfill cover [9]; and disposed in landfill.

The USGS publishes data on clinker manufacturing in the U.S., including raw materials consumed and total production. For 2015, they estimate 125 Tg of raw materials were used to produce 76.04 Tg of clinker [10, pp. 16.12-16.13]. The major constituent of this 49 Tg difference is CO_2, evolved in the conversion of $CaCO_3$ in limestone to CaO in clinker. USGS estimates that clinker is 65% CaO, which would result in the emission of 0.51 Mg of CO_2 per Mg of clinker, assuming all CO_2 is from $CaCO_3$ [11, p. 37]. This value is changed by minor amounts as other mineral input sources of CO_2 are accounted for (e.g. dolomite, iron carbonite). Production of 76.04 Tg of clinker would therefore have generated 38.78 Tg of CO_2: 125 – (76.04 + 38.78) = 10.18 Tg of lost mass, which can be assumed to be mainly CKD.

Much of the CKD is recycled internally, however, and cannot all be classed as NHIW. According to the accounting standards utilized here, we count tonnage that is landfilled as well as that which is beneficially used external to the process that generated it. The EPA calls this quantity "Net CKD" [6, p. 4], and publishes production ratios for the dry process (0.060 Mg CKD/Mg clinker) and the wet process (0.107) [6, p. 6]. These figures are based on survey data from the American Portland Cement Association in the mid-1990s. With 2015 dry and wet process clinker production at 73.51 Tg and 2.54 Tg, respectively [10, p. 16.13], net CKD generation for that year can be estimated to be 4.68 Tg. Assuming the mass balance figure is accurate, this would suggest that 5.49 Tg of CKD is reused internally. This estimate vastly outweighs the USGS reported value of CKD used as an input to clinker and cement manufacturing: 0.02 Tg and 0.16 Tg, respectively [10, p. 16.12].

More recent surveys of Portland Cement Association member companies establish a ratio of landfilled CKD to clinker produced. The most recent data, from 2006, shows the ratio at just 16 kg landfilled CKD / Mg clinker [9, p. 6]. If this value is still accurate for 2015, that would mean 1.22 Tg of CKD was sent to landfill, and 4.68 – 1.22 = 3.47 Tg CKD was beneficially used.

2.7.4.4 International comparison

European waste data suggests that the U.S. nonmetallic mineral product manufacturing industry generated 16.26 ± 13.50 Tg of NHIW in 2015 (Table 2.7-7). The main constituent of this waste stream is mineral waste (11.37 ± 11.96 Tg), a category that includes stone cutting wastes, ceramic wastes, soils, particulates and dust, glass wastes, cement kiln dust, etc. An additional 2.14 ± 2.23 Tg of other mineral wastes was also generated, including construction and demolition waste and ash, as well as 1.10 ± 0.83 Tg of glass wastes. The balance of the account is made of mixed categories of wastes, including chemical and medical waste (0.17 ± 0.26 Tg), mixed ordinary waste (0.93 ± 0.72 Tg), and other waste (0.50 ± 0.24 Tg).

Table 2.7-7. *NHIW from the nonmetallic mineral product mfg industry estimated using European waste data*

	Waste intensity (Mg/$1,000)		**US Waste 2015 (Tg)**	
	Average	*Std. Dev.*	*Average*	*Std. Dev.*
Chemical and medical wastes	1.42	2.17	0.17	0.26
Glass wastes	9.21	6.96	1.10	0.83
Other waste	4.18	2.04	0.50	0.24
Mixed ordinary wastes	7.80	5.99	0.93	0.72
Mineral wastes	94.93	99.86	11.37	11.96
Other mineral wastes	17.85	18.61	2.14	2.23
Total Waste	135.73	112.65	16.26	13.50

Sum of individual wastes may not equal "total waste" due to rounding errors and because of inconsistencies in the raw data.

2.7.4.5 Triangulation & Synthesis

For this sector, only two estimates (PACE and PARW) are available for comprehensive, subsectorally-resolved triangulation. Historical forecasting is available additionally for lime manufacturing and both historical forecasting and materials balance estimates are available for NHIW from cement manufacturing. The estimate based on international waste statistics can be used to provide a high-level comparison, but is limited in its applicability at the subsectoral level.

2.7.4.5.1 Clay product and refractory manufacturing

Two estimates of NHIW from clay product and refractory manufacturing (NAICS 3271) are available: 0.10 Tg (PARW) and 0.57 Tg (PACE). Given that the PARW data is generated in the subject year and PACE data is 32 years old, the smaller figure is likely more reliable. And since wastes from this sector are not refining wastes, they may be more sensitive to technology improvement than we observe in other sectors such as pulp and paper and metals. On the other hand, the PARW data has a widely-observed underestimate of NHIW from other sectors; this may be mitigated by the overrepresentation of clay and refractory product manufacturing in Pennsylvania. The triangulated value of NHIW from this subsector is likely in the range reported by the two estimates: 0.10 – 0.57 Tg.

2.7.4.5.2 *Glass and glass product manufacturing*

Three estimates are available for NHIW from the glass and glass product manufacturing subsector (NAICS 3272): 0.78 Tg (PACE); 3.40 Tg (PARW), 3.15 Tg of which is glass cullet; and 1.10 ± 0.83 Tg (international). The lower PACE estimate is within the uncertainty band of the estimate from international statistics, while the upper PARW estimate is well outside. The PARW estimate may be artificially inflated due to mistaken inclusion of glass non-process wastes (like glass bottles), although there is no specific evidence to this claim. The triangulated range is that between the mean international estimate and the PARW estimate of cullet generation: 1.10 – 3.15 Tg.

2.7.4.5.3 *Cement and concrete product manufacturing*

Estimates of NHIW from cement and concrete product manufacturing (NAICS 3273) range across three orders of magnitude: 0.12 Tg (PARW); 4.44 Tg of CKD (historical forecast); 14.87 Tg (PACE), including 3.47 Tg of solid waste and 11.40 Tg of air pollution control residue; and 10.18 Tg (material balance), 4.68 Tg of which is CKD disposed of as waste or beneficially used. The PARW value is unreasonably low; it is possible that the vast majority of the CKD that is produced by cement manufacturers in the state is beneficially used to an extent that exempts them from reporting to the Residual Waste Program. On the other hand, the PACE estimate of APC residue is very high; it is also possible that in 1983 cement manufacturers were not using any of the generated CKD as an internal recyclate. This leaves the material balance and historical forecast values, which are close mainly because they are co-determined by the same empirical data. Nonetheless, the material balance estimate is the most reasonable given the range of options and what is known about industry operations.

2.7.4.5.4 *Lime and gypsum product manufacturing*

NHIW estimates from lime and gypsum product manufacturing (NAICS 3274) also spans three orders of magnitude: 0.09 Tg (PARW), including 0.06 Tg of gypsum waste; 1.83 Tg of lime and limestone particulates from historical forecasting; and 3.31 Tg from PACE, including 1.84 Tg from lime manufacturing and 1.47 Tg from gypsum. Again, the PARW value is so low as to be unrealistic. The remaining two estimates have a surprising convergence, with both producing an estimate of NHIW from lime manufacturing of nearly the same value: 1.83-1.84 Tg. PACE also includes a similar-sized estimate of NHIW from gypsum manufacturing: 1.47 Tg (well beyond the 0.06 Tg estimated using PARW data).

2.7.4.5.5 *Other nonmetallic mineral product manufacturing*

NHIW from the final subsector, other nonmetallic mineral products manufacturing (NAICS 3279), has just two estimates: 0.21 Tg (PARW) and 2.78 Tg (PACE). As the PARW values have been biased quite low (by orders of magnitude) for other subsectors in this industry, it would be prudent to again select the PACE-based value. However, the PACE values are three decades old, and this subsector includes those industrial processes which have changed a lot in the intervening years, so here we will report the range defined by both estimates: 0.21 – 2.78 Tg.

2.7.4.5.6 Summary

In total, the triangulated estimate of NHIW from the nonmetallic mineral product manufacturing sector in 2015 is 9.40 – 14.49 Tg (Table 2.7-8). The upper bound of this estimate is close to that estimated from international statistics: 16.26 Tg, and more so when the generic waste categories are excluded: 14.78 Tg. Of course, the high degree of variability associated with this estimate makes it an unreliable predictor, but it can be useful as a comparative value. The largest constituent of this waste account is cement kiln dust, of which there was 4.68 Tg generated in 2015. Glass, lime, and gypsum wastes are also significant in the account.

Table 2.7-8. *Triangulated estimate of NHIW from the nonmetallic mineral product manufacturing sector, 2015*

NAICS	Subsector/Waste material	NHIW (Tg) *L*	*M*	*H*	Notes
3271	Clay products and refractories	0.10		0.57	*Waste refractories*
3272	Glass and glass products	1.10		3.15	*Glass cullet*
3273	Cement and concrete products				
	Cement kiln dust		4.68		*At least 3.47 Tg beneficially used*
3274	Lime and gypsum products				
	Lime wastes		1.84		
	Gypsum wastes		1.47		
	Subtotal		***3.31***		
3279	Other nonmetallic mineral products	0.21		2.78	
	Grand Total	**9.40**	**11.95**	**14.49**	

2.8 Primary Metal & Fabricated Metal Product Mfg (NAICS 331-332)

2.8.1 Summary

The primary metal and fabricated metal product manufacturing sectors (NAICS 331-332) are estimated to have generated 34.13-37.34 Tg of NHIW in 2015. Iron and steel mills and steel product manufacturing are the source of roughly 54% of this waste, followed by nonferrous metals production (22%), foundries (19%), and fabricated metal products (5%). Slags and spent foundry sands are the largest components of the waste stream, and are also widely beneficially used. Red mud, the byproduct of alumina production, is the only metal ore concentration waste included in the scope of these sectors (the others are considered mining activities), and is nearly 14% of the total waste stream.

2.8.2 Industry structure

The Primary Metal (NAICS 331) and Fabricated Metal Product (NAICS 332) Manufacturing sectors produce ferrous and nonferrous metals and metal products. Firms in the Primary Metal Manufacturing sector produce metal from ore and ore concentrate (primary production) as well as scrap metal (secondary production), comprising five NAICS industry subsectors (Table 2.8-1) [1]. Ferrous metal outputs include both iron and steel, while nonferrous metals include aluminum, copper, zinc, lead, and other metals and alloys. These firms produce metals in basic shapes, produced by rolling, drawing, and extruding. NAICS 3315 includes foundries, which manufacture castings of ferrous and non-ferrous metals in a wide variety of shapes and sizes.

Table 2.8-1. NAICS 2017 structure of the primary & fabricated metal product manufacturing sectors [1]

331 Primary Metal Manufacturing	332 Fabricated Metal Product Manufacturing
3311 Iron and Steel Mills and Ferroalloys*	3321 Forging and Stamping
3312 Steel Products from Purchased Steel	3322 Cutlery and Handtools
33121 Iron and Steel Pipe and Tube from Purchased Steel	3323 Architectural and Structural Metals
33122 Rolling and Drawing of Purchased Steel	3324 Boilers, Tanks, and Shipping Containers
3313 Alumina and Aluminum Production and Processing*	3325 Hardware
3314 Nonferrous Metal (except Al) Production & Processing	3326 Springs and Wire Products
33141 Nonferrous Metal (except Al) Smelting & Refining	3327 Machine Shops; Turned Products; and Screws, Nuts, and Bolts
33142 Copper Rolling, Drawing, Extruding, and Alloying	3328 Coating, Engraving, Heat Treating, and Allied Activities
33149 Nonferrous Metal (except Cu and Al) Rolling, Drawing, Extruding, and Alloying	3329 Other Fabricated Metal Products
3315 Foundries	
33151 Ferrous Metal Foundries	
33152 Nonferrous Metal Foundries	

* These sectors have a single 5-digit subsector

Firms involved in Fabricated Metal Product Manufacturing take as inputs the products from NAICS 331 and produce a broad range of finished metal products. The sector is structured roughly by the types of products manufactured, in nine NAICS industry subsectors (Table 2.8-1): forged and stamped products (often intermediates for the other subsectors), cutlery, architectural products, tanks and boilers, hardware, springs, screws and related products, and other products. Processes used in NAICS 332 are highly varied, but include surface treatments and coatings alongside various thermal and mechanical techniques.

Together, these two sectors contribute roughly 11% of the country's total manufacturing GDP; the ratio ranged between 10% and 12% from 2010-2016. Fabricated Metal Manufacturing (NAICS 332) added more than twice the value of Primary Metal Manufacturing (NAICS 331) [2]. This says nothing about the total physical volume of production from the two sectors; rather, it is because the products in NAICS 332 are more valuable than those in NAICS 331. Within NAICS 331, iron and steel production is the largest subsector (NAICS 3311), followed by foundries (NAICS 3315), non-ferrous metals (NAICS 3314), aluminum (NAICS 3313), and finally steel made from purchased steel (NAICS 3312) (Figure 2.8-1). Within NAICS 332, just three subsectors provide two thirds of the total value add: architectural and structural metals (NAICS 3323), machine shops and turned products (NAICS 3327), and other products (NAICS 3329) (Figure 2.8-2). Another three subsectors provide an additional quarter of the total value add: forging and stamping (NAICS 3321), boilers, tanks, and shipping containers (NAICS 3324), and coating, engraving, heat treating and allied activities (NAICS 3328). The final three subsectors are considerably smaller: cutlery and handtools (NAICS 3322), hardware (NAICS 3325), and spring and wire products (NAICS 3326).

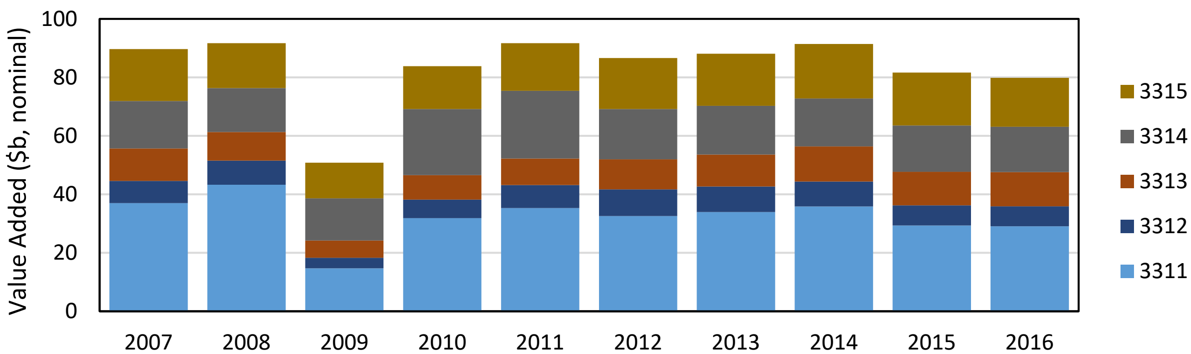

Figure 2.8-1. *Value added (billion $, nominal) from industry subsector 331, 2007-2016 [2]*

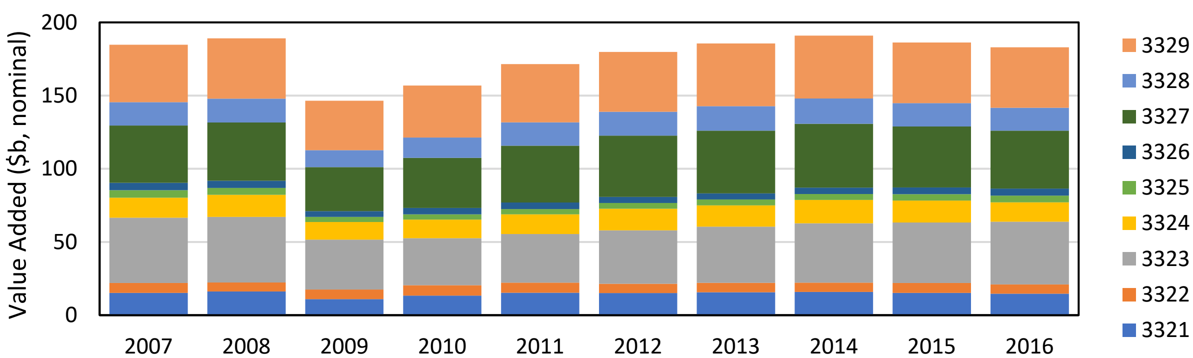

Figure 2.8-2. *Value added (billion $, nominal) from industry subsector 332, 2007-2016 [2]*

2.8.3 Solid wastes from NAICS 331-332

Wastes from the primary metal and fabricated metal product manufacturing sectors are generated in three categories: primary and secondary metal production; foundries; and fabricated metal product manufacturing. All primary and secondary production of both ferrous and non-ferrous metals (NAICS 3311-3314) yields mineral wastes like dross and slag and pollution control residuals like air pollution control dust and wastewater treatment sludge. Additional wastes are specific to particular metal products. Integrated iron and steel mills include coking plants with waste products similar to those found in chemicals manufacturing [3]. The production of hot rolled steel results in mill scale and sludge; surface treatments of iron and steel generate waste pickling liquors; and the shaping of basic steel shapes creates steel grinding swarf [4]. The production of alumina from bauxite via the Bayer process generates red mud; the subsequent conversion of alumina to aluminum using the electrochemical Hall-Héroult process generates process wastes from the manufacture and use of carbon anodes [5]. The production of copper, zinc, and lead, as well as other non-ferrous metals, also generate process wastes in addition to slags and pollution control residues, including wastes from electrochemical processes and mineral wastes unique to each smelting process (e.g. goethite and leach cake residue from zinc production) [6]. Wastes from metalcasting foundries (NAICS 3315) are predominantly spent foundry sands, molds, and cores, but also include chemical wastes, slags, and pollution control dust and sludge [7].

Metal products fabrication (NAICS 332) generates a wide variety of wastes, including metal shavings, paint wastes, surface treatment liquors, oils, and pollution control dusts and sludges. A more comprehensive list of wastes from both primary metal and fabricated metal product industries as included in the European Waste Catalog are listed in Table 2.8-2 [8].

Not all of the wastes generated in these two industry sectors are in scope for this accounting project. Many of the wastes are hazardous, including three RCRA listed wastes: EAF dust (K061) and spent pickle liquor (K062) from steelmaking; and spent potliners (K088) from aluminum production. Many other wastes exhibit hazardous characteristics, often due to the presence of heavy metals. Effectively all wastes from lead production and some from other non-ferrous metals production are excluded due to this criterion.

Many process wastes are also recovered and recycled; metalliferous wastes can often be re-smelted or reprocessed to extract more of the valuable raw material. This is the case with some steel, copper, and lead slags; aluminum dross and skimmings, steel mill scales, and others. Similarly, pollution prevention initiatives and environmental regulations have led to efforts to recover and reuse waste foundry sands and surface treatment chemicals (pickling liquors). In addition, many other wastes, including iron and steel slag, pisolites, and some foundry sands, have found mature beneficial uses, usually in construction and fill applications, and as a result are seen by their generators as byproducts, not wastes. In line with the system scope determination for this accounting project, all non-hazardous solid and land-applied process residuals are to be accounted for here, with the exception of those which are recycled internally.

Table 2.8-2. *Primary and fabricated metal product mfg wastes as listed in the European Waste Catalog [8]*

Activity	Waste category	
Iron and steel industry	- wastes from the processing of slag - unprocessed slag - solid wastes from gas treatment	- mill scales - sludges and filter cakes
Nonferrous metal thermal metallurgy	- slags from primary and secondary production - dross and skimmings - flue-gas dust - other particulates and dust - solid wastes from gas treatment - sludges and filter cakes from gas treatment	- wastes from cooling-water treatment - red mud - waste alumina - anode scraps - tar-containing wastes from anode manufacture
Ferrous & non-ferrous casting	- furnace slag - casting cores and molds - flue-gas dust	- other particulates - waste binders - waste crack-indicating agent
Chemical surface treatment & coating of metals	- pickling acids - pickling bases - phosphatizing sludges - sludges and filter cakes - aqueous rinsing liquids	- degreasing wastes - eluate and sludges from membrane systems or ion exchange systems - saturated or spent ion exchange resins
Shaping, physical & mechanical surface treatment of metals	- ferrous & non-ferrous metal filings and turnings - ferrous & non-ferrous metal dust and particles - mineral-based machining oils - machining emulsions and solutions - synthetic machining oils - spent waxes and fats - welding wastes	- machining sludges - waste blasting material - metal sludge (grinding, honing and lapping sludge) - readily biodegradable machining oil - spent grinding bodies and grinding materials

2.8.4 NHIW estimation

2.8.4.1 Historical forecasting

Multiple historical sources of empirical data on NHIW generation from the primary metals and fabricated metal products manufacturing sectors were identified for use in this project. The availability and quality of these data vary significantly, with the best and most recent data available for ferrous and non-ferrous metals production. Data on NHIW from foundries and metal fabrication is much poorer, scarcer, and less complete. The reasons for this discrepancy seem to be threefold. First, wastes from primary metal production (and not foundries and metal product fabrication) were included in the Bevill Amendment exclusions from RCRA subtitle C regulations. During the 1990s, the EPA and its contractors conducted detailed studies of the hazards posed by these and other wastes excluded by the Amendment, which led to the collection and publication of waste quantities and compositions. Second, the beneficial uses and reprocessing possibilities of slags and other metalliferous wastes from metals production have been of interest both to the government and to industry associations like the American

Iron & Steel Institute (AISI), which have collected and published data on their industry's progress towards particular waste-related goals. Finally, and relatedly, foundries and metal fabricators are much more numerous and often smaller scale than primary metals processors. They also have less-centralized and less-powerful industry associations who have not identified non-hazardous wastes as priorities.

Most data on NHIW from the iron and steel industry comes from the 2001 *Steel Industry Technology Roadmap* by AISI, which included a 1999 account of "slags, dusts, sludges, and scale generation" from blast furnace ironmaking, BOF and EAF steelmaking, ladle treatment of molten steels, and steel casting and rolling [4, pp. 53-73]. The relevant section of the report focused on potential metal recovery from these wastes, but also included accounts of total waste generation. Data in this report is closely related to that presented in a 2000 Department of Energy report on the *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (consultants from Energetics, Inc. worked on both reports) [3]. That earlier source presents waste data for 1994, so with the exception of mill scale and sludge, the later estimates were used here.

It should be noted that the one major NHIW category for which official accounts are maintained is iron and steel slag, which is reported by the USGS in their *Minerals Yearbooks* and *Minerals Commodity Summaries*. However, as these reports make clear, the quantities accounted for by the USGS are marketed slag, not generated slag. Effectively all blast furnace slag is thought to be beneficially used, but generators may stockpile slag from one year to the next for financial or other reasons; marketed steel slag might be only 50% of total generated steel slag. The AISI report appears to report generated slag values for 1999, so those quantities are used instead of the 2015 reported values of marketed slag from the USGS.

Data on NHIW from non-ferrous metals production was drawn primarily from two EPA reports on mineral processing wastes, one from 1998 [6] and one from 1990 [9], both of which served to help clarify regulations around Bevill Amendment excluded wastes. The 1990 report documented major wastes from 12 mineral products (or product categories), including alumina, copper, lead, and zinc. Data was collected from processing facilities for 1988. The later report expanded both the list of mineral products and types of wastes considered. The objective of this report was to document potential hazard of the various wastes from these mineral processing activities. As such, some of the wastes determined to be explicitly non-hazardous lacked detail on generation quantities. The 49 minerals and metals covered by this report included alumina and aluminum, copper, lead, and zinc, as well as many other non-ferrous metals that are produced in too-small quantities to be considered here. NHIW from aluminum production was also documented by a DOE publication, *Energy and Environmental Profile of the U.S. Aluminum Industry* [5].

No reliable data on NHIW from foundries, metalcasting, and metal product fabrication were identified apart from the 1985 EPA report on industrial non-hazardous waste disposal practices by SAIC [10]. For foundries and metalcasting, that report relied on a 1978 survey by the American Foundrymen's Society (AFS) that surveyed ferrous and non-ferrous foundries to derive waste generation factors. Iron and steel foundries were reported to generate between 0.32 and 0.79 metric tons of waste per metric ton of castings, with steel foundries on the higher end and iron foundries on the lower end [10, p. 4-209]. The AFS survey included just four non-ferrous foundries; SAIC did not derive waste generation factors from this small data set but did project the waste generation values forward to 1984 using casting volume data. While the report documents many different types of foundry wastes, the data is reported in the aggregate, stating that the large majority of the waste is spent foundry sand.

The SAIC report acknowledges that no comprehensive studies of NHIW from that large and diverse sector were available. The report includes an extensive table of wastes from the major manufacturing processes used in metal product fabrication, but with no associated waste quantities. The one extant data point is from an unpublished 1983 EPA inventory of non-hazardous industrial sludges. The SAIC report also cites an earlier EPA study that argues that most of the wastes from this sector are hazardous.

The forecasting method for primary metal manufacturing and foundries used physical factors, that is, production tonnage of pig iron, BOF and EAF steel, alumina, primary and secondary aluminum, copper, zinc, and ferrous and non-ferrous castings. The forecast for fabricated metal products manufacturing used economic factors.

Results from this historical forecasting method suggest that 33.07 Tg of NHIW was generated by the primary metal and fabricated metal products sectors in 2015 (Table 2.8-3). Slightly more than half of this quantity comes from iron and steel mills (NAICS 33111): 5.83 Tg of blast furnace slag, 7.73 Tg of steel slag, 2.88 Tg of mill scale, and the rest (1.28 Tg) dust and sludge. Steel manufacturing generated an additional 1.40 Tg of sludge, dust, and swarf (grinding residue). Most of the NHIW from aluminum manufacturing (NAICS 33131) comes from the production of alumina: 2.66 Tg of red mud, 0.20 Tg of other alumina wastes, 0.21 Tg of aluminum skims and drosses, and 0.20 Tg of other aluminum wastes. In the other non-ferrous metals production sector (NAICS 33141), copper production generated 2.29 Tg and zinc production generated 0.13 Tg of NHIW, mostly slag. Ferrous and non-ferrous foundries (NAICS 3315) generated 4.49 Tg and 3.31 Tg of NHIW, respectively, mostly foundry sands. Finally, fabricated metal products manufacturing (NAICS 332) generated 0.45 Tg of non-hazardous wastewater treatment sludges.

Table 2.8-3. *NHIW from the primary and fabricated metals industries estimated by historical forecasting, 2015*

Subsector/Waste Type	Gg (Base year)	Base year	Tg (2015)	Source
33111: Iron & steel mills				
Blast furnace slag	10,614.06	1999	**5.83**	[4, p. 58]
Blast furnace dust	353.80	1999	**0.19**	[4, p. 60]
Blast furnace sludge	589.67	1999	**0.32**	[4, p. 60]
BOF slag	5,624.55	1999	**3.16**	[4, p. 62]
BOF dust	231.33	1999	**0.13**	[4, p. 57]
BOF sludge	1,097.69	1999	**0.62**	[4, p. 57]
EAF slag	3,628.74	1999	**3.98**	[4, p. 57]
Ladle treatment slag	725.75	1999	**0.59**	[4, p. 57]
Ladle treatment dust	20.87	1999	**0.02**	[4, p. 57]
Mill scale	3,329.37	1994	**2.88**	[3, p. 88]
Subtotal			***17.72***	
33121-2: Steel manufacturing				
Rolling sludge	907.18	1994	**0.78**	[3, p. 88]
Grinding swarf	635.03	1999	**0.51**	[4, p. 73]
Other dusts	127.01	1999	**0.10**	[4, p. 73]
Subtotal			***1.40***	
33131(3): Alumina production				
Red mud	2,800.00	1988	**2.66**	[9, p. 3-4]
Evaporator salt waste	2.00	1991	**0.00**	[6, p. 82]
Bauxite residue	137.00	1991	**0.12**	[6, p. 82]
Waste alumina	7.00	1991	**0.01**	[6, p. 83]
Spent cleaning residue	3.00	1991	**0.00**	[6, p. 83]
Pisolites	72.92	1988	**0.07**	[6, p. 83]
Subtotal			***2.86***	
33131(3-4): Aluminum production				
Flue dust	39.00	1991	**0.02**	[6, p. 84]
Sweepings	23.00	1991	**0.01**	[6, p. 84]
Baghouse bags and spent plant filters	19.00	1991	**0.01**	[6, p. 84]
Skims and discarded drosses	439.00	1994	**0.21**	[6, p. 85]
Anode prep waste	20.00	1991	**0.01**	[6, p. 85]
Cryolite recovery residue	30.00	1991	**0.01**	[6, p. 85]
Sludge	80.00	1998	**0.03**	[6, p. 86]
Secondary aluminum baghouse fines	102.02	1995	**0.11**	[5, p. 72]
Subtotal			***0.41***	
33141: Copper smelting and refining				
Smelter slag	2,500.00	1988	**1.27**	[9, p. 6-5]
Converter and anode furnace slag	380.00	1988	**0.19**	[9, p. 6-6]
Slag tailings	1,500.00	1988	**0.76**	[9, p. 6-6]
Calcium sulfate wastewater treatment plant sludge	140.00	1988	**0.07**	[9, p. 6-7]
Subtotal			***2.29***	
33141: Zinc smelting and refining				
Zinc slag	157.00	1988	**0.08**	[9, p. 14-2]
Goethite and leach cake residues	15.00	1991	**0.01**	[6, p. 752]
Saleable residues	10.00	1991	**0.00**	[6, p. 753]
Spent synthetic gypsum	16.00	1991	**0.01**	[6, p. 754]
Wastewater treatment plant sludge	34.00	1991	**0.02**	[6, p. 755]
Waste ferrosilicon	17.00	1991	**0.01**	[6, p. 756]
Subtotal			***0.13***	

Table 2.8-3 (cont.). *NHIW from primary and fabricated metals industries estimated by historical forecasting, 2015*

Subsector/Waste Type	Gg (Base year)	Base year	Tg (2015)	Source
3315(1-2): Foundries				
Ferrous foundry sand and other waste	10,117.00	1978	**4.49**	[10, p. 4-213]
Non-ferrous foundry sand and other waste	2,104.00	1984	**3.31**	[10, p. 4-239]
Subtotal			***7.80***	
332: Fabricated metal products				
Wastewater treatment sludge	300.00	1983	**0.45**	[10, p. 4-74]
Subtotal			***0.45***	
TOTAL			**33.07**	

Data from the 1983 PACE survey yields an estimate of NHIW from these two subsectors of 23.09 Tg: 12.1 Tg from iron and steel mills, 6.0 Tg from foundries, 2.4 Tg from nonferrous metals production, 2.3 Tg from metals fabrication, and just 0.3 Tg from steel product manufacturing (Table 2.8-4). A quarter of the waste from iron and steel mills and nonferrous metal mills is air pollution control residuals; that fraction is less for the other subsectors.

Table 2.8-4. *NHIW from primary & fabricated metal product manufacturing estimated from PACE, 2015 [11]*

NAICS	Description	1983 (Gg)		2015 (Tg)
		NHIW	***APC***	***Total***
3311	Iron and steel mills and ferroalloy manufacturing	6,846.2	2,324.7	12.1
3312	Steel product manufacturing from purchased steel	221.5	17.8	0.3
3313-4	Nonferrous metal production and processing	2,238.1	644.5	2.4
3315	Foundries	5,806.8	630.8	6.0
332	Fabricated metal product manufacturing	1,422.3	105.9	2.3
331-332	**TOTAL**			**23.09**

2.8.4.2 Spatial Up-Scaling

Scaling up data from the Pennsylvania Residual Waste Program produces an estimate of NHIW generated by the primary metals and fabricated metal products manufacturing sectors of 8.97 Tg in 2015 (Table 2.8-5). Pennsylvania produces 9.6% of the national economic output of primary metals and 5.3% of fabricated metal products; within primary metal manufacturing this fraction ranges from 14.5% of national iron and steel mill output to 5.1% of aluminum, with steel products, other nonferrous metals, and foundries in between. This estimate likely excludes a large fraction of generated wastes that are highly beneficially used, like iron and steel slag (0.79 Tg) and foundry sands (1.68 Tg), because of the reporting requirements of the PARW program. Wastewater and pollution control sludges make up 20% of the total waste stream (1.79 Tg) and are generated in significant quantities from all subsectors except for foundries. Foundry pollution control wastes are in the form of dust (0.41 Tg). Each sector also generates quantities of wastes specific to the processes and materials used in each, such as spent pickle liquor from iron and steel (0.29 Tg), dross and skims from non-ferrous metals

Table 2.8-5. *NHIW from primary and fabricated metals industries estimated by up-scaling from PARW data, 2015*

Subsector / Waste type	PA Waste (Gg)	US Waste (Tg)
3311: Iron and steel mills and ferroalloy manufacturing	**394.1**	**2.72**
Slag	115.2	0.79
Refractory material	15.6	0.11
Mill scale	10.2	0.07
Spent pickle liquor	38.2	0.26
Sludge	159.7	1.10
Dust	7.1	0.05
Other manufacturing waste	18.3	0.13
Plant trash & other waste	29.7	0.20
3312: Steel product manufacturing from purchased steel	**54.9**	**0.69**
Refractory material	14.3	0.18
Spent pickle liquor	2.1	0.03
Waste oil	9.3	0.12
Sludge	20.8	0.26
Other manufacturing wastes	3.3	0.04
Plant trash & other waste	5.1	0.06
3313: Alumina and aluminum production and processing	**19.2**	**0.38**
Dross, skims	10.7	0.21
Waste oil	1.5	0.03
Sludge	0.9	0.02
Other manufacturing wastes	4.1	0.08
Plant trash & other waste	2.0	0.04
3314: Nonferrous metal (except Al) production and processing	**110.9**	**1.18**
Slag	38.7	0.41
Dross, skims	2.6	0.03
Refractory material	3.3	0.03
Sludge	26.8	0.29
Fly ash	9.7	0.10
Other manufacturing wastes	12.5	0.13
Plant trash & other waste	17.3	0.19
3315: Foundries	**165.6**	**2.88**
Foundry sand	96.6	1.68
Slag	25.9	0.45
Refractory material	5.2	0.09
Dust	23.5	0.41
Other manufacturing wastes	9.0	0.16
Plant trash & other waste	5.4	0.09
332: Fabricated metal product manufacturing	**63.0**	**1.13**
Foundry sand	3.1	0.05
Slag	2.4	0.04
Refractory material	2.5	0.04
Mill Scales, Heat Treat Scales	1.0	0.02
Sandblast Abrasive And Residue	1.2	0.02
Grindings, Shavings	0.8	0.01
Sludge	7.2	0.13
Dust	5.7	0.10
Waste oil	8.1	0.15
Contaminated soil	3.9	0.07
Other manufacturing wastes	7.6	0.14
Plant trash & other waste	19.7	0.35
331-332: TOTAL	**807.7**	**8.97**

production (0.24 Tg, mainly from Al production), foundry slag (0.45 Tg), and a variety of residuals from metal fabrication. No red mud is present in this data because no alumina production occurs in Pennsylvania. Plant trash makes up 10.5% of all NHIW in this account.

2.8.4.3 Material balance

Materials balance methods are ideal for industrial processes that convert a raw material into a refined one; primary metals production (NAICS 3311, 3313-4) is therefore a good candidate. Other subsectors of NAICS 331-332 have limited or no data or models available to support a materials balance estimate. For primary metals, we base our analysis on the approach developed by Ayres & Ayres [12].

2.8.4.3.1 Iron & steel: Ironmaking

Blast furnace inputs are iron ore pellets, sinter, and iron and steel scrap; coke; and limestone and dolomite flux. These inputs are combined with air to produce molten iron, slag, and blast furnace gas (BFG), as well as air pollution control dust and sludge [3, p. 43]. Using official data and estimates of composition, we construct a material balance for blast furnace ironmaking to estimate slag production for 2015.

In 2015, U.S. blast furnaces consumed 39.18 Tg of iron-bearing materials: 32.1 Tg of concentrated ore pellets, 4.92 Tg of sinter, and 2.16 Tg of scrap; and 7.99 Tg of coke [13, p. 37.5]. The ore pellets and sinter are estimated to have a composition of 62.5% iron, 5% silica, 2% moisture, 0.35% other minerals, with the balance the oxygen combined with iron [12, p. 104]. Scrap metal is assumed to have a composition of carbon steel, defined as having no greater than 2.1% alloying elements (we assume 1% carbon content and 1% metal alloying content). These numbers mean that the iron content of blast furnace inputs totaled 25.25 Tg; an additional 2.02 Tg of mineral content was converted to slag and the rest evolved as BFG.

The coke used in steel production is mainly carbon, with quantities of ash and sulfur from the coal used in coking. According to the EIA, coal used in producing coke in 2015 had an average ash content of 7.59% and a sulfur content of 1.05% [14, p. 51]. Assuming 1.432 Mg of coal per Mg of coke produced, the 7.99 Tg of coke consumed in blast furnaces was made of 7.00 Tg of carbon, 0.87 Tg of ash, and 0.12 Tg of sulfur. Some of the carbon and sulfur ends up in the molten pig iron, the ash and some sulfur is converted to slag, and the rest is evolved as BFG.

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are converted to slag and BFG in blast furnaces. Based on the chemical compositions of these minerals, between 52-56% of this flux is converted to slag while the other 44-48% is evolved as CO_2 in BFG. No data is available on the quantities of flux used in 2015, but can be estimated using quantities and compositions of blast furnace products (see below).

Blast furnaces produced 25.4 Tg of pig iron in 2015 [13, p. 37.5]. The composition of pig iron can vary, but generally includes 91-95% iron, 4.0-4.5% carbon, and the rest a mix of silicon, manganese, phosphorus, and sulfur [3, p. 42]. This composition gives us the first opportunity to check the mass balance. As stated above, blast furnace charge contains 25.25 Tg of iron. Based on pig iron composition ranges, pig iron contains between 23.06-24.23 Tg of iron. This difference, 1.12-2.14 Tg of iron, is too large to explain by the trace quantities of iron oxide in slag or the ferrous content of air pollution control dust. It is either due to errors in the reported mass data or errors in composition of the blast furnace charge. Most likely the charge data is slightly too large. A composition error would require either iron content of pig iron to be higher than 95% (leaving little room for the minimum 4% carbon content) or the iron content of the charge materials to be lower than 62.5% standard benchmark for iron and steel manufacturing [16, p. 39.1]. Furthermore, there is always stockpiling at iron and steel mills and the reporting process to the AISI survey likely includes some estimation on the part of the mill compliance officer.

The other main solid-phase output from blast furnaces is slag. Blast furnace slag composition can also vary widely depending on the quality and composition of the charge materials, but generally includes the following mineral constituents (wt.%): CaO (38-42%), SiO_2 (34-38%), Al_2O_3 (10-12%), MgO (8-10%), MnO (0.5-1.0%), S (1-2%), and Fe_2O_3 (0.1-1.5%) [3, p. 52; 15, p. 2]. Multiple methods are available for estimating slag quantities. First, we can examine the amount of silica (SiO_2) present in the input iron ore and the mass fraction of silica in blast furnace slag. Based on an input of 37.02 of pellets and sinter and an estimated 5% concentration of SiO_2, there is 1.85 Tg of silica that must be removed in slag. If slag contains between 34-38% SiO_2, this means a total of 4.87-5.44 Tg of slag. Some silica is also likely delivered via ash in the coke charge, so this range might be slightly low. A second method assumes that all lime (CaO) and magnesia (MgO) in the slag come from the limestone and dolomite flux and all other slag constituents are delivered in the charge materials: 1.85 Tg of silica and 0.13 Tg of other minerals in pellets and sinter, 0.02 Tg of alloying metals in scrap, and 0.87 Tg of ash in coke—2.87 Tg in total. If CaO and MgO make up 48-50% of slag composition (depending on the relative amounts of limestone and dolomite used as flux), these other minerals make up the remaining 50-52% of the total slag mass, which can be estimated at 5.74-5.98 Tg.

Two intensity factors can also be used to estimate slag generation. The US DOE estimates that 0.25 Mg of flux is needed per Mg of pig iron produced [3, p. 41]. For 25.4 Tg of pig iron, this means 6.35 Tg of flux. Depending on the limestone/dolomite ratio, the CaO and MgO left over in the slag is 3.31-3.56 Tg. Adding this value to the 2.87 Tg of other slag components of the input materials, slag generation is estimated to be 6.18-6.43 Tg. Finally, USGS reports that the ratio of slag to pig iron production is 0.25-0.30, depending on the ore grade of iron ore pellets used [17, p. 69.1]. According to this estimate, for 25.4 Tg of pig iron produced, between 6.35-7.62 Tg of slag would be produced.

The four material-balance estimates of blast furnace slag range from 4.87-7.62 Tg. We contend that the most likely of the four estimates is the second: 5.74-5.98 Tg. This estimate relies the most on principles of material balance and least on intensity factors. It also does not hinge completely on a single compositional estimate, as the first does.

The USGS publishes annual reports on iron and steel slag. However, the values contained in this report are explicitly *not* representative of slag produced. Rather, they are the quantities of slag sold or beneficially used. This difference is important as slag is often stockpiled from year to year and, although most slag is beneficially used, a large fraction of steel slag is not. These two trends (stockpiling and non-use) push the estimate in contrary directions, so there is neither a way to estimate slag generation from slag sales nor use the published values as an upper or lower bound. For example, USGS reports 8.8 Tg of blast furnace slag sales in 2015, a quantity well above all four material-balance estimates of slag generation [17, p. 36.5].

It is possible but not necessary to complete the mass balance of blast furnace production, as the final conversion involves oxygen from the atmosphere, which is effectively without constraints. Therefore, the meaningful calculation of BFG (and air pollution control dust and sludge) is not possible.

2.8.4.3.2 Iron & steel: Steelmaking

Steel furnaces produced a total of 78.5 Tg of raw steel in 2015, 37% from basic oxygen furnaces (BOF) and 63% from electric arc furnaces (EAF) [13, p. 37.1]. Carbon steel (with no greater than 2.1% carbon content) comprised 93.4% of total raw steel output, with the rest a mix of stainless (11% chromium) and other alloy steels. The main iron-bearing inputs to steelmaking furnaces include 22.2 Tg of molten iron from blast furnaces, 48.7 Tg of scrap steel (including 4.99 Tg of internal scrap), and 2.72 Tg of direct-reduced iron [18, p. 38.9]. In addition, steelmaking consumes 1.48 Tg of iron ore (pellets and sinter) [16, p. 39.8], 1.11 Tg of ferroalloys [19, pp. 25.6-7], 4.71 Tg of lime flux [20, p. 43.8], 0.03 Tg of fluorspar flux [21, p. 26.7], and 0.01 Tg of sulfur used for steel surface pickling [22, p. 74.9].

Subtracting outputs from inputs gives a total lost mass of 2.00 Tg. This mass must account for slag, dust & sludge, emissions (such as the carbon content of CO_2 evolved from steelmaking), and ferrous sulfate in the spent pickling liquid. Even if the entire lost mass value were somehow credited just to slag production, it is likely an underestimate. USGS reports 8.9 Tg of marketed steel furnace slag in 2015, which like blast furnace slag is not a measure of slag generated, but gives a sense of the large scale of slag output [17, p. 69.5]. USGS also cites an intensity factor of steelmaking slag generated at a rate of 10-15% of raw steel output, which for 2015's production quantity would be 7.89-11.8 Tg. The significant gap between these values and that calculated from the material balance above suggest there is an error in the USGS steel data, either inputs or outputs. Since the output data seems to be corroborated by AISI statistics, the error is more likely to lie with ferrous input data.

One way to bypass the potentially misleading ferrous input statistics is to examine just those slag-forming components of the inputs, including the fluxes (4.71 Tg of lime and 0.03 Tg of fluorspar) and the mineral constituents of the 1.48 Tg of iron ore consumed in steel furnaces (0.08 Tg at 5% silica and 0.35% minerals): 4.82 Tg total. This is potentially an underestimate as well, as it excludes slagged alloying metals from scrap iron and steel consumed in EAF steelmaking and any iron oxide remaining in the slag after reprocessing. It also potentially suffers from the same input data errors noted above.

Another approach to bound the estimate is given by AISI, who claim that 100-220 kg of BOF slag is generated per Mg of BOF steel and 62.5-100 kg of EAF slag is generated per Mg of EAF steel [4, pp. 62, 65]. With BOF and EAF steel output of 29.4 Tg and 49.4 Tg in 2015, respectively, we would estimate BOF and EAF slag production rates of 4.94-10.9 Tg and 1.84-2.94 Tg, respectively. These values are likely overestimates as they do not account for internal reprocessing and recovery of iron entrained within the slags.

2.8.4.3.3 Non-ferrous metals

Limitations in both input/output data and process information constrain the usefulness of material balance methods for estimating wastes from non-ferrous metals production. Specifically, using Ayres's models as a guide, we are limited to estimating just two wastes: red mud from alumina production and copper smelter slag (no lead smelting occurred in the U.S. in 2015, else those wastes would also be calculable using this method).

Red mud is produced from the conversion of bauxite to alumina in the Bayer process. In 2015, U.S. alumina plants produced 4.75 Tg of alumina from 9.34 Tg of bauxite [23, pp. 10.8-9]. The process also consumes lime and caustic soda. USGS reports that 1.33 Tg of lime was consumed in nonferrous metallurgy in 2015, but does not distinguish between the production of alumina and sulfide ore processing (mainly copper and gold). Ayres cites a 1975 report that claims 0.039 Mg of lime and 0.035 tons of caustic soda are consumed per ton of alumina produced [12, p. 107]. If these values are accurate, lime consumption totaled just 0.19 Tg and caustic soda 0.17 Tg. Red mud production was therefore the difference between bauxite, lime, and soda inputs and alumina output: 4.94 Tg.

Ayres developed extensive, mass-balanced process models of copper, lead, and zinc in a 2003 book [24]. We use those models in combination with USGS-reported production values to estimate non-ferrous slags, as simple input/output relationships such as those used above are insufficient to represent the complex metallurgy of non-ferrous metals production. Ayres calculated that 1.55 Mg of copper slag was produced for every Mg of smelted copper; it includes silicates, lime, and most of the metals present in the copper ore [24, p. 51]. In 2015, U.S. copper smelters produced 0.522 Tg of primary copper [25, p. 20.8], which according to Ayres's intensity factor means the generation of 0.80 Tg of copper slag.

Material balance methods are not applicable for estimating wastes from foundries or metal product fabrication.

Table 2.8-6. *Summary of results from material balance estimates of NHIW from primary metals production, 2015*

Subsector	Waste type	2015 (Tg)
Iron & steel	*Blast furnace slag*	5.74-5.98
	BOF slags	4.94-10-9
	EAF	1.84-2.94
Alumina	*Red mud*	4.94
Copper	*Copper slag*	0.80
Total		**18.26-25.56**

2.8.4.4 International comparison

European waste data suggests that the U.S. primary metals and fabricated metal products industry sectors generated 64.18 ± 59.15 Tg of NHIW in 2015 (Table 2.8-7). There seems to be little overlap between this waste account and the scope of analysis defined above. For example, metallic wastes comprise nearly 20% of this total waste account and mixed ordinary wastes 16%. Combustion wastes is the largest component, 43% of the total, and may be accounting for some mineral wastes. Other relevant waste categories are "other mineral wastes" (11.32 ± 15.02 Tg), which presumably includes furnace and smelter slags and air pollution control dusts, and "other wastes" (2.42 ± 2.32 Tg), which may include non-hazardous treatment sludges.

Table 2.8-7. *NHIW from primary and fabricated metal products mfg estimated using European waste data*

	Waste intensity (Mg/$1,000)		**US Waste 2015 (Tg)**	
	Average	*Std. Dev.*	*Average*	*Std. Dev.*
Metal wastes, ferrous	16.71	13.96	9.95	8.31
Metal wastes, non-ferrous	2.37	2.26	1.41	1.35
Metal wastes, mixed	1.02	1.13	0.61	0.67
Mixed ordinary wastes	17.06	45.45	10.15	27.05
Other mineral wastes	19.03	25.23	11.32	15.02
Combustion wastes	46.73	49.69	27.81	29.58
Other wastes	4.05	3.90	2.41	2.32
Total Waste	**107.82**	**99.38**	**64.18**	**59.15**

Sum of individual wastes may not equal "total waste" due to rounding errors and because of inconsistencies in the raw data.

2.8.4.5 Triangulation & Synthesis

2.8.4.5.1 NAICS 3311: Iron and steel mills

Three of the estimates of NHIW from iron and steel mills (NAICS 3311) are subsector-wide: 17.72 Tg (historical forecasting), 12.1 Tg (PACE), and 2.72 Tg (PARW). Both historical forecasting and material balance methods provide estimates of slag from blast furnaces and steelmaking furnaces. The material balance estimate of blast furnace slag agrees very well with that from the historical forecast: 5.74-5.98 Tg and 5.83 Tg, respectively. The historical estimate of BOF slag is somewhat lower than the range provided by AISI waste intensity factors: 3.16 Tg vs. 4.94-10.9 Tg, while the historical estimate of EAF slag is somewhat higher than the AISI-based estimate: 3.98 Tg vs. 1.84-2.94 Tg. On the other hand, the other estimate of overall steelmaking slag from the material balance method is quite a bit lower than the total steelmaking slag estimate from the historical record: 4.82 Tg vs. 7.79 Tg (including ladle treatment slags). Considering the historical forecast estimate is based on relatively recent empirical data and there are serious questions as to the validity of the steelmaking input/output data used in the material balance estimate, it seems prudent to use the historical estimate of steelmaking slags for this account.

PARW data also include an estimate of iron and steel slag: just 0.79 Tg (plus an additional 0.11 Tg of refractory material). Considering the system boundary inconsistencies between this project and the PARW program (e.g. the inclusion vs. exclusion of beneficially used wastes), it is likely that the 0.79 Tg represents the small fraction of iron and steel slag that is *not* beneficially used. Another major inconsistency is seen with the two estimates of mill scale: 2.88 Tg from historical forecasting vs. 0.07 Tg from PARW. This gap is not surprising given the economic incentive to try to recover iron content from mill scale through reprocessing: the historical estimate is that of scale generated; the PARW estimate is that of scale discarded.

There is agreement between the historical forecast and PARW estimates of sludge generation: 0.94 Tg of sludge per the historical forecast and 1.10 Tg of sludge per PARW. However, the PARW composition is unreliable, and sludge may refer to any number of waste materials, while the historical data examined specific sources of sludge waste from iron and steel mills.

Overall, examination of the four relevant estimates (historical forecast, PACE, PARW, and material balance) suggests that the historical forecast is the most reliable and consistent with the system boundaries of this accounting project.

2.8.4.5.2 NAICS 3312: Steel products

NHIW from the manufacture of steel products from purchased steel (NAICS 3312) is estimated with three of the methods: historical forecast, PACE forecast, and PARW up-scaling. The three estimates do not share exactly the same system boundaries, with changes to the sectors between SIC and NAICS and the difference between economic system boundaries (PACE and PARW) and physical activity system boundaries (historical forecast).

The historical forecast shows 1.40 Tg of NHIW from this sector: 0.78 Tg of rolling sludge, 0.51 Tg of grinding swarf, and 0.10 of dust. The PACE forecast estimates a total of 0.3 Tg, mainly unspecified NHIW with very little air pollution control residue. The PARW up-scaling estimates 0.69 Tg from this sector: the main components are 0.26 Tg of sludge, 0.18 Tg of refractory material, and 0.12 Tg of waste oil. As in iron and steel mills, the historical forecast estimate appears to be the most reliable. PARW again excludes waste flows that are recycled or beneficially used, which would include some rolling sludge and grinding swarf, and PACE is too undifferentiated to know the reliability of its estimate.

2.8.4.5.3 NAICS 3313: Alumina and aluminum

NHIW from alumina and aluminum manufacturing (NAICS 3313) must be considered in two categories: red mud and everything else. Red mud is estimated by historical forecasting and material balance: 2.66 Tg and 4.94 Tg, respectively. The latter estimate relies on contemporary data about inputs and outputs, and therefore endogenizes information about ore grade. It is the preferable estimate here.

Estimates of other wastes from alumina and aluminum production are provided by historical forecasting and PARW up-scaling. PACE gives an estimate of these wastes combined with those from other non-ferrous metals generation. The historical forecasting method estimates 0.20 Tg of other alumina waste and 0.41 Tg of aluminum production wastes; PARW estimates 0.38 Tg of NHIW from the whole subsector. However, there is no alumina production in Pennsylvania, so there is actually good agreement between the two estimates. In fact, both methods estimate 0.21 Tg of aluminum dross and 0.02-0.03 Tg of sludge. These similarities are enough to conclude that the historical forecasting method is likely still accurate, despite the underlying data being somewhat older than is preferable.

2.8.4.5.4 NAICS 3314: Other non-ferrous metals

Historical forecasting estimates 2.29 Tg of copper production wastes (2.03 Tg of slag and slag tailings, 0.19 Tg of converter and anode furnace slag, and 0.07 Tg of sludge) and 0.13 Tg of zinc production wastes (0.08 Tg of slag). PARW up-scaling estimates 1.18 Tg of NHIW from non-ferrous metals production (excluding aluminum), including 0.41 Tg of slag and 0.29 Tg of sludge. Material balance estimates 0.80 Tg of copper slag. Because of the comparative reliability and detail from the historical forecast data (which were built on extensive, empirical studies during the 1990s), the estimates of NHIW from copper and zinc from the historical forecast method is likely the best candidate for the account.

Interestingly, the PACE estimate agrees somewhat with the other historical forecasted estimate when we consider that SIC 33 excluded the production of alumina, and therefore the estimated 2.4 Tg of NHIW does not include red mud. This 2.4 Tg is close to the total 2.83 Tg of NHIW from aluminum, copper, and zinc production estimated by the historical forecasting method.

2.8.4.5.5 NAICS 3315: Foundries

Three of the methods produce estimates of NHIW from ferrous and non-ferrous foundries (NAICS 3315): 7.80 Tg from historical forecasting, 6.0 Tg from PACE, and 2.88 Tg from PARW upscaling. The historical forecasting estimates are both based on data that is quite old, and therefore may not reflect current foundry sand and core management practice. However, the PARW account seems to reliably underestimate actual quantities of NHIW generated in these industry subsectors. We can disambiguate the high vs. low estimates by using an admittedly flawed survey of foundry sand practices conducted by the American Foundry Society in 2007 [26]. This survey suggests that 8.53 Tg of spent foundry sands were generated in 2007 [27]. This quantity was not used in the historical forecasting method because it is considered to be quite unreliable. However, there are widely circulated assertions of the quantities of spent foundry sands generated in the U.S.: 6-10 million tons [28] and 10-15 million tons [29] are commonly reproduced ranges. These admittedly unreliable references would tend to suggest the historical forecasting and PACE estimates are the more accurate ones.

On the other hand, both the AFS and historical forecasting data are based on a very small sample size of foundries. If the PACE data forecast estimates 6.0 Tg of all waste from foundries, 10% of which is air pollution control residue, that suggests that somewhat less than 5.38 Tg of NHIW from foundries is spent foundry sands, as the quantity must also account for sludges, oils, waste metals, and other metalcasting wastes. Unfortunately, this estimation and triangulation process does not definitively dispose of the uncertainty around spent foundry sands, but does provide some evidence for an overall NHIW generation rate of 6.0-7.80 Tg in 2015. The much lower value from PARW finds significantly less support in the balance of evidence.

2.8.4.5.6 NAICS 332: Fabricated metal products

NHIW from fabricated metal products (NAICS 332) is estimated at 0.45 Tg by historical forecasting, 2.3 Tg by PACE forecasting, and 1.13 Tg by PARW upscaling. The historical data includes a single estimated data point for potentially hazardous sludge, and so can be excluded from consideration. Given the large variability in this industry sector, it is prudent to incorporate both of these estimates into the final account.

2.8.4.5.7 Summary

In total, the primary metal and fabricated metal products manufacturing sectors (NAICS 331-332) are estimated to have generated 34.13-37.34 Tg of NHIW in 2015 (Table 2.8-8). Nearly all of the triangulated estimates come from the historical forecasting method, in large part due to the relative recentness and robust origins of the base data. Material balance was useful in verifying some values of slag generation and providing a new estimate of red mud generation. The PACE forecast and PARW up-scaling were not particularly useful in estimating NHIW from these subsectors. The total triangulated estimate is slightly more than half the value estimated from international data. The subset of that estimate defined by mineral wastes ("other mineral wastes" and "combustion wastes") sums to 39.14 Tg, similar to the triangulated estimate.

The largest component of this waste stream comes from iron and steel mills, followed by foundries. The largest waste streams, iron and steel slag and spent foundry sands, are also those that are beneficially used the most widely (albeit not necessarily to their highest and best uses). Accordingly, this waste account will look quite different from one that excludes beneficially used wastes (e.g. PARW). The inherent recyclability of metals and the usefulness of many of the mineral and refractory byproducts from metals smelting and refining mean that even more of the wastes currently disposed could likely be reprocessed and beneficially used in the future.

A final point concerns data quality and availability. Like the EPA assessment of NHIW from the 1980s that motivated this research project, the reproduction of NHIW estimates in this sector in official and industry reports contributes to a misunderstanding of the waste burdens from metals production. The routine publication of slag shipments rather than slag generation by the USGS undermines the ability to implement policy for waste reduction and pollution prevention, as well as the more mundane expansion of beneficial use practices. Similar problems exist with spent foundry sands. The lack of data coupled with the significant attention placed on this waste stream by agencies like the EPA and DOT potentially mislead good faith efforts to improve environmental performance of the metalcasting industry. More empirical observation of foundry waste generation is definitely warranted.

Table 2.8-8. *Triangulated estimate of NHIW from primary metal and fabricated metal product sectors, 2015*

NAICS	Subsector/Waste material	NHIW (Tg) L	NHIW (Tg) H	Notes
3311	Iron and steel mills and ferroalloys			
	Blast furnace slag	5.74	5.98	Beneficially used
	Blast furnace dust & sludge	0.52		
	BOF slag	3.16		Beneficially used
	BOF dust & sludge	0.75		
	EAF slag	3.98		Beneficially used
	Ladle treatment dust & slag	0.60		
	Mill scale	2.88		Recycled
	Subtotal	***17.63***	***17.87***	
33121-2	Steel product manufacturing			
	Rolling sludge	0.78		Reprocessed
	Grinding swarf	0.51		Reprocessed
	Other dusts	0.10		
	Subtotal	***1.40***		
33131(3)	Alumina production			
	Red mud	4.94		
	Other wastes	0.20		*Incl. evaporator salt waste, bauxite residue, waste alumina, cleaning residue, pisolites*
	Subtotal	***5.14***		
33131(3-4)	Aluminum production			
	Skims and discarded drosses	0.21		Reprocessed
	Other wastes	0.05		*Incl. sweepings, baghouse bags, filters, anode prep waste, cryolite recovery residue*
	Sludge	0.03		
	Secondary aluminum baghouse fines	0.11		
	Subtotal	***0.41***		
33141	Copper smelting and refining			
	Smelter slag & slag tailings	2.03		
	Converter and anode furnace slag	0.19		
	Calcium sulfate WWTP sludge	0.07		
	Subtotal	***2.29***		
33141	Zinc smelting and refining			
	Zinc slag	0.08		
	Other wastes	0.03		*Incl. goethite, leach cake residues, synthetic gypsum, waste ferrosilicon*
	WWTP sludge	0.02		
	Subtotal	***0.13***		
3315	Foundries			
	Ferrous foundry sand and other waste	--	4.49	Beneficially used
	Non-ferrous foundry sand and other waste	--	3.31	Beneficially used
	Subtotal	***6.00***	***7.80***	
332	Fabricated metal products (***subtotal***)	***1.13***	***2.30***	
331-332	**Grand Total**	**34.13**	**37.34**	

3 Conclusions

Non-hazardous industrial waste (NHIW) is among the most significant unexamined waste streams in the country. While other waste categories are the subjects of regular study and accounting by the EPA, the NHIW stream has not been officially quantified since the mid-1980s. In this report, we present the first comprehensive and repeatable account of NHIW tonnage and composition in the United States in over three decades.

Using a combination of four independent methods, we estimate that NHIW generation totaled between 244-264 million metric tons (Tg) in 2015. The single largest component of this waste stream is an estimated 114 Tg of waste phosphogypsum generated in the manufacture of fertilizer. Wastes and byproducts from basic chemicals manufacturing totaled an additional 16–20 Tg. Food, beverage, and tobacco manufacturing was found to generate 44–46 Tg of NHIW, most of which are wastes from fruit and vegetable processing (24 Tg) and meat preparation and processing (13 Tg). Primary metals production, including foundries, generated 34–37 Tg of NHIW in total: 13 Tg of iron and steel slag, 7.8 Tg of ferrous and nonferrous foundry sands, and 4.9 Tg of red mud from alumina production. Paper mills and printing generated 13 Tg, mainly wastes from pulp, paper, and paperboard mills: wastewater sludge (4.5 Tg), ash (2.2 Tg), and other wastes (4.5 Tg). Nonmetallic minerals processing is responsible for an additional 9.4–15 Tg, a large fraction of which is cement kiln dust (4.7 Tg). The remaining industry sectors included in the analysis—petroleum and coal products; wood products; and textiles, apparel, and leather products—generated 6.4–7.4, 1.3–1.6, and 0.5–0.7 Tg, respectively.

The four estimation methods that contribute to the construction of this account are: 1) historical forecasting using empirical results from past studies; 2) spatial up-scaling using data from the Pennsylvania Residual Waste program; 3) material balance using publicly available data on industry inputs and outputs; and 4) comparison with European waste accounts. Each of these estimation methods would be inadequate on its own, but when taken together, we find that they yield an account that is robust and of sufficient detail to be useful for environmental and industrial policy.

The scope of the study includes all materials generated as wastes, irrespective of their disposition, by primary materials processing and basic manufacturing activities in the United States, as identified by the North American Industry Classification System (NAICS). More advanced manufacturing and assembly activities (NAICS 333-339) are excluded. Other exclusions include materials processing activities included as part of the mining industry as well as byproducts with long-standing and economically mature beneficial uses, such as wood waste from sawmills. Other beneficially used wastes, like food processing scraps and iron and steel slag, are included in the account because of the potential for environmentally preferable uses over current practice.

The results from this study suggest that the quantity of NHIW generated in the United States is roughly equivalent with that of MSW. The methodology presented here is based on publicly available data and official statistical products. As such, it is intended to be repeated so that the account can be maintained and regularly updated. Such an account would be invaluable for the cultivation of eco-industrial policies like industrial symbiosis and other circular economy strategies.

4 Materials and Methods

4.1 Introduction

Methods for indirect observation and estimation of materials accounts are largely based on two principles central to industrial ecology: that materials stocks and flows are endogenous to the economy, and that materials follow regular life cycles. The first principle has been explored and elucidated in theories of industrial and socio-economic metabolism, whereby material stocks and flows are embedded in economic, societal, and/or institutional (as well as spatial and temporal) contexts via observable and quantifiable relationships. The second principle serves to place specific materials in a chain of stocks and flows with predictable (or at least model-able) patterns and environmental consequences: crude materials are extracted from the earth, refined, manufactured into products, used, and disposed—everything goes somewhere; there is no such place as *away*. Using one or both of these principles, one can estimate any number of unobserved materials accounts—at a given spatial and temporal scale and with some requisite uncertainty factors—by transforming existing data such as financial information, materials accounts of some past (or future) time or different place, or other related material flows using models of industrial or socio-economic metabolism. In the simplest cases, these models are linear transformations and extrapolations based on physical laws, stoichiometric balances, or, only slightly more complicatedly, materials prices or other linear—but not purely physical—scaling factors. As the input data is found further abstracted away from the target information, models must become more complex and build on increasingly diverse fields; engineering, environmental science, economics, political science, and other social sciences are all useful sources for model structure and parameter values.

The literature record discussed in the previous chapter confirms the availability of data and estimation methods for the construction of new waste accounts of NHIW in the United States. The 1985 SAIC report to the EPA relies in part on figures extrapolated from empirical work performed sometimes a decade earlier [1]. Such models use simple ratios of waste output to industrial production in the extrapolation, indicators of waste intensity that assume no change to waste producing conditions. Acknowledging that this assumption is not necessarily sound—especially considering that the regulatory program the SAIC report was supporting was designed in part to decrease industrial waste output—Ayres & Ayres leveraged their trademark industrial metabolism approach to estimate NHIW using public records of industrial production and consumption [2]. This method benefits from the internal reliability check provided by the materials balance constraint, although that is not enough to overcome all possible errors in source data, system boundaries, material flow models, or combinations thereof. More recently, the Yale University student team demonstrated the feasibility of using sub-national data, specifically the reports from the Pennsylvania Residual Waste program, to estimate national NHIW generation patterns [3]. As in the extrapolations that enabled SAIC (and others) to forecast contemporary figures from historical data, these authors calculated waste intensity factors at the industry sector and scaled them up using the ratio of national to state industrial production (in economic terms). Similar methods have been applied to EU NHIW data, although these waste intensity factors have not been applied to the U.S. context [4].

Given the unreliability of source data, questionable validity of the metabolic models, and inability to calculate meaningful quantitative uncertainty factors, no single estimation method is capable of producing a reliable result. Therefore, we employ a meta-method in which multiple estimates of the same waste flow are calculated from independent data sets using distinct estimation methods and examined in relation to each other. In this way, the multiple estimates serve to corroborate each other in triangulation. Assuming the error in each of the estimation methods is independent (as a result of independent data and models), the triangulation approach can produce a defensible range of NHIW generation rates for each industry sector examined.

The use of three methods in triangulation—historical forecasting, spatial up-scaling, material balance—has been validated in previous work [1]. Here we add a fourth method, international comparison. Each of the four estimation methods and our approach to triangulation and synthesis are described below.

4.2 Historical forecasting

Historical forecasting allows empirical findings from the past to be translated to the present by a relevant scaling factor, as in the following model:

$$W_n = p_n \sum_i \frac{w_{i,0}}{p_0} \tag{1}$$

where W_n is the total amount of waste generated by a given industry in year n, p_n is the production of the industry in year n, $w_{i,0}$ is the amount of waste type i generated by the industry in the base year, and p_0 is the production of the industry in the base year. The factor p can be measured in either physical or economic units, depending on the context. The ratio w/p is also known as the *waste intensity.*

Historical data can be drawn from a wide range of sources. Ideal sources are empirical studies (usually industry or government surveys) conducted and validated in recent years. Validity of this estimation method declines the older the data is and the smaller the original sample. If recent industry association and government reports are unavailable, we turn to the SAIC estimate of NHIW generation in 1985. That estimate was based on an extensive literature review, drawing on industry-specific studies conducted by the EPA and its contractors in the years leading up to the report, studies conducted by industry associations, published scholarly literature, and interviews with experts.

An additional source of data that in this analysis is treated separately from the other historical forecasts is the 1983 Pollution Abatement Costs and Expenditures (PACE) survey. PACE was "the only comprehensive source of pollution abatement costs and expenditures related to environmental protection in the manufacturing sector of the United States" [6, p.3]. It was conducted annually from 1973 to 1994, once in 1999, and once again in 2005. In addition to economic information, from 1973 to 1983 the PACE survey reported physical units of air, water, and solid waste pollutants removed; this reporting was ceased in 1984 for reasons of data reliability [7]. The physical data was reported by discharge medium for each industry sector, but no detail about waste composition was included. The 2005 incarnation of the PACE survey seems to have collected physical data on NHIW generation from survey respondents, but this data is not part of the report [8]. If it were made available, it would likely prove useful to the estimation of contemporary NHIW generation patterns. Nevertheless, for each industry sector, we utilize data from the 1983 PACE survey as an additional historically forecasted estimate for use in triangulation.

Ideally, the data comprising the base case for this analysis would be itself based on direct observation of the industry in question, either via surveys (reported by the waste generator) or case studies (reported by the analyst). It is important to understand the objectives of the original data collection in order to determine its utility in forecasting. It is also important to have clarity about system boundaries, to ensure that any changes to the definition of the industry between the base year and the target year are accounted for—the step change in many government statistics in 1997 happened as a result of the transition from SIC to NAICS, with concomitant changes to industry classifications and definition. Finally, the base case data should have information on specific waste types (like many of the accounts in the SAIC estimate), as opposed to a single total waste quantity (like PACE). The specific approach to waste categorization here can vary; some studies focus on general physical categories like sludge, ash, sand, etc., while others further subdivide these categories by process source. The more detailed the data, the greater the opportunity for nuanced analysis of the forecast results.

For use as scaling factors, data on industrial production is often collected and published by the relevant industry trade association. In some cases this information is also reported in the *Statistical Abstract of the United States*. The US Census Bureau-produced *Annual Survey of Manufactures* and *Economic Census* publishes information on production and sales, sometimes including physical units. In the frequent case that physical production data is either not available or not applicable (for aggregated waste data from complex industry sectors, for example), data on economic output is used instead.

The method for using economic output data as the scaling factors for historical forecasting is significantly more complex than using physical output data. First, if the base year is before 1997, a crosswalk must be established between the SIC and NAICS industry codes for each waste flow being forecasted. Next, for each industry subsector in each year, we note the

“Value of Industry Shipments” from the *Annual Survey of Manufactures*. This value is the economic proxy for industrial production, but it is a nominal value and must be adjusted for inflation. The standard deflator published in national economic accounts is based mainly on a generic basket of consumer prices. Because we are using very specific industrial production data, this deflator is insufficient. Furthermore, our economic factors need to hew as closely as possible to physical production, so we calculate industry sector-specific deflators using Chain-Type Quantity Indexes for Gross Output by Industry from the U.S. Bureau of Economic Analysis [9]. That data is published only at highly aggregated levels for the entire study period (roughly the 1970s through 2015): 11 categories of durable goods industry sectors and 8 categories of nondurable good sectors. So, to determine the real industrial production term at the subsectoral level for a given year, we divide the value of industry shipments from the target subsector by the value of industry shipments from the high-level sector (one of the 19 represented in the BEA database), and multiply that ratio by the Total Gross Output of the high-level sector. This algorithm is represented symbolically below:

$$p_{i,n} = \frac{S_{i,n}}{S_{j,n}} G_{j,n} \tag{2}$$

where $p_{i,n}$ is the production term for industry subsector *i* (part of sector *j*) from equation (1) above (when n=0, this is the production term from the base year), $S_{i,n}$ is the nominal value of industry shipments for subsector *i* in year *n*, $S_{j,n}$ is the nominal value of industry shipments for sector *j* (containing subsector *i*) in year *n*, and $G_{j,n}$ is the real value (or index) of gross output for sector *j* in year *n*.

The use of a historical forecasting estimation method grounds this research in the historical record, for better or worse. Given a prevailing lack of coherence surrounding industrial waste classification in the United States, the historical forecasting approach enables partial comparability to past industry-scale NHIW accounts. It forces system boundaries to be defined if not the same as at least in relation to how they were in a previous era when data like NHIW generation was a policy priority. It might be argued that the need to collect rational data in support of the environmental policy agenda may have influenced how industries were defined and classified by the government agencies tasked with collecting and analyzing that data. American industrial activity is qualitatively and quantitatively different today than it was then, with new industrial classification schemes to bear out those changes. The disappearance of NHIW from the policy agenda (along with many of the data collection programs that fell victim to the deregulation wave of the 1980s and 1990s) means that any alignment between industrial environmental output and industrial classification will have also disappeared, if it ever even existed in the first place.

There is substantial room for uncertainty and error in the estimates produced using historical forecasting. Specifically, today’s industries look somewhat different from how they looked in the 1970s and 1980s. Using data collected within one set of boundaries to tell a story about activity within a different set of boundaries is tricky business. In combination with any unaccounted for effects and unreliable base year data, the results of the forecasting might be well off the mark.

4.3 Spatial Up-Scaling

Solid waste policy is conducted largely at the state level in the US; per RCRA, the EPA sets a federal regulatory floor which states are free to exceed, which many do. This means that even though no data is collected at the national level on NHIW generation (at least not since the mid-1980s), the same is not necessarily true for the states. As it turns out, it is not, but just barely, thanks to one special and invaluable case: Pennsylvania. By considering the national representativeness of Pennsylvania industry, data collected at the state level can be used to estimate national NHIW generation.

The spatial up-scaling method used here is a refinement of one developed by Barr et al. [3]. As a part of their exploration of the PA Residual Waste (PARW) database, which was until then unexamined by industrial ecologists, the authors proposed a method of estimating "waste stream flows in other state or at the national level" via the calculation and use of "waste stream intensit[ies]" [3, p. 21]. The authors defined waste stream intensities in tons/$: the quotient of tons of waste generated in a given industry and the economic output of that industry. This factor could be applied to the industry-level economic output of other states and the entire US. Using the highest level of economic aggregation, the 2-digit NAICS codes, the authors used this method to estimate national NHIW generation at 386 million metric tons in the year 2002. Barr et al. do not really discuss the representativeness of PA industry or waste generation to national industry, except in saying that "defined at a level that is granular enough, the waste streams per dollar of output should be quite consistent across manufacturing facilities" [3, p. 21].

The method employed in this research relies on just two types of variables, wastes (*w*) and economic factors (*r*), the former tabulated by type *i* and available only at the state (Pennsylvania) level, and the economic factors available at both state and national levels. The method is represented formally as:

$$W_{US} = \frac{r_{US}}{r_{PA}} \times \sum_{i} w_{i,PA} \tag{3}$$

Through its Residual Waste Program, the Pennsylvania DEP has been collecting data and publishing reports biennially since 1992. Every facility generating 13 short tons of residual waste per year is required submit a report for each waste stream generated in excess of 1 ton per year that includes: the waste code, tonnage, medium of discharge (solid, liquid, sludge, or gas), the 5-digit NAICS industry code most closely describing the activity that generated the waste, and details of disposal. The state DEP hosts the most recent reports (in the form of Excel spreadsheets) on its website. The PARW program defines 118 waste codes split into nine broad waste categories. The database is also large, on the order 10,000 unique entries per reporting year, and messy. Considerable effort was spent cleaning the database, eliminating outliers and duplicates and correcting mis-entered industry codes.

PARW data are collected during even years; this study focuses on 2015, which required us to average the data reported for 2014 and 2016. This average occurred at the lowest practical level of aggregation: subsector-waste type. Lower levels are available, such as disaggregation by specific generator or by disposal route, but these parameters were not relevant to our scale-up estimation method, and so were ignored.

We used Total Value of Shipments as the scaling factor for the up-scaling estimate. The *Annual Survey of Manufactures* includes national figures for shipment value at the 5-digit NAICS code level, but state figures are limited to the 4-digit NAICS code level. The requisite detail for state-level figures is only available in the *Economic Census,* a product released every five years. To achieve the necessary level of sectoral specificity, we took the Shipment Value for each 5-digit NAICS code in Pennsylvania in 2012 (the most recent *Economic Census*) and forecasted it to 2015 based on the change in Shipment Value in Pennsylvania for the containing 4-digit NAICS code, as in:

$$V_{PA,2015}^{5-digit} = V_{PA,2012}^{5-digit} \times \frac{V_{PA,2015}^{4-digit}}{V_{PA,2012}^{4-digit}} \tag{4}$$

After the scale-up, results are then aggregated based on the expected waste types from each industry subsector.

This method has two main strengths. First, the raw data is highly disaggregated, enabling the construction of detailed waste accounts. Second, the availability of waste data generated in (or around) the target year, 2015, provides experimental control for time effects better than any of the other methods used in this research. Of course, the data and method introduce their own types of error.

The term “spatial up-scaling” is a bit of a misnomer, in that the scaling has little to do with space per se. States and nations are geographic entities, one inside the other, so the scaling is occurring from one spatial extent to another. But there is nothing about the method that is uniquely spatial; it could easily be applied to data observed via any other sampling technique. And herein lie the main drawbacks of the method, that by nearly any criteria, the PARW is not a good sample of national industry. This is not to say it could not be in some way representative, for it very well could be. Without knowing much about the national population, no self-respecting geographic statistician would select a sample from just one state.

Pennsylvania is a moderately large, highly industrial state, which makes it a better source of data for this exercise than, say, Hawaii would be. But its industry is old. Although the data set controls for time effects, it does not control for effects of vintage, the specific economic conditions of the Rust Belt, and other characteristics dependent on state jurisdiction.

As it happens, waste management policy is one of these state-dependent characteristics. Pennsylvania being unique among the states in its approach to residual waste management, it is possible that generation rates are even less nationally representative than previously thought. Although most of the residual waste regulations focus on rules for disposal, which would have limited effect on waste generation, the mere existence of the biennial report very well could. Like the observer effect in physics, which holds that the act of observing a phenomenon changes that phenomenon, or the theory of change behind the Toxics Release Inventory, which states that public disclosure of environmental pollution leads to pollution reductions (either directly through firm risk aversion or indirectly through investor pressure), the biennial residual waste report could have over the decades affected the waste generation patterns of Pennsylvania industry. Possible mechanisms for this effect are varied. The regulation focuses on source reduction, waste minimization, and beneficial use; it is possible that by forcing firms to be conscious of their waste outputs they are more likely to implement such strategies.

Additionally, there is some reason to question the representativeness of the industry definitions and system boundaries. Many facilities conduct a variety of industrial activities than span NAICS categories. The PARW reporting form instructs the generator to assign a unique industry classification code to each waste flow “that most nearly describes the activity that generated this waste.” In contrast, the U.S. Census Bureau “assigns and maintains only one NAICS code for each establishment based on its primary activity (generally the activity that generates the most revenue for the establishment)” [10]. So, there is possibly some inconsistency between the specific composition of the industry at the state level, where establishments that conduct many activities would credit one industry activity with generating the most waste and another with generating the most revenue.

Irrespective of these representativeness errors, the self-reported nature of the database itself introduces error. Numerous instances of mis-coded waste streams were found, and there are likely many that went uncaught. The physical state (medium) determination can be a challenging one, and the same waste code for the same facility can be reported as liquid, solid, or sludge from year to year, possibly depending on the perspective of the compliance officer tasked with completing the report.

4.4 Material balance

A materials balance is the most elegant and abstract of the estimation methods employed here. At its core is a single physical law—the law of conservation of mass—that similarly undergirds key industrial ecology methods like LCA and MFA. The applicability of this method to the task of NHIW estimation is neither novel nor inevitable: not novel because of the half-century of scholars using similar methods to estimate quantity and composition of industrial process residuals; not inevitable because NHIW estimation benefits both from the close physical relationship between industrial processing and industrial residuals and, essentially, from the availability of data on both raw material consumption and refined material production.

The materials balance method used here builds directly on that developed by Ayres & Ayres to estimate what they called "lost mass," the residues of industrial production that are unaccounted for in national statistics and present potential environmental risk. The method proceeds through the following steps:

1. *Develop a qualitative description of the industrial sector*
   Identify key transformation processes and all input, output, and intermediate material flows. For most industries, Ayres & Ayres have done this work [2]; it behooves those of us living in the future to check their models against any significant qualitative changes that may have occurred in the industries of interest. Sources and types of NHIW should be identified here.

2. *Calculate unit processes*
   Quantify ranges of input and output flows for unit transformation processes using life cycle inventories, government and industry reports, textbooks and engineering literature, and engineering and stoichiometric analysis. This information will be used to perform corrections, calibration, and uncertainty analysis on the model.

3. *Populate model with published data*
   Major material inputs and outputs are nearly all available in government or related publications. Take care to watch out for unit consistency and water/moisture content.

4. *Fill in missing data*
   For material flows lacking reported data, use the materials balance constraint (waste = in - out) and the unit process ratios calculated in #2.

5. *Rationalize (inevitable) inconsistencies*
   Inevitably, there will be conflict between the masses of inputs and outputs in each transformation process and between the output of one transformation process that becomes the input to another. There are various ways to rationalize these conflicts, including defining the material flows in terms of ranges rather than single point estimates. Additionally, it is recommended that the data be examined across multiple years, not just the year of interest, as a way to identify any idiosyncrasies of the year of interest.

As explained by Ayres & Ayres [2], the material balance method for estimating NHIW generation is made possible by a rich catalog of information about the physical economy of the United States. This catalog draws from numerous sources, not all of which will be discussed here.

US government data is published by a few different agencies. Agriculture data, including forestry, is published by the US Department of Agriculture and US Forest Service. Data on minerals and metals is handled by the US Geological Survey. Fuel data is the purview of the Energy Information Administration. The Census Bureau's industry publications also sometimes contain useful information on materials and products purchased and sold by each industry. The *Statistical Abstract of the United States*, published until from 1878 to 2012 by the Census Bureau and subsequently picked up by ProQuest, rolls up many of these government data sources.

Outside of the US, useful data about the US can be found in the Food and Agriculture Organization, the International Energy Agency, and various UN offices. Comparative data is available from the EU statistical office.

Industry production and consumption statistics often originate with the relevant industry trade associations, many of which publish annual statistical reports. Data useful for calculating unit process ratios are pervasive in textbooks and the broader engineering literature.

In their multiple applications of this method to the problem of NHIW, Ayres & Ayres argue a strong case for why the results from a materials balance approach are superior to bottom-up statistics on waste and other industrial residuals. First, unlike the various survey approaches that have been used to estimate NHIW generation, materials balance offers a consistent methodology for all industrial residuals, something that is ultimately necessary for any sort of comparability both cross-sectionally (across industries) and longitudinally (across time). The exclusive reliance on publicly available data facilitates (while extraordinary that it is even possible, and credit is due to the data analysts and statisticians who make it possible) an efficient, repeatable estimate, as Ayres & Ayres state: "The data we have used is sufficiently standard so that it should be possible for a government agency to compile and present these data on a routine basis" [11, p. 1].

The economy-wide scope of the method makes it able to capture residuals generation from all sources, not just those that can be identified and surveyed, and factory-agnostic, which makes it robust against any sampling error that can plague survey methods. Any technology change that might lead to a change in residuals generation would be reflected in the consumption and production data, and so would be indirectly accommodated. Despite originally having been developed in an effort to better account for environmental externalities, the reliance of materials balance on physical law rather than economic drivers and proxies further increases its reliability. Finally, although Ayres & Ayres routinely avoid the opportunity to explicitly incorporate uncertainty factors in their analysis, instead opting for values (with two significant digits!) and periodic acknowledgments of qualitative error, it is actually very easy to account for uncertainty through the use of reasonable ranges in magnitudes for each material flow.

Materials balance has its drawbacks as well. The observations being limited to raw materials and refined products, the only industrial residuals that can be estimated must be derived from that refining process, i.e. process residuals, as opposed to secondary or ancillary wastes like packaging or plant trash. The results are necessarily highly aggregated, with the method offering limited ability to identify different types of wastes within gross categories. Relatedly, it can be a challenge to distinguish among media of waste output. For estimating total lost mass this is not necessarily a problem, but since environmental pollution control is largely medium-based, it is an important distinction to be made. Further complicating this issue, many gas-phase and some liquid-phase wastes undergo chemical transformation before their discharge: the most obvious example here is the oxidation/combustion process. To follow the strict materials balance guidelines would require estimating the mass of oxygen consumed in incineration, yet that requires an assumption about the completeness of combustion, which for biomass burning is an open question. So, there is some sensitivity to the uncertainties of the transformation processes.

Like all models, the results from materials balance are only as reliable as the inputs to the model, including both the materials data and process ratios. The use of both types of data does enable an internal reliability check, and the process of assembling a materials balance model can bring great clarity to published material flow data. Nevertheless, hewing to the law of conservation of mass is not always a sufficient condition for validity. For example, an important term left from the way we have defined that physical law avoids the possibility of on-site storage—in industrial ecology terms additions to or removals from stock—that can screw up the balance. By looking at the balance over many years, an idiosyncratic stock dynamic can be diagnosed (such as the stockpiling of purchased raw materials in a down economic year).

Finally, the method implicitly defines the boundaries of the industries of interest based on technological activities. This is not in itself a drawback, but simply inconsistent with how the industries are defined in practice. Although NAICS (like SIC before it) does define the various activities contained within each industrial classification, the reality is that the boundaries are fuzzy, and firms or facilities that have activities spanning multiple classifications are categorized into the one that generates the most economic activity, not the one that transforms the most material (although there is likely substantial overlap).

The many requirements and constraints of material balance modeling makes it inapplicable to some of the industry sectors studied here.

4.5 International comparison

Just as state-level data can be used to develop national-level estimates, waste data from one country can be used to estimate waste generation in another. Here, we use data reported by 29 European countries under the EU Regulation on Waste Statistics (849/2010) to derive waste intensity factors which are then applied to U.S. industrial scaling factors to estimate NHIW generation in the U.S.

This estimation method is substantially similar to the Spatial Up-scaling method described above, the main difference being the base waste data and the specific scaling factors utilized. Another difference is that instead of relying on a single point estimate of a waste stream, we have a population of up to 29 individual waste accounts from which to derive waste intensities, allowing for some degree of statistical analysis.

The EU Regulation on Waste Statistics requires all member states and other subject countries to report a wide range of data on solid waste type, generator, and disposal every two years (evens, so 2012, 2014, etc.) [12]. The Regulation defines a waste catalog of many hundreds of types of waste types, both hazardous and non-hazardous (this catalog is used in each industry sector report here to define the types of wastes expected to be generated by that sector). The reporting requirement distills this list down to 51 waste categories for countries to quantify (21 hazardous and 30 non-hazardous) from 19 sources (18 industrial/economic sectors from NACE rev. 2 and households). The regulation excludes any wastes recycled on-site.

Altogether, this database of industrial waste generation and disposal is unmatched worldwide in its comprehensiveness and diversity of sources. The challenge in using data from so many countries is that the standard definition of an industrial waste intensity factor—Mg/$ output—requires a consistent denominator in order to compare one country to another. Here is the method we developed:

1. *Tabulate waste by country & by industry sector*
   First we retrieved data on NHIW generation by country and economic sector from the Eurostat database [13]. For this study, which focuses on the year 2015, we used 2014 European waste data (as data is only reported in even years). Relevant data is available for 29 countries, 10 manufacturing sectors, and 40 waste categories (including 30 unique categories and 10 higher-level categories).

2. *Determine industrial output by country & industry sector*
   Industrial output in 2014, measured by nominal (current) national currency units (Euros, Pounds, etc.) was retrieved for the 29 countries and 10 industry sectors that made up the waste database from the OECD Statistics website [14]. In order to convert these figures to a consistent basis, we used exchange rates between national currencies and US dollars published by the UN [15]. The level of industry sector aggregation used in this report is set by the availability of data in this step.

3. Calculate waste intensity factors

   Waste intensity factors are calculated by dividing waste tonnage by industrial output, converted to US dollars from national currency units. For each industry sector-waste type pair, weighted averages and standard deviations of all 29 waste intensity factors (one from each country) are calculated. The average is weighted by national NHIW generation in each industry sector, so larger, more industrial countries like France and Germany will often have more sway over the average than smaller countries like Iceland and Malta. Weighting factors vary from industry sector to industry sector. Weighted average and weighted standard deviation for a particular waste type in a particular industry sector are calculated using the following formulas:

   Weighted mean

$$\bar{x}^* = \frac{\sum_{i=1}^{N} w_i x_i}{\sum_{i=1}^{N} w_i}$$

   Weighted standard deviation:

$$sd_w = \sqrt{\frac{\sum_{i=1}^{N} w_i (x_i - \bar{x}^*)^2}{\frac{(M-1)}{M}\sum_{i=1}^{N} w_i}}$$

   where x_i is the tonnage of the target waste type generated in the target industry sector in country *i*, w_i is the total sectoral waste generated in country *i*, *N* is the total number of countries, *M* is the number of non-zero reporters (some countries do not have a particular industry, so their x_i value would be zero), and $\bar{x}^*$ is the weighted mean.

4. *Estimate US NHIW generation by applying US scaling factor*

   With weighted average waste intensity factors and standard deviations calculated for all the waste type-industry sector pairs, these factors can be applied to the US by multiplying them by industrial output data for the target year, 2015, published by the Bureau of Economic Analysis [16].

There is considerable variation among the waste intensity factors calculated from the reporting countries. It is unclear as to why this is, considering the consistent guidance provided from the EU. However, the variation justifies the use of a weighted average rather than simply using intensity factors from a single country. One reason for the variation might be inconsistency in the classification of certain waste streams. One country may classify it as one type while another may classify it as another type. There may also be different regulations about beneficial use or on-site recycling from country to country.

Another limitation of this method is the high level of aggregation of the waste intensity factors. Data is only available at the top industry sectoral level, so there is limited ability to compare specific waste streams with results from other methods. Altogether, the variation calls for more research into the specific national waste accounts of the reporting countries.

4.6 Triangulation & Synthesis

Each of the estimation techniques presented above, while methodologically valid, is open to considerable scrutiny regarding its accuracy. Some of the sources of error have been discussed, but in general terms, the context of this research provides few if any opportunities for external corroboration of model parameters when considered in isolation. As a result, here we use multiple independent models, each of which having its own dedicated data source and, consequently, independent error, to increase the reliability of the ultimate estimate. The methods rely on each other for corroboration. We call this meta-method “triangulation,” after the principle of Cartesian geometry that enables the identification of an unknown point from two fixed points and known angles.

In social science, triangulation is a term sometimes used for the very approach taken in this research. According to Bryman, “triangulation refers to the use of more than one approach to the investigation of a research question in order to enhance confidence in the ensuing findings” [17]. There is some overlap between triangulation and any generic multi-method research, but “there are good reasons for reserving the term for those specific occasions in which researchers seek to check the validity of their findings by cross-checking them with another method.”

In each industry analysis, the results from the four estimation methods are compared at the lowest level of aggregation allowed by the available data. For instance, where there are estimates available at a 4-digit NAICS code level, those estimates are compared and a triangulated total is asserted. Sometimes the triangulation can occur at the level of waste material. The international comparison figures are only available at the highest level of aggregation, and therefore provides a high-level comparison rather than contributing to the construction of the detailed inventory.

For this project, a triangulation approach is justified. Not only do we lack direct observation of the phenomenon in question, we also lack sufficient literature justification for the selection of any particular model structure or parameter. The methods proposed are theoretically sound, but so far there has been little evidence that materials balance, up-scaling, forecasting, or international comparison is accurate. But, if conducted in parallel, using results from each in corroboration, triangulation can yield results with enhanced confidence and evaluate the relative accuracy of each estimation method.

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