

Accounting for Non-Hazardous Industrial Waste in the United States

by

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Abstract

This dissertation presents a method for estimating the tonnage and composition of non-hazardous industrial waste (NHIW) flows in the United States. For thirty years, it has been an accepted fact that NHIW is generated at a rate of 6.9 billion Mg per year, making it the largest waste flow in the country by more than an order of magnitude. However, this value was generated in 1985, has not been updated since, and is thought to account largely for the weight of dilute process water disposed in surface impoundments rather than solid waste generated by industry.

To address this data gap, and lacking the resources to collect new, national-scale information, I propose an approach by which three independent estimates of NHIW generation based on existing data are used to corroborate each other at the industry sector level. The individual estimates are compared in triangulation so as to control for the errors, uncertainties and other validity concerns unique to each. The methods are: forecasting from historical waste accounts, modeling industrial materials flows to calculate lost mass, and up-scaling state-level data reported to the Pennsylvania Residual Waste Program.

I apply the triangulation method to three industrial sectors for the year 2010, yielding estimates of (all in million Mg) 9.7–14.9 from pulp and paper, 21.2–24.7 from iron and steel, and 0.96–1.24 from petroleum refining. These values suggest that the total quantity of NHIW is measured in the hundreds of millions of Mg, not the billions as claimed by the prevailing EPA account. It therefore appears that NHIW generation rates are comparable to those of municipal solid waste.

Accurate waste accounting based on reliable, repeatable, and efficient methods is an important tool for characterizing current environmental challenges and understanding trends and the effects of key drivers. Waste accounts are also essential for developing and tracking progress on sustainability strategies like industrial symbiosis, in which wastes like NHIW are used as substitutes for raw materials throughout the economy. The method developed here satisfies these needs and answers what has been an open question for nearly three decades.

Thesis Supervisor: John E. Fernández

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For my grandfather
Melvin Joseph Gardner, MIT '50

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Abbreviations

AF&PA	American Forest & Paper Association
AISI	American Iron and Steel Institute
API	American Petroleum Institute
ASM	Annual Survey of Manufactures
BEA	Bureau of Economic Analysis
BOD	Basic oxygen demand
BOF	Basic oxygen furnace
BR	Biennial (RCRA Hazardous Waste) Report
C&D	Construction & demolition (waste)
CC	Continuous cast
CRM	Cold-roll mill
DAF	Dissolved air flotation
DEP	Department of Environmental Protection
DER	Department of Environmental Resources
DFO	Distillate fuel oil
DHEW	Department of Health, Education, and Welfare
DOE	Department of Energy
DPO	Domestic Processed Output
DRI	Direct reduced iron
EAF	Electric arc furnace
EBIC	Environmentally-balanced industrial complex
EC	Economic Census
EEC	Earth Engineering Center (of Columbia University)
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERCO	Energy Resources Company, Inc.
FCC	Fluid catalytic cracking
FPL	Forest Products Laboratory
GAO	Government Accountability Office
HRM	Hot-roll mill
HSWA	Hazardous and Solid Waste Amendments of 1984
IE	Industrial ecology
IEA	International Energy Agency
IFS	Industrial Facilities Survey
LCA	Life cycle assessment
MCA	Mineral Commodity Summaries
MECS	Manufacturing Energy Consumption Survey
MFA	Material flow accounting (or analysis or assessment)
Mg	Megagram (equal to 1 metric ton)

MSW	Municipal solid waste
MYB	Minerals Yearbook
NAICS	North American Industry Classification System
NCASI	National Council for Air and Stream Improvement
NCMP	National Commission on Materials Policy
NHIW	Non-hazardous industrial waste
NOS	Not otherwise sorted
OAQPS	Office of Air Quality Planning and Standards
OECD	Organization for Economic Co-operation and Development
OH	Open hearth (steelmaking)
OTA	Office of Technology Assessment (of the U.S. Congress)
PADD	Petroleum Administration for Defense District
PARW	Pennsylvania Residual Waste (Program)
PM	Primary mill
PMPC	President's Materials Policy Commission
PPI	Producer Price Index
RCRA	Resource Conservation and Recovery Act of 1976
RFF	Resources for the Future
RFO	Residual fuel oil
RTI	Research Triangle Institute
SAIC	Science Applications International Corporation
SAUS	Statistical Abstract of the U.S.
SIC	Standard Industrial Classification (System)
SP	Soaking pit
UN	United Nations
US	United States (of America)
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geologic Survey
VOC	Volatile organic compound
WRI	World Resources Institute
WSA	World Steel Association

I Introduction & Motivations

“The difficulties in studying waste in industry are many.”

–Committee on Elimination of Waste in Industry of the Federated American Engineering Societies, 1921

I.1 Introduction

Industrial ecology (IE) is the study of the flows of materials and energy through human industrial systems and between those systems and the environment. Unique for an academic discipline, IE has a strong normative bent, inasmuch as the research is conducted in order to foster an environmentally preferable future, even as there is debate over precisely what that future looks like. Although the nakedly interventionist vision of Frosch & Gallopoulos (1989) has been tempered by decades of academic detachment since their catalyzing article in *Scientific American*, the field remains one committed to science in service of real-world change. Today, IE research maintains a sometimes uncomfortable tension between its normative and descriptive poles. Some industrial ecologists first ask “What is happening?” and then “How can we make it better?” while others ask “How can (or should) the world work?” and then “What do we need to know to get it there?” In both cases, methods employed involve characterizing materials flows, as this is the main currency of the field.

This dissertation draws from both descriptive and normative traditions of IE. It is motivated by widely-held assumptions and claims about the possibilities for eco-industrial transformation of the economy, and an interest in moving one step closer to realizing that vision. It provides an approach to populate robust and dependable accounts of material flows lacking contemporary empirical observation in order to critique said proposals and also possibly generate new strategies for environmental improvement. In estimating non-hazardous industrial waste generation in the United States, this work illustrates a general approach for material flow accounting and answers a long-standing question in the field. With the results from this research, I hope to dispel myths and galvanize further study and action.

I.2 Waste, metabolism & material flows

According to the eminent anthropologist Mary Douglas, waste is “matter out of place” (Douglas, 1984; as cited in Reno, 2014). To Douglas, waste (or dirt, in the original) is not identified by some quality intrinsic to the substance, but is instead defined relationally, as “an outcome of spatial constructivism, [and] of how we organize our environment” (Viney, 2011). That is to say, Douglas

and her intellectual descendants¹ see waste, dirt, rubbish, pollution, or any other unwanted substance as a construct of a particular cultural, societal—and within that, spatial—context. With this understanding, as poet Anne Carson writes, “the poached egg on your plate at breakfast is not dirt; the poached egg on the floor of the Reading Room of the British Museum is” (Carson, 1990; as cited in Syson, 2010). Mere dirt becomes pollution when, according to Sophie Gee, “a substance has crossed a border and become threatening to the system to which it now, improperly, belongs” (Gee, 2010; as cited in Viney, 2011).

Industrial ecologists also consider waste as matter out of place, with *place* defined not as a specific socio-cultural milieu but, in the most general sense, as the anthroposphere, or the global human socio-economic system (Baccini & Brunner, 2012). The anthroposphere is often presented in contrast with the biosphere, the global environmental system that wholly encompasses and gives life to humanity, and to which we then position ourselves in opposition, as if it is something to be conquered or controlled, if not feared (McPhee, 1989). Douglas’s displacement of matter is therefore not just an anthropological concept, but a tangible, physical linkage between the economy and the environment. The consequences of this flux of materials are dispassionately wrapped up in the terms *global environmental change* and the *Anthropocene*, while vast and increasing quantities of air, water, and land pollution threaten not only the environmental system to which the anthropogenic wastes are deposited but, due to the embeddedness of the economy within the environment, the anthroposphere as well (Waters et al., 2016; Steffen et al., 2015).

The displacement of matter that has ushered in the Anthropocene is not unidirectional; it flows from the environment into the economy as well as the reverse. (Krausmann et al. 2009). With this, a coherent model of global material flows begins to emerge: resources are extracted from the earth, transformed into goods and services, and returned as wastes. The goal of socio-economic metabolism, as this model has come to be known, is similar to that of the metaphor’s biological antecedent: to satisfy the material and energetic needs of a population. Maintenance of an increasingly-affluent population requires substantial material throughput, which historically has been satisfied via large extractions of resources from the environment, resulting through the transformational mechanisms of the economy in large excretions of waste (Figure 1-1a).

The magnitude of the extraction (input) and disposal (output) material fluxes can be thought of as being roughly proportional to the magnitude of the pressure the economy places on the environment. To reduce that pressure, some argue that we must reduce the material throughput of the economy, which would then produce less waste and demand fewer resources. Dematerialization strategies of this type range from gradual technological improvements (Wernick et al., 1996) to more radical proposals to control population or shrink the size of the economy (Martínez-Alier et al., 2010). The socio-economic metabolism model suggests an alternative

¹ See: *Critical discard studies*, <http://discardstudies.com/>

approach, in which a material-intensive economy might be able to be maintained with reduced input and output fluxes by making better use (and reuse) of material resources already in stock (Figure 1-1b). This strategy, summarized by Frosch & Gallopoulos (1989) as “wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment” and essentialized by McDonough & Braungart (2002) as “Waste = Food,” is a core premise of industrial ecology.

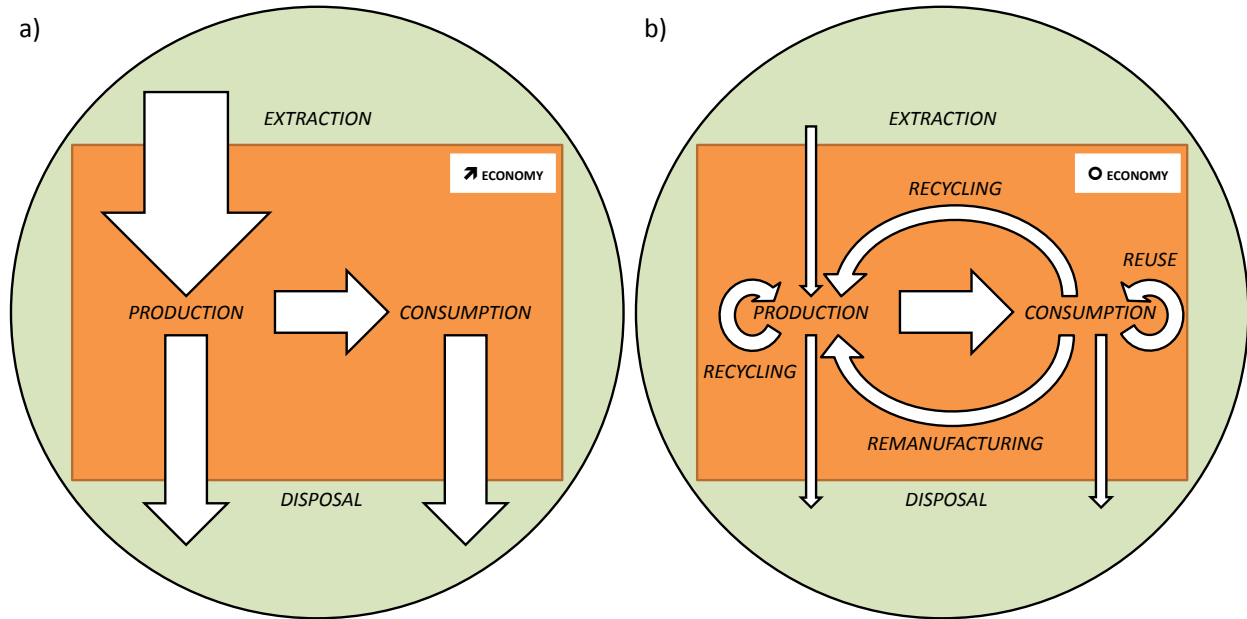


Figure 1-1. Two archetypes of socio-economic metabolism: a) linear and b) circular. The economy (rectangle) is embedded in the environment (circle)

The circular economy approach to sustainability is certainly a compelling one; after all, it promises us that we can retain our material-intensive lifestyles and save the planet at the same time. To a certain extent, the seeds of circularity already exist in the economy in municipal waste recycling systems, eco-industrial parks, and products designed for reuse and recycling. But do these seeds (and others) genuinely have the potential to transform the economy into one that operates within the constraints of sustainability? To answer this question—among any number of others regarding the environmental performance of the economy—we would first need to know which materials are used where and for what, in essence, assigning numbers to the diagrams in Figure 1-1 via a system of materials—and waste—accounting. Wernick & Irwin (2005) argue for the development of national material flows accounts (MFA) by drawing a parallel with the national financial accounts that underpin economic policy (p. 1):

“National Income Accounts, initiated in the 1930s and formalized in the federal government in the 1940s, still provide a foundation for U.S. fiscal and monetary policy. The need to provide these numbers is now taken for granted. Government leaders and managers would not think of making fiscal or monetary policy without them. Members of the public look to indicators based on these accounts to make their decisions. Similarly, companies and investors cannot do business without the numbers from financial accounting. Yet policymakers, firms, and the public lack any similar set of numbers for the material flows that are at the center of environmental issues.”

That final statement is not strictly true, at least not any more, as many countries have in fact implemented national materials accounting schemes, such as Japan’s “Fundamental Plan for Establishing a Sound Material-Cycle Society,” which includes data collection provisions (J MoE, 2010), and the EU’s annual compilation of economy-wide MFAs by each member state (Eurostat, 2013). The US lags far behind these two examples, with regular accounts constructed for specific materials in a highly decentralized and disaggregated manner, if at all.

1.3 Waste in the U.S.

The aforementioned central premise of industrial ecology—that closing material loops can lead to eco-industrial restructuring—hinges in part on there being sufficient solid waste of the correct type to substitute for enough raw materials to make an environmental difference. So, how much waste is there? The Environmental Protection Agency, which collects and publishes what serves as waste accounts in the US, estimates that in 2010, Americans generated 225 million Mg of municipal solid waste (MSW, i.e. garbage), of which 34.1% was either recycled or composted (US EPA, 2011). In the same year, American industry generated between 31–32 million Mg of hazardous waste (BR, 2011). But towering over these two figures is the quantity of non-hazardous industrial waste (NHIW). The EPA estimates that “American industrial facilities generate and dispose of approximately 7.6 billion tons [6.9 billion Mg] of industrial solid waste each year” (US EPA, 2016). This staggering figure is 31 times as large as the MSW flow and 220 times as large as industrial hazardous waste. As a waste category, NHIW “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” (Dernbach, 1993, pp. 10–11). These are the very waste materials that are ideal candidates for industrial symbiosis and other beneficial reuse strategies (Eckelman & Chertow, 2009). It would therefore seem that the path to eco-industrial transformation of the US economy may indeed run through NHIW.

Looking a bit closer, however, reveals that all is not as it seems. The quote from the EPA’s *Guide for Industrial Waste Management* cited above continues, admitting that “this number was generated back in the 1980s...” (US EPA, 2016). A decades-old estimate of waste is almost certain to be unreliable today. After all, in 1990, MSW generation was 190 million Mg (US EPA, 2011)

and in 1991 hazardous waste generation was 280 million Mg (BR). Over the next 20 years, those figures would change by 18% and -89%, respectively! Part of this change can be attributed to the periodic adjustment of boundaries of analysis and statistical methodologies, but there are other drivers as well. Population and affluence are two major drivers of all material flows (Chertow, 2000b). The size, makeup, and technological capacity of American industry would have a direct influence on industrial waste generation, so any changes in those dimensions—of which there have been many over the past quarter century—are sure to be reflected in waste outputs.

The regulatory apparatus surrounding industrial waste generation likely also has an influence. The Resource Conservation and Recovery Act (RCRA), which is the EPA's primary solid waste law, assigns considerable regulatory burden to generators, managers, and disposers of hazardous wastes, both to protect human and environmental health and to incentivize hazardous waste reduction. One can hypothesize that the observed decrease in hazardous waste generation from 1991 to 2010 is due in part to factories either reducing their overall waste output or doing a better job isolating the toxic and hazardous substances in smaller and smaller volumes. The unintended consequence of this latter scenario might be a concomitant increase in non-hazardous waste generation. The Clean Air Act and Clean Water Act also both have the effect of transmuting waste material from gaseous and aqueous forms (respectively) to solid form for disposal. If these laws work as intended, they would exert upward pressure on solid waste generation rates, both hazardous and non-

This list of driving factors is not exhaustive, but is sufficiently populated to cast doubt on the current validity of a now thirty-year-old waste figure, and according to Eckelman & Chertow, “there has been no reliable nationwide estimate of generation or disposal made [since]” (2009, p. 2551). Nevertheless, estimates of NHIW abound, suggesting, at least on the surface, that there may be more information out there.

- “The volume of industrial solid waste is 36 times larger than that of municipal waste and 25 times larger than that of hazardous waste” (Dernbach, 1993, p. 10).
- “For every ton of municipal discards wasted, about 71 tons of manufacturing, mining, oil and gas exploration, agricultural, coal combustion, and other discards are produced” (Platt & Seldman, 2000, p. 18).
- “For every pound of trash that ends up in municipal landfills, at least 40 more pounds are created upstream by industrial processes” (Makower, 2009).
- “Industries (everything from manufacturers of paper, steel, glass, and concrete to food processing, textiles, plastics, and chemical manufacturing, to waste treatment) do waste prolifically, generating 7.6 billion tons a year” (Leonard, 2010, p. 185).
- “The total industrial waste tonnage generated in the United States [is] around 12 billion tons” (MacBride, 2012, p. 88).

These five representations of NHIW tonnage seem to differ widely—36 times, 71 times, 40 times, 7.6 billion tons, 12 billion tons—but in fact all point back to the very same reference that the EPA still uses as well, the 1988 EPA *Report to Congress: Solid Waste Disposal in the United States*. This report was the public source of the 7.6 billion ton [6.9 billion Mg] figure for NHIW. In 1992, the now-defunct U.S. Congressional Office of Technology Assessment (US OTA) referenced this same value in their background paper on *Managing Industrial Solid Wastes*, where it was used to represent US manufacturing wastes, although a billion tons or so were shaved off the total to avoid double counting coal ash (US OTA, 1992). In total, the US OTA estimated 11–12 billion tons of non-hazardous solid waste. With these two numbers and the EPA’s MSW accounts, each of the figures from the five references above can be recreated.

Most of the authors cited seem to be aware of the anachronistic provenance of the NHIW figure they were repeating. Dernbach, writing soon after the EPA report was published, could speak with some authority in the present tense. Platt & Seldman and Leonard hide the decades-long gap in their references. Makower and MacBride, to their credit, fully acknowledge that the numbers they are repeating are out of date, even going so far as to critique their reliability and bemoan the lack of a more up-to-date estimate, while still using the present tense. But, nevertheless, this same estimate is repeated over and over again, to the point at which any caution, nuance, or subtlety has been nearly completely lost in the public understanding. This phenomenon is exemplified by the following example: In September 2013, while in London, I visited a sustainable cities museum built by Siemens called The Crystal. This museum includes exhibits on the future of energy, water, transportation, agriculture, and many other dimensions of sustainable cities, including waste. There, in London, in a museum targeting a global audience built by a German company, was written “For every rubbish bag you put out for collection there will have been 70 bags of waste produced when making the goods and products that ended up in the bin.” This exhibit did not list its references, but I have a hard time believing it is anything other than Platt & Seldman, who calculated in 2000 nearly the same ratio—71:1—from the 11–12 billion tons estimate of industrial waste published by the US OTA in 1992, which in turn included 6.5 billion tons of manufacturing waste from the 7.6 billion tons originally reported to Congress by the EPA in 1988, who got it from a 1985 survey of industry. In this case both the date and the country of origin had been lost in translation, with the result peddled as a provocative—yet baseless—truth.

Further investigation turns up more issues. It turns out that the data in the 1988 EPA document represented not non-hazardous industrial waste *generation*, but instead *on-site disposal*. This is a nontrivial distinction, both because it excludes all of the wastes that are disposed off-site and, crucially, because it is sensitive to medium of disposal. The picture that comes to mind when one hears “solid waste” is that of a bag of garbage or perhaps a landfill, where the material is largely solid, if perhaps covered in slime. Industrial wastes, on the other hand, are often disposed of in process wastewater. If those waters are not discharged to a river or lake, in which case the factory would need a permit from the EPA under the Clean Water Act, then they are classified as “solid”

(land disposed) waste, and regulated under RCRA. When the factories surveyed by the EPA heard the question “What is the total amount of waste disposed on-site?” they included the tonnage of disposed process waste water in their response. While, strictly speaking, that water is part of the non-hazardous waste output of that factory, including it severely limits both the comparability of the statistic with other waste flow statistics and the usefulness of the number for informing industrial ecology strategies, which rely on the raw material substitutability of the waste, i.e. the solid fraction. One estimate suggests that just 3% of the 6.9 billion Mg is solid material, reducing the value to a mere 200 million Mg of NHIW (in 1988) (MacBride, 2012, p. 100).

So, how much waste is there? It turns out that, at least in the case of NHIW, which had initially appeared as a great candidate for reuse and recycling, we really don’t know. In this dissertation, I take one step towards finding an answer and dispelling the numerous myths and misapprehensions surrounding this value.

1.4 Why non-hazardous industrial waste?

It does seem odd that nobody would know how much NHIW is generated today, especially considering that at one time people thought it was in the billions of tons per year. The lack of attention paid to this waste reflects the environmental and materials policies of the country. Nevertheless, there are good reasons to focus on it now, aside from the sake of sheer intellectual curiosity or developing a marginally more complete economy-wide material flow account.

First, the 6.9 billion Mg estimate of NHIW has been used multiple times to argue that the waste priorities in the country are misplaced. If people only knew the vast quantities of waste generated in industry, writes Makower (2009), “the locus of concern could shift away from beverage containers, grocery bags, and the other mundane leftovers of daily life to what happens behind the scenes—the production, crating, storing, and shipping of the goods we buy and use.” MacBride (2012) makes a similar argument, but embeds hers in a broader thesis about how the focus on reducing, reusing, and recycling MSW (consumption-based wastes) enables NHIW and other production-based wastes—and the industries that generate them—to go on unexamined and undisturbed. If in fact what we thought was the size of that waste flow overstated the case by an order of magnitude or more, the policy disinterest in NHIW, while still unfortunate, may not be a tragedy or conspiracy after all.

Second, irrespective of its comparative magnitude, characterizing the tonnage and composition of the NHIW helps to further an understanding of the environmental risk of current industrial activity. Although categorized as non-hazardous by the regulator, “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) ... the extremely high volume and overall toxicity of industrial solid waste probably presents greater total human health and environmental risk than hazardous waste” (Dernbach, 1993, p. 11). Furthermore, the aqueous medium of disposal

elevates the risk of many industrial wastes. NHIW is often stored or disposed in man-made ponds or lagoons called surface impoundments, which, when they fail, can have potentially calamitous outcomes (MacBride, 2012, p. 88). If poorly designed or controlled, the waste can also seep out of the impoundment, contaminating surface- and groundwater.

Finally, NHIW includes many of the wastes that have been identified and used for industrial symbiosis and beneficial reuse strategies (Chertow & Park, 2011). Maintaining robust accounts of NHIW enables the strategic (i.e. not *ad hoc*) deployment of sustainability interventions, furthering the vision of industrial ecology (Chen & Ma, 2015). Recycling these waste materials can yield double environmental dividends. It avoids the impacts associated with disposal (see above) and, by substituting for raw materials, the impacts associated with raw materials extraction. The strategy is not environmentally faultless, as it would require intermediate processing (upgrading waste materials to raw material quality), as well as any other ancillary activities like transportation. But on balance, at least theoretically, the practice is environmentally preferable (Eckelman & Chertow, 2009; 2013).

1.5 Research objectives

The objective of this research is, put simply, to establish a contemporary account of NHIW generation in the United States. The account will answer the questions: How much is there? What is it made of? And what industries generate it? In service of this objective, and, I hope, to avoid the telephone-game of misunderstanding that succeeded the last published estimate of NHIW in the US, this research develops a method for waste accounting that is efficient and repeatable.

1.6 Outline of dissertation

The dissertation that follows includes six chapters, in addition to this introduction.

Chapter 2 expands on many of the concepts and arguments presented in this chapter, presents other background information, and establishes the historical and theoretical context in which the research is conducted.

Chapter 3 elaborates on the specific methods used here to populate the waste account and estimate NHIW generation.

Chapters 4–6 detail the application of the estimation method to three industry case studies: pulp and paper (4), iron and steel (5), and petroleum refining (6). Pulp and paper is treated as the exemplar case, and goes into more methodological detail and background than the other two.

Chapter 7 summarizes the results of the case studies and draws conclusions about total NHIW generation rates and patterns.

2 Background, History & Context

This chapter presents three narratives that are useful for understanding the context of this research project:

A) background on past scholarly approaches to estimating NHIW generation rates; B) history of the construction and definition of official governmental NHIW accounts; and C) discussion and classification of waste accounting methods along with examples.

2.1 Background & literature review

Scholarly efforts to clarify the account of NHIW generation in the US began just four years after the EPA's 1988 *Report to Congress*. In a 1992 issue of the journal *Hazardous Waste and Hazardous Materials* (now *Environmental Engineering Science*) dedicated to presentations and discussions of industrial waste data, Allen & Behmanesh expressed a lack of confidence in the 6.9 billion Mg estimate published by the EPA, claiming that "the accuracy of the data ... is difficult to assess" (p. 93). Their skepticism was stoked in part by the availability of another nearly contemporaneous estimate of non-hazardous industrial waste in the US constructed for the EPA by consulting firm SAIC in 1985, which concluded that just over 390 million Mg of NHIW was generated annually. Allen & Behmanesh sought to clarify this 17-fold discrepancy by examining "raw material usage and product manufacturing rates for various industry sectors." Using back-of-the-envelope calculations for two industrial processes, paper and chlorobenzene manufacturing, the authors argued that the difference between the two estimates was most likely due to the inclusion or not of process wastewater, concluding that "waste mass measured on a dry weight basis can be very different from total waste" (p. 95). This argument is further reinforced by the fact that the 1988 EPA figures claimed 96.6% of the total 6.9 billion Mg of NHIW was disposed in surface impoundments, which are lagoons for storing aqueous wastes. Just 3.4% (235 million Mg) was disposed in landfills, waste piles, or other land application units. It is conceivable that the remaining 165 million Mg of SAIC's total could have been the dry fraction of the aqueous wastes discharged to surface impoundments, suggest a very reasonable solids fraction of 2.5%.

Although Allen & Behmanesh looked at just two industrial processes, their use of rudimentary material balance logic foreshadowed a series of publications on the topic of NHIW in the US by industrial ecology pioneer Robert Ayres and his long-time co-author (and wife) Leslie Ayres. Ayres justifiably shows up (or should show up) in every industrial ecology dissertation; his contributions to the field are difficult to overstate. Beginning in the 1960s, Ayres and his collaborators advocated for materials accounting alongside economic accounting to, among other reasons, internalize environmental externalities (Ayres & Kneese, 1969). Over time, Ayres's work developed into a framework of "industrial metabolism," a high-level but comprehensive model of

the major material flows in an economy and between the economy and the environment, metabolically regulated by economic forces (Ayres et al. 1989). Such a model enabled Ayres and colleagues to derive any number of as yet unobserved material flow accounts from a combination of reliable government statistics and deftly applied materials balance logic.

2.1.1 Material balance and material flow accounting

Starting in 1993, Ayres & Ayres turned their attention to aggregate waste generation in the US. Despite the nominal focus on “waste reduction potential,” their motivation seems to have been the same as it was for Allen & Behmanesh one year prior and for this very dissertation 23 years later: it was—and still is—simply unclear how much waste is generated in the US. Ayres & Ayres, who completed their first pass in 1994 with a detailed look at waste (or “lost mass,” in their convention) from highly complex US chemical industries, claimed that their indirect materials balance approach was superior to the “conventional measurement-based approach.” Relying as it did on “well-established government statistics,” it enabled repeatability and avoided the close reading and interpretation of ad hoc waste statistics that Allen & Behmanesh showed was necessary. Ayres & Ayres further demonstrated the material balance/industrial metabolism method’s ability to clarify between wet and dry wastes and be robust to difference sources of waste, including, notably, non-point sources, which direct accounting methods can easily overlook.

The scope of the Ayres’ analysis was broader than that represented by either estimate from the EPA, its 1988 *Report to Congress* or the 1985 SAIC report. To Ayres & Ayres, “lost mass” from industry included displaced materials like eroded topsoil and mining overburden, as well as high volume ore refining and fuel preparation wastes that were largely excluded from the EPA’s estimate. As such, the aggregated results from their studies are not directly comparable with the EPA’s figures, although the Ayreses do also present waste generation on an industry-by-industry basis. The results from the initial two white papers (Ayres & Ayres, 1993; 1994) are crude, serving mainly as a demonstration of the method, and the results can be safely disregarded. A comprehensive assessment of waste outputs for the year 1988 was published in a chapter of a 1999 National Academy of Engineering volume entitled *Measures of Environmental Performance and Ecosystem Condition*.² Ayres & Ayres estimate that lost mass for that year reached nearly 1.1 billion Mg, including 146 million Mg of ash, slag, and other “process wastes,” a category roughly equivalent to NHIW (Table 2-1). The vast majority of lost mass (900 million Mg) was comprised of ore concentration wastes and 25 million Mg was non-combusted agricultural residues. An additional 8.3 billion Mg of overburden and lost soil was also found.

² This book is one of many published from the late 1980s through the mid-2000s by the US National Academies that present novel and potentially high-impact industrial ecology research. The National Academies were major catalysts for the field of industrial ecology, and these volumes are not well known among today’s students of the field.

Table 2-1. Estimated dry industrial waste streams in the US, 1988 (Ayres & Ayres, 1999)

Sector	Noncombustible organic wastes	Concentration wastes (million Mg)	Process wastes (ash, slag, etc.)
Agriculture	>25		
Food processing	?		
Forestry, pulp, paper			18.1
Mining		845.3	
Chemicals		57.2	22.9
Primary metals			3.3
Stone, clay, glass			10.0
Fossil fuel and electric power			92.0
TOTAL	>25	902.5	146.3

Ayres & Ayres further expanded their analysis and updated the basis year to 1993 in their 1998 book *Accounting for Resources, 1*. Here, more sophisticated models enabled the authors to improve the resolution and fidelity of their results, in dimensions of both waste source and disposition. Thirty-three separate industrial sectors were studied, 23 of which were found to produce “unsaleable solid wastes” totaling 1.2 billion Mg. Again, 900 million Mg were attributed to ore and fossil fuel processing wastes, 236 million Mg to other industrial processing wastes, and 54 million Mg to unusable agricultural wastes, primarily from livestock (Table 2-2). Of the 236 million Mg that is roughly comparable with our NHIW category, a full 70% was generated by two industries, food and kindred products (SIC 20) and electric power from coal (SIC 491).

The change from 1988 to 1993 is a modest one, but somewhat less so when ore processing wastes are excluded. Economic changes in the US over that five-year period are reflected in the input data, although the expansion of the industry models in the later study is likely responsible for much, if not all, of the change. Despite the conceptual simplicity of the materials balance conceit, the approach is not quite as elegant as the Ayreses claim. Although there is sufficient raw material input and product output data to estimate bulk quantities of missing mass, the models tend to be somewhat less constrained than would be required for policy-relevant characterizations of wastes and pollution. Literature and theoretical sources are therefore necessary for many of the compositional and substance flow details of the models, introducing an uncertainty that the Ayreses do not adequately address. Throughout the studies, some figures are given with order-of-magnitude precision while others have up to three or four significant digits. This can give a false sense of certainty in the results when in fact there is significant uncertainty; the authors place great confidence in the reliability of source data that they do little to validate or even critique. Furthermore, despite having produced two independent estimates of waste outputs, they do not compare the results to examine changes in the economy or the validity of the modeling approach.

Table 2-2. Estimated dry industrial waste streams in the US, 1993 (Ayres & Ayres, 1999)

SIC	Sector	Unsalable solid wastes (million Mg)
02	Livestock	53.8
101	Iron ore	148
10	Non-ferrous metals mining	569.36
12	Coal mining and cleaning	20
131	Oil and gas drilling and pumping	34
147	Mineral mining	129.5
20	Food and kindred products, total	88.2
201	Meat products	3
203	Fresh and preserved vegetables and fruits	5
204	Grain mills	2.3
206	Sugar mills and confectionery	8.6
207	Fats and oils	6.5
208	Beverages	0.65
24	Lumber and wood products, total	4.3
261	Pulp	13.2
262	Paper	4.3
2911	Petroleum refining	4
3241	Portland cement	7.3
3312	Coking	3
3312	Pig iron and steel	0.6
333	Non-ferrous metal smelting, refining	4.82
491	Electric power from coal	78.4
xx	Fuel consumption	2.2
TOTAL		1,191.03

Ayres's research efforts during the 1980s and 1990s dovetailed with—and in some respects directly motivated—other work on characterizing the material flow accounts of entire economies. Ongoing research was advancing theories of socioeconomic and industrial metabolism through one-off studies, with the objective of eventually realizing Ayres & Kneese's (1969) vision of regular, robust physical accounts—including by definition that of NHIW outputs—collected and utilized alongside economic ones. Wernick & Ausubel (1995a) offered the first comprehensive account of “national materials flows” for the United States, focused on the year 1990. This study was essentially an impressive synthesis of available data, rather than the result of a modeling effort. Wernick & Ausubel (1995) also proposed a set of metrics that would embed national material flows into an environmental policy context. They claimed a total of industrial materials processing wastes (excluding ore concentration and beneficiation and agriculture wastes) at 136.2 million Mg,

referencing a 1993 conference presentation by Rogich et al as the source. Donald Rogich was at the time the chief of the Division of Mineral Commodities of the U.S. Bureau of Mines, a constituent agency of the Department of the Interior responsible for, among other things, collecting, analyzing, and disseminating information about minerals and materials usage in the U.S. I have been unable to locate a copy of that presentation to verify Wernick & Ausubel’s claim, although I did find a later report with the same title (Rogich, 1996), that included no waste data. Elsewhere in their article, Wernick & Ausubel (1995a) discuss the myriad sources that Rogich et al. had used, which included the 1988 EPA *Report to Congress*.

After the closure of the U.S. Bureau of Mines, the locus of US material flow accounting, along with Rogich himself, moved to the World Resources Institute (WRI). In the second report of WRI’s material flow research program, which involved a collaboration with pioneering research institutes in Germany, Japan, Austria, and the Netherlands, Matthews et al. (2000) presented an analysis of the output side of economy-wide material flow accounts for the five participating countries over the period 1975–1996. The scope of this analysis was even broader than Ayres & Ayres’ had been, as the objective was to understand the total physical outputs of these five economies in all three media (or “gateways,” meaning air, water, and land), and the relationships between quantities of these outputs and macro-economic characteristics. The indicators employed include Domestic Processed Output (DPO) by gateway; DPO to land in turn is comprised of dissipative and non-dissipative flows. Non-dissipative flows of DPO to land most closely resemble the industrial wastes estimated by Ayres & Ayres, and were estimated to be just over 430 million Mg in 1996 (Figure 2-1).

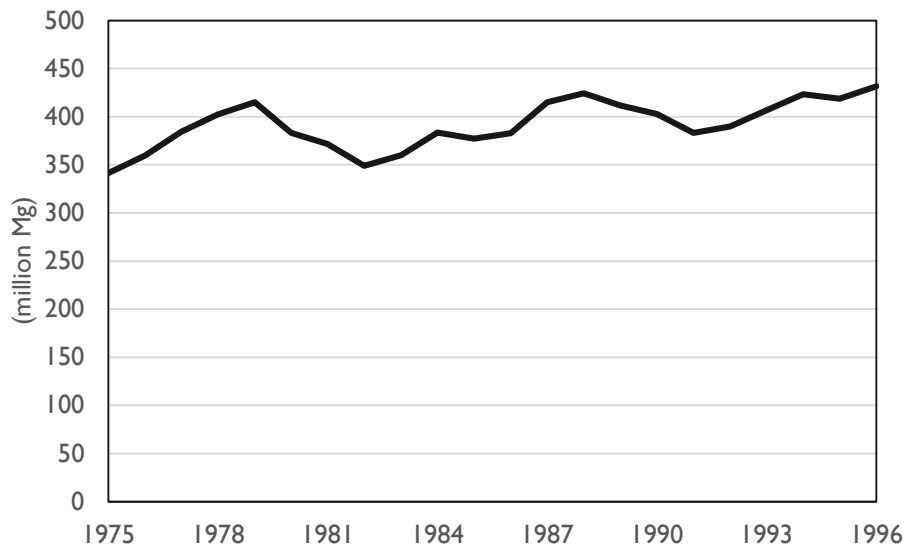


Figure 2-1. DPO to land, non-dissipative, in the US, 1975–1996 (Matthews et al., 2000).

The third report of the WRI MFA project presented a comprehensive economy-wide MFA of the United States, examining material flows in four major economic sectors: “metal and minerals, nonrenewable organic materials (including fossil fuels), agriculture, and forestry” (Rogich et al., 2008). Although this report at least nominally meets the Ayres condition of regular accounting (data is presented from 1975–2000), it also is extremely highly aggregated. This, it seems, is the tradeoff one must expect between comprehensiveness and specific policy relevance. Just as high-level economic indicators like GDP are used to gauging the general health of the economy but offer little guidance on individual economic sectors,³ the high-level material flow indicators like DPO serve a specific, not-universally applicable, purpose. Like its antecedent of national financial accounts, in which high-level indicators are constructed from lower-level accounts, WRI’s MFA of the USA is constructed from flows of 169 materials and substances. But unlike financial accounts, in which lower-level indicators are also policy-relevant, many of the lower-level subsidiary material flows do not map well to current materials management schemes, especially on the output side. Increasingly, we care about the emission of specific substances to the atmosphere like CO₂, but for solid wastes, many policy programs are focused on sources rather than substances: how much is from cities, how much from industry, etc.?

The WRI Materials Flows Database, the data and models underlying the WRI MFA, is not included with the published report (Rogich et al., 2008). The database used to be available on the WRI website, but since that organization has shifted its focus away from material flows and other industrial ecology research and revamped its website, the database seems to have disappeared. I accessed it before the disappearance, and although the fact that it was never published for peer review makes me hesitant to use the models for my own devices, I did find it interesting that many of the material flow calculations and embedded assumptions in waste generation (e.g. processing yield) seem drawn directly from the prior lost mass work of the Ayreses, although their publications are not referenced in any of the three WRI MFA reports (Adriaanse et al., 1997; Matthews et al., 2000; and Rogich et al., 2008).

2.1.2 Recent developments

The WRI MFA appears, for the time being, to have exhausted the potential for the particular combination of materials balance / industrial metabolism and available government statistics to illuminate new details (or generalities) about the materials flows of the US. As the discussion above indicates, that vein of research diverged from the original goal of characterizing NHIW, which suggests either a lack of interest in the waste question or, equally likely, an acknowledgement

³ There is a lively and ongoing debate about the validity of GDP as a high-level indicator for economic health and wellbeing, e.g. Costanza et al. (2014), but even opponents usually advocate replacing it with a more nuanced and inclusive aggregated indicator, not dispensing with one altogether.

that Ayres & Ayres took the approach as far as it would go. What would be needed for any further refinement of the NHIW generation rate would be a new source of data. As it happens, one was forthcoming.

The scholarship around NHIW up until this point was motivated very much as the EPA was, to simply (or not so simply, as the case was) get a handle on how much waste was being generated and, for Ayres & Ayres and their ilk at least, how that has been changing over time. At the same time that Ayres, Rogich, and their international partners were developing models of industrial and socio-economic metabolism and populating economy-wide material flow accounts, activities that would become a central part of the emerging field of industrial ecology, another group of researchers was studying how those material flows could be made more environmentally sustainable. This research thrust, which also would become a core element of industrial ecology, is often seen as being catalyzed by the 1989 *Scientific American* article by Frosch & Gallopoulos, “Strategies for manufacturing”.⁴ In it, the authors lay out arguments for the “sustainable industrial ecosystem,” which is predicated on intensive waste recycling and reuse between industry sectors, a practice that has become known as “industrial symbiosis” (Chertow, 2000a).

Marian Chertow has conducted a wide range of pioneering work on industrial symbiosis, including developing models for the formation of new symbioses (Chertow & Ehrenfeld, 2012), cataloging and classifying exchanges within existing eco-industrial parks (Chertow & Park, 2011), and characterizing the environmental benefits and costs of industrial symbiosis (Eckelman & Chertow, 2009; 2013). Chertow can also be credited with introducing the confusion surrounding the EPA’s NHIW estimate to a broader—if still academic—audience, when she wrote in the journal *Social Research*, “It would be difficult to overstate the uncertainty of estimates of non-hazardous wastes” (Chertow, 1998, p. 51). In 2009, Eckelman & Chertow made use of what seems to have been a previously unexamined data set from the Pennsylvania Residual Waste (PARW) program to assess the life-cycle environmental benefits of reuse and recycling of NHIW in that state. By substituting for raw materials throughout the industrial system, this reuse was found to offset upwards of 0.9 million Mg of CO₂-eq.

The data set was further analyzed by two teams of Yale University graduate students in the Spring 2009 semester. One team attempted to identify gaps in the residual waste (NHIW) data (Dana, Foley & Mazrui, 2009), while the other examined what other types of conclusions could be drawn from the data (Barr et al., 2009). Barr et al. realized that if NHIW generation rates are stable between Pennsylvania and the rest of the country, this data of unprecedented detail could be used

⁴ Although many point to this article as the “birth” of industrial ecology, that accolade is not necessarily fully deserved. For example, Ayres (1978) had expounded upon many of the very same strategies that Frosch & Gallopoulos presented, and in fact the “further reading” inset in the *Scientific American* article points readers to Ausubel & Sladovich (1989). It should be mentioned, though, that to the extent to which they catapulted the industrial ecology concepts into the public sphere, Frosch & Gallopoulos should be commended and recognized.

to provide an estimate for national NHIW generation as well. By calculating the tons of waste per dollar of revenue generated in each industry and then multiplying that intensity figure by national-scale industrial revenues, the team estimated NHIW generation in the US at 385 million Mg for the year 2002. This calculation was performed at the highest level of economic aggregation (2-digit NAICS codes); lower-level variability would assuredly result in a different figure, but likely one of the same order of magnitude.

The final relevant contribution to the now decades-long scholarly quest for the NHIW figure comes not from an industrial ecologist or engineer of any stripe, but from a political scientist who spent more than a decade working as the Deputy Director for Recycling at the New York Department of Sanitation. Samantha MacBride, now a professor at the Baruch College School of Public Affairs, argued in her 2012 book *Recycling Reconsidered* that today's recycling system is not actually creating a more sustainable world. Instead, it has been coopted by industrial actors who have successfully distracted the recycling movement from advocating for policies and focusing on waste streams that would genuinely lead to environmental improvement. One example MacBride uses to defend this thesis is that of NHIW, specifically, that the EPA-reported generation figures are "an order of magnitude greater than the tonnage of municipal solid waste that every book, volunteer effort, government program, or household conversation about trash and its problems seemed to focus on ... yet very little had been published about this far larger quantity" (MacBride, 2012, p.88).

MacBride's goal with her NHIW example was to explain how the vast tonnages of industrial waste bypassed the attention of recycling and zero-waste advocates. She does this in part by digging deep into the history of the EPA's regulatory approach to solid waste and in part by assessing what, if anything, those advocates knew about the waste stream. The answer to the second part is "not a lot." MacBride found few conversations about the topic in one of her primary data sources, the GreenYes listserv managed by the Grassroots Recycling Network. One post to that listserv referenced the 1988 EPA figure and the reported 97% disposed in surface impoundments to suggest "the total size of the industrial solid waste and municipal solid waste streams appear to be comparable in terms of annual generated weight" (MacBride, 2012, p.100). Another post, which also acknowledges the EPA figure as "a very misleading statistic," goes on to reference Oregon statistics that showed the quantity of industrial waste disposed in landfills being slightly more than one third that of MSW in 1999 (p.101).

MacBride uses these two claims not to abandon her thesis but to evidence the industrial cooption of the recycling movement. She (rightfully) acknowledges that the 97%-to-surface-impoundment statistic is not *just* process wastewater, it is NHIW contained *within* process wastewater, or in her words, "the percentages do not convey information about how much of these manufacturing-waste tonnages is water and how much is solids" (p. 103). As for the Oregon statistics, MacBride argues that because most NHIW is disposed on-site (according to the EPA), it is exempted from state-level oversight, including data collection. The Oregon statistic cited above

may be accurate for the waste tonnages going to off-site disposal facilities, but says nothing about on-site disposal. That such a gap exists in the regulatory frame is not accidental, according to MacBride's research, but an intentional outcome of a legislative and bureaucratic machine heavily influenced by industrial actors. As for the other GreenYes post, there is no evidence that industry somehow intervened to brainwash recycling experts, but the result is one that MacBride's industrial bogeymen would not object to: a gargantuan number either completely overlooked or incorrectly downscaled.

2.2 History of U.S. NHIW accounting

The story of NHIW accounting in the US is the story of federal-level solid waste policy and regulation as the source of data, as the motivation for assessing the material flow and as an outsized influence on defining the boundaries and composition of the waste category in the first place. Although materials and resource policies had been on the books going back to the 1800s, little was done to assess the industrial waste burden in any detail much before the passage of the Resource Conservation and Recovery Act of 1976 (RCRA).

2.2.1 Pre-RCRA activities

Federal policies for materials accounting date back at least to the 1879 establishment of the U.S. Geologic Survey (USGS), which to this day maintains a remarkably detailed account of national metals and minerals production and consumption information (after 67 years the responsibility of the U.S. Bureau of Mines) (Geiser, 2001, p. 144). Besides the ongoing federal role in managing forest and mineral resources, little attention was paid to economy-wide materials use, with no mention of industrial waste generation outside of some industry-specific studies. National experiences of materials and resource scarcity during the first half of the twentieth century, combined with the post-WWII economic boom, rapid industrialization, and specter of yet another war motivated new ideas about the federal government's role in materials management. In the midst of the Korean War, President Truman established the President's Materials Policy Commission (PMPC), headed by William S. Paley, the then-president of CBS (p. 146). The Paley Commission, as it came to be known, was charged with making recommendations to the President about ensuring the long-term availability of "production materials" to the country. In an expansive five-volume report entitled *Resources for Freedom*, the Paley Commission advocated for a national materials policy that would include, among very many other things, making "fuller use of known resources" such as waste materials (PMPC, 1952, pp. 8-10):

"In mining minerals we still leave an astounding fraction in the ground and in using mined or harvested materials we frequently throw away large quantities. About 50 percent of the commercial grades of coal, and more than 50 percent of the petroleum in an average pool

are left behind in the process of production. Roughly one out of every 10 pounds of copper in ores is thrown on the tailings heap; more sulfur is blown from the smokestacks of industry than is consumed; enough natural gas was wasted in 1950 to supply the gas needs of 11 million of the Nation's homes. A considerable fraction of 'harvested' resources also goes unused: only 65 percent of the average tree that is cut ends up as useful material; millions of tons of agricultural growth—stalks, for example—are lost every year because there is no economical way to use them.

These physical wastes are not necessarily economic wastes, for it frequently costs more to eliminate them than the savings would be worth. But technical advances that will make it profitable to reduce these physical wastes will enormously benefit the Nation's materials supply. At present, many profitable opportunities to cut physical wastes are being neglected by industrial companies whose equipment and production methods are outmoded and wasteful, or who have not explored carefully enough the potential profit in waste reduction.”

These wastes-as-resources opportunities were framed in economic rather than environmental terms, and made scant reference to waste materials that we would define as NHIW (except perhaps in the second half of the first sentence of the quote above). Neither did the Commission call for whichever executive department would ultimately wield the powers of national materials policy to develop comprehensive accounts of either the physical wastes or economic potentials, nor did they attempt such an accounting themselves. Nevertheless, it is evidence that the Commission did acknowledge, however obliquely, the role of waste in the nation's materials portfolio.

That acknowledgement may not have lasted very long, however. In 1952, Paley established a non-profit organization dedicated to expanding on the ideas presented in the Commission report called Resources for the Future (RFF), which would eventually support foundational research on industrial metabolism, material flows, and industrial residuals management (Geiser, 2001, p. 148). In 1963, RFF published a thousand-page inventory and 40-year forecast of national materials requirements called *Resources in America's Future* that made no mention of waste at all except in the context of driving water requirements for industrial waste disposal (Landsberg, Fischman & Fisher, 1963).

By the end of the 1960s, national materials priorities had shifted decidedly towards recovery and recycling, mirroring the broader emergence of a national environmental consciousness. A few months after President Nixon proposed an executive branch reorganization that would create the Environmental Protection Agency, Congress created the National Commission on Materials Policy (NCMP) for reasons, at least on the surface, very similar to those motivating the PMPC. But as the introduction to the Commission's final report states, “commissions are creatures of their times” (NCMP, 1973, p. 1-3). Where the PMPC was concerned mainly with resource scarcity, the NCMP was focused on environmental impact and conservation. According to Geiser (2001, pp. 149–150), the final report, *Material Needs and the Environment Today and Tomorrow*, “provided 108 detailed recommendations heavily weighted toward conservation of

materials, accelerated recycling of wastes, increased attention to waste management, and more efficient materials use.” In the area of solid waste management, the Commission recommended that “the amount of solid waste requiring disposition be increasingly reduced where possible by methods of recycling, reuse, and recovery; industry develop and expand technology and markets that will allow for practical use of all bulk waste; [and] industry dispose of waste, including mine tailings, in a manner to facilitate eventual recovery of valuable resources” (NCMP, 1973, p. 4E-6). In support of these recommendations, the Commission relied on what very well might be the earliest estimate of economy-wide solid waste generation (or what Makower (2009) calls the “Gross National Trash”). According to an unreferenced EPA estimate, the tonnage of solid waste generated in the US in 1971 totaled 4,450 million tons (4,040 million Mg), with industry contributing 140 million tons (127 million Mg) (NCMP, 1973, p. 4E-3). The Commission report also included a second, more detailed account of solid waste from 24 industrial sectors, but that estimate totaled just 91 million tons (86 million Mg) for the year 1965 and a forecasted 87.2 million tons (79 million Mg) for the year 1975.

A little bit of digging turns up highly probable sources of both of the NHIW estimates referenced in the NCMP report. The National Materials Policy Act of 1970 that created the NCMP was one of two amendments to the Solid Waste Disposal Act of 1965 enacted as P.L. 91-512. The other, the Resource Recovery Act of 1970, ordered the EPA to create “a comprehensive report and plan for the creation of a system of national disposal sites for the storage and disposal of hazardous wastes...” (US EPA, 1974a, p. 1). To meet this requirement, the EPA contracted Booz-Allen Applied Research to quantify “the hazardous waste problem.” The contractor developed a method for estimating the quantity, composition, and source (industry and geography) of hazardous wastes based on conversions from quantities of total industrial waste, but due to “the nearly complete lack of data describing waste quantities in the literature,” Booz-Allen had to develop that as well (US EPA, 1973b, p. III-1). To illustrate their point, the authors point to two conflicting surveys of industrial waste both published in 1969, one from the state of California and the other from the U.S. Department of Health, Education and Welfare (DHEW), which was responsible for implementing federal waste management policy before the establishment of the EPA.

As a result, Booz-Allen built a completely new database by mining the technical literature to develop waste production factors, which are “multipliers which can be applied to production data of a particular industry in a given geographic location for estimating waste quantity” (US EPA, 1973b, p. III-8). By multiplying the waste production factors for 10 industry sectors⁵ by the output of those industries at a national level, the contractors estimated total industrial waste generation to be approximately 153 million tons (139 million Mg) in 1967, 71% coming from SIC 28—Chemical Industry. Approximately 10% of this total waste flow was estimated to be hazardous or potentially

⁵ The report actually calculates 18 distinct waste values, but eight of them are for subsectors of other industries also studied, for example, SIC 201—Meat Products, 203—Canning, 208—Beverages as constituent of 20—Food.

hazardous. Seeing as how both this and the NCMP reports were published in 1973, I can easily imagine the Commission staff receiving an incomplete, draft version of the Booz-Allen results from the EPA that overestimated their final values by 10% or so. Alternatively, the Commission may have taken the waste production factors from the Booz-Allen report and applied them to 1971 industrial production data, possibly yielding a value closer to their ultimate estimate of 140 million tons. In either case, the NCMP would not have had a published report to reference, hence the uncited and unsupported figure.

As for the other estimate referenced by the Commission, it happens to come from the same DHEW report dismissed by Booz-Allen as being unreliable. This study presented an inventory of industrial waste generation and disposal for 24 industry sectors based on interviews with 320 facilities in 1965 (US DHEW, 1969, p. II-1). The results of this study are exactly those referenced by NCMP, although the Commission seems to have found the data reprinted a National Bureau of Standards report (which I was unable to locate).

Building on the preliminary Booz-Allen estimate of industrial waste generation, in 1974 the EPA Office of Solid Waste Management Programs “conducted a six-months long, in-house study of industrial residues” by gathering and evaluating “all available information concerning industrial waste” (Lehman, 1976, p. 3). This study used the materials accounting framework illustrated in Figure 2-2, in which waste materials from an industrial process are classified as “1) process sludges and residuals; 2) air and water pollution control sludges and residuals; and 3) wastes reused in the basic process or recycled in the secondary materials market” (pp. 3-5). The results of the study claim that the first two waste categories (i.e. excluding internally recyclable materials or scrap) totaled an annual average of 234 million dry Mg of industrial waste for the years 1970-1974, compared with 122 million Mg of MSW. The study also anticipated the effects of air and water pollution control regulations that would come into effect later that decade on solid waste. Projected total industrial waste generation was forecasted to double by 1983, with a large fraction of that growth due to increases in pollution control residues.

In the first half-decade of the 1970s, the EPA commissioned numerous sector-specific studies on industrial waste, most focused on hazardous waste generation, but many of these, like the Booz-Allen report before them, provided a total waste estimate as part of the process of calculating the hazardous fraction. No other economy-wide accounts of NHIW would be forthcoming until after the passage of RCRA.

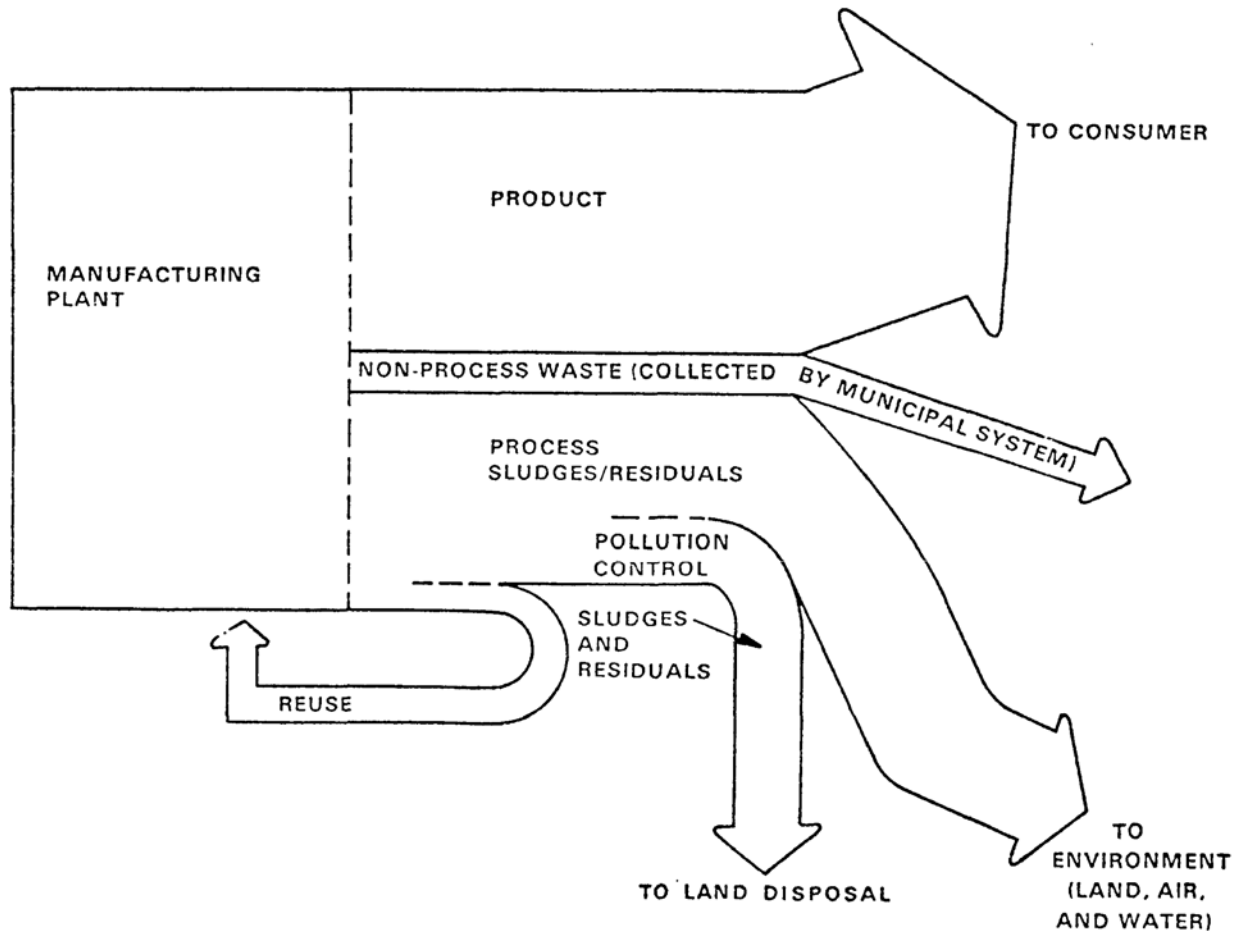


Figure 2-2. “Industry process outputs” (Lehman, 1976, p. 4)

2.2.2 RCRA and after

The federal role in solid waste management in the US began in 1965. Before this time, “solid waste management [was] a local function performed by individual citizens, private contractors, and county and municipal governments” (Kovacs & Klucsik, 1977, p. 212). In 1964, the responsibility for waste management remained overwhelmingly with local government; only two states had state-wide programs and only another 12 had any sort of “identifiable solid waste activities” (p. 213). The goal of the Solid Waste Disposal Act of 1965 was relatively modest: to encourage the states to develop resource recovery and solid waste disposal programs through federal grants and technical assistance. The federal role was increased just five years later with the enactment of the Resource Recovery Act of 1970, which in addition to motivating the Booz-Allen study discussed above, started to promulgate national “guidelines for solid waste collection, transport, separation, recovery and disposal systems” (p. 215). Despite these guidelines, increased state activity, and

expanded federal funding, by the mid-1970s “the volume of solid waste requiring disposal continued to increase and ... little real progress toward protecting the environment from waste pollution had been made” (p. 216).

The Resource Conservation and Recovery Act of 1976 (RCRA) completely overhauled the federal approach to waste management policy. Although states and localities would remain important partners, RCRA placed the EPA firmly in the driver’s seat, and created distinct regulatory pathways and bureaucracies for different classes of waste materials. Despite the orientation of the law’s name towards what we would today call sustainability or industrial ecology, resource recovery ended up as a secondary priority to hazardous waste management. The reason for this can be explained partly by the bill’s peculiar legislative history, which ended up excluding most of the proposed resource recovery measures (Kovacs & Klucsik, 1977, pp. 216–220; Geiser, 2001, p. 151). In addition, Geiser credits (or blames) the Love Canal tragedy of the late 1970s as having diverted the nation’s attention towards the risks of hazardous waste at the expense of conservation.

The largest part of the law, Subtitle C (42 U.S.C. §§6921–6939g), defined the hazardous waste management program. Instead of directly limiting the generation of hazardous wastes, which lawmakers feared may “adversely affect the production of products the manufacture of which created hazardous waste” (Kovacs & Klucsik, 1977, p. 227), the law was designed to isolate hazardous materials from the environment until they could be safely disposed or destroyed. The EPA was authorized to set up a system of recordkeeping, labeling, and reporting that would track all hazardous waste materials—which they were also required to define—from “cradle to grave,” including generation, transport, storage, treatment, and final disposal. In addition to providing a record that could be used to ensure regulations were being followed, this reporting requirement would also generate accounts of national hazardous waste patterns with unprecedented resolution. Although the burdensome reporting requirements would likely encourage some to attempt to cheat, RCRA established harsh penalties for anyone found in violation of the regulations, which would be made even more severe by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), also known as the Superfund law.

The non-hazardous waste provisions of RCRA Subtitle D (42 U.S.C. §§6941–6949a) as passed in 1976 left nearly all regulatory and oversight responsibilities in the hands of the states. The objectives of this program were “to assist in developing and encouraging methods for the disposal of solid waste which are environmentally sound and which maximize the utilization of valuable resources and to encourage resource conservation.” The mechanisms by which the EPA were to accomplish these goals were similar to those under the superseded Solid Waste Act and Resource Recovery Act amendments: financial and technical assistance contingent upon EPA approval of a state’s waste management plan. The main EPA regulatory role under Subtitle D would be to set performance standards for disposal sites of MSW and other non-hazardous wastes. New open dumps would be prohibited and many existing disposal sites would have to be closed or upgraded to sanitary landfills to protect human and environmental health.

An important if overlooked contribution of RCRA was to expand the definition of solid waste. Under the Solid Waste Act, the term “solid waste” referred to “garbage, refuse, and other discarded solid materials, including solid-waste materials resulting from industrial, commercial, and agricultural operations, and from community activities,” but excluded “solids or dissolved material in domestic sewage or other significant pollutants in water resources, such as silt, dissolved or suspended solids in industrial waste water effluents, dissolved materials in irrigation return flows or other common water pollutants.” At the time, most waste from industry was generated in aqueous form, so use of this definition would have excluded a substantial fraction of industrial waste outputs. It is, I should note, unclear the extent to which this was the operative definition in any of the pre-RCRA industrial waste estimates. Lehman (1976) presents his estimate in dry mass, but does not mention if it includes dissolved or suspended solids in process effluent. I would guess it did not.

RCRA expanded the scope of the definition to also include “sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities,” while continuing to exclude dissolved materials in sewage, irrigation return flows, and industrial effluent regulated under the Clean Water Act, as well as nuclear waste. Using this definition, the EPA circulated a solid waste fact sheet in 1978 claiming industrial waste generation rates at 344 million Mg per year, 10-15% of which was estimated to be hazardous, leaving 292-310 million Mg of NHIW, growing at a rate of 3% per year (US EPA, 1978). The fact sheet includes no references, and I was unable to track down its source.

By the end of the 1970s, it was widely acknowledged that the EPA was not meeting its requirements laid out by RCRA (US GAO, 1980). Work was ongoing (albeit belatedly) to develop the Subtitle C regulatory program, but this came at the expense of the rest of the law, including the support the EPA was mandated to provide to states developing their own Subtitle D waste management plans. In a 1980 Report to Congress, the US GAO laid out the poor state of affairs regarding the EPA’s progress under Subtitle D and other resource recovery requirements. The report acknowledges that the research which had been conducted in support of the hazardous waste program often included estimates of total waste generation, but with low fidelity as to composition and disposition of the non-hazardous fraction, essential information for any resource recovery and Subtitle D policy programs.

In January 1978, the EPA formed an internal Industrial Waste Task Force to coordinate the Agency’s approach to NHIW under RCRA. The Task Force was charged with “(1) data collection, (2) the development of guidelines for the recovery of industrial wastes, (3) the promotion of industrial waste exchanges, and (4) the development of State industrial waste management programs” (US GAO, 1980, p. 42). The Task Force was initially focused on obtaining better information about industrial “waste generation, disposal problems, and possible recovery

alternatives,” and by the middle of 1979 had completed research on four industry sectors: ferrous and non-ferrous metals, inorganic chemicals, and coal-fired utilities. One year later, ERCO, Inc. delivered a report on the next four: pulp and paper, food processing, textiles, and agricultural chemicals (US EPA, 1980). Unlike many earlier estimates of non-hazardous industrial waste generation, these studies were in-depth, empirical investigations, involving numerous site visits, interviews, and detailed industry research to ensure data representativeness. According to the US GAO, “at the conclusion of the fact-finding stage, the EPA [planned] to write a comprehensive strategy for industrial waste disposal and recovery,” which would presumably include a robust account of NHIW quantities and composition.

In December 1978, the EPA proposed its Subtitle C regulations. In its proposal, the Agency specifically deferred judgment on a set of high-volume wastes for which insufficient information was available at the time to determine degree of hazard. These so-called “special wastes” included “cement kiln dust; utility waste, including fly ash, bottom ash, and scrubber sludge; phosphate mining and processing waste; uranium and other mining waste; and oil drilling muds and oil production brines,” and the EPA promulgated a reduced set of regulatory requirements for facilities managing them until proper assessment could be completed (Luther, 2013). In the Solid Waste Disposal Act Amendments of 1980, the exclusion from Subtitle C regulation of these materials was codified in what has become known as the Bevill and Bentsen Amendments, named after the Congressmen who proposed them. The exclusion was not intended to be permanent; the Amendments required the EPA perform additional study of the waste materials and regulate them accordingly. The evaluation process would continue for 20 years, and result in the vast majority of Bevill-Bentsen wastes remaining excluded from Subtitle C oversight.

I bring up this part of the history not because it directly contributed to the development of a NHIW account but because it illustrates the malleability of that category. Just as RCRA expanded the definitional boundaries of “solid waste,” the Bevill and Bentsen Amendments resulted in a transfer of a huge volume of waste material from one category to another with no actual physical change occurring. NHIW is defined in a negative way, that is, it includes everything except that designated as hazardous, a characteristic clearly not just defined by physical attribute.

The Hazardous and Solid Waste Amendments of 1984 (HSWA) were a major revision of RCRA, particularly relating to land disposal of hazardous wastes (Ward & Harris, 1985). These amendments emerged from numerous concerns about both the structure of RCRA and the EPA’s progress in implementing the law as written. Most of the concerns dealt with hazardous materials, but there was also a question about the adequacy of the non-hazardous waste regulatory program to meet the goals laid out in Subtitle D of protecting human health and the environment. The HSWA ordered the EPA to prepare a report answering this question and proposing recommendations within the next three years (HSWA §302(a), (b)).

The EPA promptly embarked on an expansive study of the Subtitle D universe involving 21 distinct data collection projects characterizing Subtitle D waste (six projects), facilities (10 projects), and state programs (five projects) (US EPA, 1988). The first phase of the research, completed in October 1986, involved 16 of the 21 ultimate projects that could be conducted using “readily available information” (US EPA, 1986). Data was collected from existing sources on “characteristics, generation volumes, and management of ... municipal solid waste, household hazardous waste, industrial waste, [and] small quantity generator hazardous waste.” A reduced set of data was also collected for “municipal sludge, municipal waste combustion ash, construction and demolition waste, agricultural waste, oil and gas waste, and mining waste.”

The industrial waste study, entitled *Summary of Data on Industrial Nonhazardous Waste Disposal Practices*, was a review of published and unpublished literature about waste from the 22 industry sectors that were “likely to be most affected by regulatory changes required under HSWA” (US EPA, 1988). The contractor, Science Applications International Corporation (SAIC), relied largely on other EPA industry research from the 1970s and 1980s—including those commissioned by the EPA Industrial Waste Task Force—to develop a detailed account of waste sources, quantities, characteristics, and management (US EPA, 1985). The results of this study, summarized in Table 2-3, show total waste generation to be 392 million Mg, 93% of which was from just seven industry sectors. The report also contained information on composition and disposal, as well as a qualitative evaluation of data quality and potential hazard.

SAIC identified numerous shortcomings with the available data. Inconsistent and out of date base years from industry to industry, the inclusion (or supposed inclusion) of water weight in some of the estimates, and the sheer unavailability of some data led the authors to conclude that “much of the information that is needed to assess the environmental effects of current industrial non-hazardous waste generation and management is unavailable” (US EPA, 1985). The authors recommended that the EPA conduct a comprehensive survey of all of the industries they examined to fill the substantial data gaps.

During the second phase of the Subtitle D adequacy review, the EPA conducted research to address many of the data gaps identified by Phase I research projects, but SAIC’s call was left unheeded. Although the EPA acknowledged a need to replace the SAIC account with “more precise estimates of the waste quantities generated from specific industrial waste sources,” the closest they came was the *Industrial Facilities Survey* (IFS) (US EPA, 1987; 1988).

RCRA Subtitle D authorizes the EPA to work in partnership with state and local government and private industry to regulate only final disposal of non-hazardous waste, not generation, transport, or any of the other preceding stages as in the Subtitle C scheme. The EPA’s efforts to characterize non-hazardous waste generation rates after the HSWA, therefore, only went as far as they served the goal of ensuring the disposal of that waste did not pose harm to human health or the environment, specifically through “ground-water contamination” (US EPA, 1988).

(Goals of promoting resource recovery from Subtitle D wastes, already secondary in RCRA's initial drafting, were subordinated even further by HSWA.) So, instead of pursuing SAIC's recommended research path, which would have started with a survey of waste generation and proceeded to track that material to ultimate disposal, the EPA instead went straight to a survey about on-site disposal. Other projects in Phase II collected data on commercial and municipal disposal sites, including those that may receive industrial waste shipped off-site.

The *Industrial Facilities Survey* had the stated objectives of developing national and industry-specific estimates of the number of on-site landfills, surface impoundments, land application units, and waste piles used to dispose Subtitle D waste and the quantities of waste disposed in each type of unit (US EPA, 1987). Consulting firm Westat, Inc. conducted an initial screening study to determine which facilities to contact for the survey. Starting with a list of 149,151 establishments in the 17 industry sectors selected for study (selected because they were determined by SAIC to either be large generators of waste or largely dispose their waste on-site), Westat developed a sampling technique that stratified by facility size and arrived at a sample of 18,051 facilities to contact. After screening out the uncontactable or out of scope facilities, the contractor administered the survey to 15,832 establishments (10.6% of the total) using "computer assisted telephone interviewing." A hard copy of the survey was also sent to each establishment beforehand to allow interviewees to prepare.

The results of the survey are presented in Table 2-4. After statistically up-scaling the survey data, Westat concluded that in 1985, 6.9 billion Mg of Subtitle D waste was managed in on-site facilities, the vast majority of which went to surface impoundments. Setting aside for a moment the factor of 17 difference between this result and the result of the SAIC survey (which Westat acknowledges in their report), there are other reasons to question the aggregated figure. First, the wastes disposed in each type of unit—landfill, surface impoundment, land application, and waste piles—are not equivalent. Landfills and waste piles are used to dispose of solid wastes, land application is for sludges, and surface impoundments are for process wastewaters and runoff. Second, the survey allowed respondents to answer the questions with any unit they wanted, including, importantly, volumetric ones. Westat writes (US EPA, 1987, p. 3-8):

"In answering the quantitative questions, respondents provided responses consistent with their recordkeeping practices. For example, respondents could provide responses to volume questions in tons, gallons, cubic yards, cubic feet, acre-feet, etc. For analysis purposes, all responses were converted to standardized units of measurement [metric tons]. In converting responses to standardized units, assumptions were made with regard to the density of waste and quantities were rounded off, all of which may contribute to nonsampling errors. We did, however, carefully check comments of each case for any elaborations on certain responses. We also ran the data through numerous edit checks to check for unusually large or small quantities."

Table 2-3. Results from the SAIC summary of industrial nonhazardous waste generation (US EPA, 1985)

SIC	Industry	Waste Generated		Year	Notes
		(Dry Mg/Yr)	(%)		
20	Food and kindred products	6.4	1.6	1976	Wet
22	Textiles	>0.05	0.0		Incomplete
24–25	Lumber and wood products; furniture and fixtures	>0.1	0.0		Incomplete
26	Pulp and paper	8.6	2.2	1977	
2812–2819	Inorganic chemicals	26.2	6.7	1979	Wet (assumed)
2819	Organic chemicals	97.4	24.8		Wet (assumed)
2821	Plastics and resins	45.0	11.5	1982	Wet (assumed)
2831–2834	Pharmaceuticals	0.3	0.1	1973	
2841–2842	Soaps; other detergents; polishing, cleaning and sanitation goods	0.03	0.0	1981	Wet (assumed)
2873–2879	Fertilizer and other agricultural chemicals	59.0	15.0		
29	Petroleum refining	1.3	0.3	1981	
30	Rubber and miscellaneous plastic products	0.5	0.1	1975	Wet (assumed)
31	Leather and leather products	0.02	0.0	1975	Incl. hazardous wastes
32	Stone, clay, glass, and concrete products	>18.6	4.7		Incomplete
3312–3321	Primary iron and steel; ferrous foundries	60.7	15.5	1983	Wet (assumed)
3330–3399	Primary non-ferrous metals; non-ferrous foundries	6.6	1.7		
34	Fabricated metal products	0.3	0.1	1983	Incl. hazardous wastes
35	Machinery except electrical	0.2	0.1	1977	Incomplete
36	Electrical machinery and electronic components	0.01	0.0	1975	
37	Transportation equipment	0.5	0.1	1980	
4911	Electric power generation	55.9	14.2	1983	Wet (assumed)
4941	Water treatment	5.0	1.3		
TOTAL		>392.6			

Table 2-4. “Waste quantities disposed of in on-site industrial facilities in 1985” (US EPA, 1988).
 LF = Landfill, SI = Surface Impoundment, LA = Land Application, WP = Waste Pile

SIC	Industry	Waste Disposed		Disposal Facility Type (%)			
		(million Mg)	(%)	LF	SI	LA	WP
20	Food and kindred products	338.8	4.9	1	78.6	20.0	0.1
22	Textile manufacturing	230.2	3.3	0.03	99.7	0.3	< 0.01
26	Pulp and paper	2,042.7	29.6	0.3	99.3	0.4	0.07
2822, 2824, 2851, 2891	Selected chemical and allied products	61.7	0.9	0.2	99.1	0.7	0.01
2865, 2869	Organic chemicals	53.4	0.8	0.4	96.3	3.1	0.08
2812–2819	Inorganic chemicals	834.4	12.1	0.4	95.1	0.01	4.5
2821	Plastics and resins	163.8	2.4	0.05	98.2	0.02	1.7
2873–2879	Fertilizer and agricultural chemicals	150.3	2.2	3.5	93.1	0.5	2.9
29	Petroleum refining	153.0	2.2	0.2	99.6	0.2	0.05
30	Rubber and miscellaneous products	22.0	0.3	2.2	97.4	0.2	0.2
31	Leather and leather products	2.9	0.0	0.3	99.4	0	0.3
32	Stone, clay, glass, and concrete	564.2	8.2	1.2	97.3	< 0.01	1.5
3312–3321	Primary iron and steel	1,179.8	17.1	0.3	99.2	< 0.01	0.5
3331–3399	Primary nonferrous metals	60.8	0.9	2.1	84.3	0.6	13.0
37	Transportation equipment	11.5	0.2	1.4	93.1	< 0.01	4.6
4911	Electric power generation	990.9	14.3	4.9	95.0	0.03	0.08
4941	Water treatment	53.4	0.8	0.3	84.5	15.0	0.1
Total		6,909.3		1.1	96.6	1.3	1.0

The density factors referenced were not included in the report. Finally, although the survey support materials differentiate between solid waste and wastewater, this distinction is not acknowledged in the survey questions themselves.

These concerns notwithstanding, the IFS more or less adequately answered the specific question posed by the EPA: how much was disposed in on-site industrial Subtitle D facilities in 1985? The original research design also included a follow-up survey by mail sent to the facilities determined by the phone survey to manage Subtitle D wastes on-site, which would have contained “more detailed questions about waste management practices” (US EPA, 1987, p. 1-4). This follow-up seems to never have happened. The deadline laid out for completion of the Subtitle D program adequacy report was 36 months after enactment of the HSWA, or November 8, 1987. The results of the Westat phone survey were not completed until December 29, 1987, leaving no time for follow-up research. It took until October 7, 1988 for the EPA to synthesize results from all 21 research programs and submit its final Report to Congress.

Had the interpretation of the IFS results acknowledged the specific question that was being answered, much of today’s confusion around NHIW generation rates may have been avoided. Westat determined the tonnage of matter entering on-site disposal units in 1985. That’s it. They did not assess waste generation rates, nor did they, to be somewhat pedantic, estimate the disposal of “solid waste,” as defined by RCRA or the survey itself. However, in the Report to Congress, the Survey results were used in place of the SAIC results in a table of estimated annual generation rates of Subtitle D waste categories. The authors of the Report favored the Westat results over the SAIC results because “for the industrial nonhazardous waste disposal study [SAIC], waste quantity information was not available for all industries, and the data that were available were often more than five years old” (US EPA, 1988, p. 3-20). They also claimed that the “reasons for [the] large discrepancy [between the two estimates] are being investigated,” but there is no evidence that this investigation took place, or resulted in any follow-up report.

When in 1992, the U.S. Congress Office of Technology Assessment (US OTA) published a background paper on *Managing industrial solid wastes from manufacturing, mining, oil and gas production, and utility coal combustion*, the authors relied heavily on data from the 1988 EPA Report to Congress. The US OTA estimated that, in total, 9.9 billion Mg of Subtitle D (non-hazardous) wastes were generated annually “as of the mid-1980s” (Figure 2-3). The authors excluded approximately one billion tons from the EPA’s manufacturing waste estimate that they claimed represented coal combustion wastes; instead, they used another EPA estimate of 77 million Mg for that waste flow. The difference between these two figures was explained as process wastewater. Why they did not apply the same factor of 7.7% to the rest of the manufacturing wastes that they acknowledge were also mostly “wastewaters with small amounts of solids” is unknown (US OTA, 1992, p. 91). Like the EPA before them, the US OTA buried the nuance of the waste estimate, specifically that it referred primarily to the disposal of process wastewater, not generation of non-hazardous waste, in the body of their report and in footnotes, while continuing to use the

aggregated figure incorrectly in the executive summary. It seems that at this point, the value was too embedded in the discourse to dislodge with mere footnotes.

It is possible that if Subtitle D waste management and resource recovery had been more of a policy priority than they were, the figure would have received the scrutiny it deserved before today. MacBride (2012, p. 93) listed three bills proposed in Congress in 1989 alone that “included provisions to comprehensively gather and publish data on manufacturing-waste generation as well as to set federal standards for disposal of manufacturing waste at the same level of stringency as applied to municipal solid waste disposal.” But none of these became law, and as RCRA and related waste legislation continued to evolve through amendments and reauthorizations in an era of deregulatory fervor, NHIW received less and less of the EPA’s attention. Today, there is some activity around the EPA’s “sustainable materials management” program, but it does not seem to include any efforts to update the 6.9 billion Mg estimate.

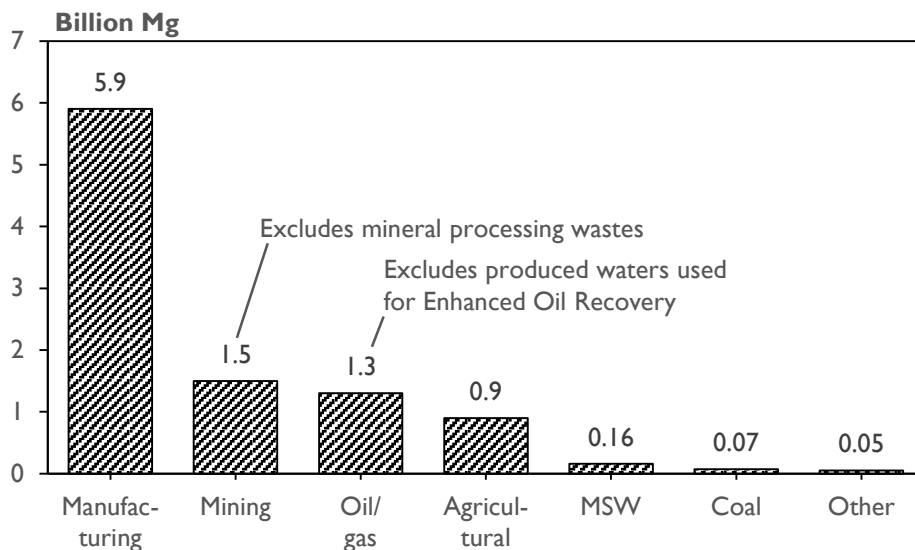


Figure 2-3. “Estimated quantities of Subtitle D wastes, 1985” (US OTA, 1992, p. 10)

2.2.3 State activities

Throughout the history laid out above, states remained essential partners in the development and maintenance of solid waste management programs. A complete discussion of the diversity of these programs would be outside the scope of this investigation, but in terms of state-level characterization of NHIW, there really are only two examples worth mentioning—Minnesota and Pennsylvania—and of those, only Pennsylvania offers any real guidance or insight. The Minnesota case is limited to a single 1987 *Nonhazardous Industrial Waste Report* from the Minnesota Waste

Management Board (MWMB) that collected data on generation and disposal of NHIW in the state. Despite being an expansive and rigorous study, it seems to have never been repeated.

In 1992, Pennsylvania became the first (and to date remains the only) state in the United States to establish regular collection and publication of data on the generation and disposition of non-hazardous industrial wastes. The Pennsylvania Residual Waste Program⁶ (PARW) traces its history to the state's Department of Environmental Resources (DER) first permitting landfills for coal ash, boiler slag, and other industrial wastes in the early 1970s under the Pennsylvania Solid Waste Management Act of 1968, among the first law of its kind nationwide to regulate the disposal of industrial solid wastes (Dernbach, 1993).

Following RCRA, the 1968 state law was replaced by the much more comprehensive Solid Waste Management Act of 1980. In addition to providing the statutory authority for Pennsylvania's hazardous waste regulatory program (approved by the EPA in 1985 in compliance with RCRA Subtitle C), the Act notably distinguished between municipal and industrial nonhazardous wastes (the latter termed "residual waste") and established unique guidance and regulatory frameworks for both categories (Dernbach, 1990). It took more than a decade for the DER (later reorganized as the Department of Environmental Protection, DEP) to develop a set of regulations for residual waste, which were finally promulgated in early 1992. These included performance requirements for different types of residual waste disposal facilities, but the centerpiece of the program was the biennial reporting.⁷

Inspired by RCRA Subtitle C, the PARW program requires any "person or municipality that generates more than an average of 2,200 pounds of residual waste per generating location per month based on generation in the previous year" (25 Pa. Code § 287.51) to report to the DEP the types and quantities of residual wastes generated, disposal location, medium, and source reduction activity (25 Pa. Code § 287.52). The Department developed extensive guidelines to support this reporting activity, including defining a residual waste classification system in nine categories: combustion residues, metallurgical process residues, sludges & scales, chemical wastes, generic

⁶ "Residual waste" is defined in the 1980 statute as "Any garbage, refuse, other discarded material or other waste including solid, liquid, semisolid, or contained gaseous materials resulting from industrial, mining and agricultural operations and any sludge from an industrial, mining or agricultural water supply treatment facility, waste water treatment facility or air pollution control facility, provided that it is not hazardous" (P.L.380, No.97). This term remains specifically relevant to the Pennsylvania regulatory program, but in general is interchangeable with the term non-hazardous industrial waste.

⁷ Credit for these regulations is due in a large part to the efforts of John C. Dernbach, Distinguished Professor of Law at Widener University. From 1987-1992, Dernbach served as Special Assistant to the Director, Bureau of Waste management, Pennsylvania Department of Environmental Resources, during which time he was a primary drafter of regulations for recycling, MSW, and residual waste. From 1992-1993, Dernbach directed the DER Advanced Science and Research Team, and from 2003-2005 returned to serve as the DEP Director of Policy.

manufacturing wastes, special handling wastes, industrial equipment & maintenance waste/scrap, non-coal mining wastes, and miscellaneous wastes (PA DEP, 2014).

The wastes that are subject to the biennial reporting requirement have changed over the years. Most significant to the aggregated account of residual waste generation was the rule change that seems to have taken effect in the 2006 reporting cycle that excluded process wastewaters discharged to a treatment plant or under a Clean Water Act (NPDES) permit. The regulations also support the beneficial use of residual waste. Although materials beneficially used in ways that resemble waste management, such as landfill cover, soil amendment, and energy recovery, are still regulated as waste, if they are “used or reused as ingredients in an industrial process to make a product or employed in a particular function or application as an effective substitute for a commercial product, provided the materials are not being reclaimed,” or have been determined by the DEP to be coproducts, they are exempted from regulatory oversight. Coproduct determinations have been made for coal ash, food waste, mushroom waste, scrap metal, steel slag, and reclaimed asphalt pavement, alongside 75 distinct beneficial use permits.⁸

Raw data from the PARW are available for the most recent three reporting cycles on the program website. Archived data is available from the DEP. A recent analysis of the data from 1992–2008 indicates that generation has been relatively stable in the state, from a low of 12 million Mg in 2004 to a high of 16 million Mg in 1994 (Figure 2-4) (Lyons, Rice & Hu, 2015). The authors argue that the evidence suggests that the “PA DEP NHIW strategies are working and that [industrial symbiosis]-type strategies are taking hold.” In this way, the PARW represents a road not taken for NHIW management in the US. In the early years of the development of PARW, which coincided with vociferous debate in the US Congress about RCRA reauthorization, Dernbach (1990) advocated for national adoption of the PA approach. This would have not only vastly improved the environmental performance of industrial waste disposal facilities nation-wide (for, as it turns out, non-hazardous does not always mean benign), but also created a reliable, repeatable, useful accounting of waste generated with dimensions including quantity, composition, medium, location, and contact information, all that would be necessary for the development of robust beneficial use programs and markets.

⁸ All of this information is available on the PA DEP website for the Residual Waste Program: <http://www.dep.pa.gov/Business/Land/Waste/SolidWaste/Residual/Pages/default.aspx>

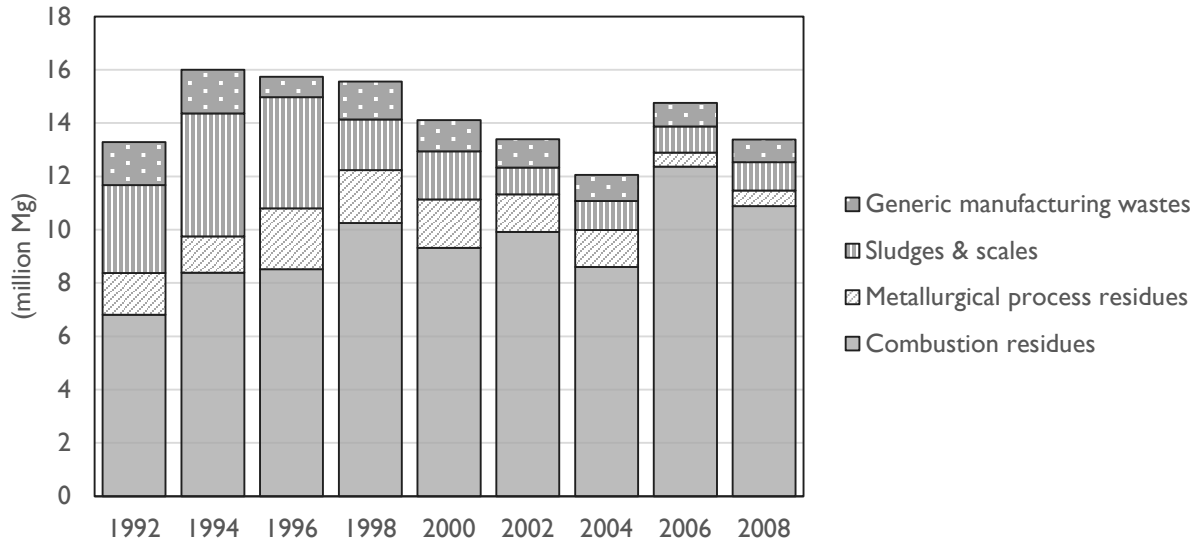


Figure 2-4. Quantity and composition of residual waste (NHIW) generated in PA, 1992–2008, from Lyons, Rice & Hu (2015).

2.3 Summary and waste accounting

In total, the review of the literature yielded a list of seven government and five scholarly estimates of NHIW generation in the US in addition to the official EPA account from the IFS (Table 2-5). The methods used to construct the various estimates have varied over the decades, as have the boundaries of analysis and degrees of certainty. For these reasons, the list of official values is not useful by itself to clarify an estimate with any confidence, nor has the record since 1988 been much better. Despite multiple efforts over the decades employing different methods and data sets, there has not been the accumulation of knowledge one would have expected. Each new estimate was performed in effective isolation from the literature record.

Nevertheless, one thing is clear from the evidence: rather than the SAIC estimate being fatally incomplete and out of date, as the EPA claimed in their *Report to Congress*, it is the IFS that generated an idiosyncratic estimate, departing substantially from any other assessment of NHIW generation before or to come (the exception being the 1992 US OTA revision of that figure). Even though no two extant values agree with each other, the range spanning a factor of five between the first value from 1965 to the material flow-derived 1996 WRI estimate is peanuts compared to the order of magnitude difference with the EPA value. The EPA suggestion that the previous SAIC value was so incomplete as to exclude 16 times more material than it included may have been legitimate at the time, but examining both those values in the context of many more estimates exposes its implausibility.

Table 2-5. Summary of the history of official and academic NHIW estimates in the US, 1965–2002

Year	NHIW estimate <i>(million Mg)</i>	Reference
1965	86	US DHEW (1969)
1967	139	US EPA (1973b)
1971	127	NCMP (1973)
1972	234	Lehman (1976)
1978	301	US EPA (1978)
1984	392	US EPA (1985)
1985	6,900	US EPA (1988)
	235	<i>(land disposed fraction)</i>
1985	5,900	US OTA (1992)
1988	146	Ayres & Ayres (1999)
1990	136	Wernick & Ausubel (1995)
1993	236	Ayres & Ayres (1998)
1996	430	Matthews et al. (2000)
2002	385	Barr et al. (2009)

Far from being merely correct or incorrect, the different estimates of NHIW in the US that have been published over the past half-century can be used to illustrate a simple if overlooked reality, that the value depends on what you are measuring and how you measure it. What, in practice, is NHIW? What activities produce it? What material does it include and exclude? Is it measured at point of generation or point of disposal? Does it include just solid material, or solid material contained in water or air? How is “hazard” defined? Does it include just wastes destined for landfill, or all waste materials, even those that are sold as byproducts? It is essential to clarify these different dimensions of waste accounting, as they influence the result and are intertwined with the accounting methods themselves.

The most straightforward way to track the generation and disposition of a material flow like NHIW would be to physically count it, as if such an undertaking were remotely feasible. Given near-infinite time and effort, each gram of process and other industrial waste would be weighed, characterized, and logged in a database at point of generation and point of disposition (disposal or recovery).⁹

⁹ This data collection scheme is presented with tongue somewhat in cheek regarding NHIW, but it is not unreasonable for certain types of air and water pollutants, where one can imagine the deployment of chemical sensors in smokestacks and sewer pipes to directly measure the flux of these materials. Furthermore, it is not only reasonable but mandatory for detailed characterizations to be performed by raw materials producers who must ensure compositional reliability of their products; any eco-industrial transformation that relies on waste as raw materials must ensure similar reliability of the composition of secondary materials flows.

A marginally more feasible alternative to this waste panopticon is that which is employed in the RCRA hazardous waste program: cradle-to-grave self-reporting. In such a system, generators, transporters, and final disposers of certain types of hazardous wastes must report quantities and categories of waste produced, handled, and disposed (along with disposal method) to the EPA. Japan implemented a similar system for hazardous waste oversight and management in 1993 and expanded it to include all industrial wastes in 1997 (Hamada et al., 2011). Taiwan also has a similar reporting scheme in place (Chen & Ma, 2015).

Like the PARW program, these national-scale schemes are examples of direct—as opposed to indirect—approaches to waste accounting. Direct accounting involves “sampling, sorting, and weighing the individual components of the waste stream” (US EPA, n.d.). It is a bottom-up technique that either observes the entire waste flow (as in the case of the PARW) or uses statistical methods to extrapolate from a representative sample (as in the case of waste auditing). The EPA discusses potential drawbacks of direct accounting methods in their MSW characterization methodology report (US EPA, n.d., p. 6):

“A disadvantage of sampling studies based on a limited number of samples is that they may be skewed and misleading if, for example, atypical circumstances were experienced during the sampling. These circumstances could include an unusually wet or dry season, delivery of some unusual wastes during the sampling period, or errors in the sampling methodology. Any errors of this kind will be greatly magnified when a limited number of samples are taken to represent a community’s entire waste stream for a year. Magnification of errors could be even more serious if a limited number of samples was relied upon for making the national estimates of MSW. Also, extensive sampling would be prohibitively expensive for making the national estimates. An additional disadvantage of sampling studies is that they do not provide information about trends unless performed in a consistent manner over a long period of time.

Of course, at the state or local level, sampling may not be necessary—many states and localities count all materials recovered for recycling, and many weigh all wastes being disposed to generate state or local recycling rates from the “ground up.” To use these figures at the national level would require all states to perform these studies, and perform them in a consistent manner conducive to developing a national summary, which so far has not been practical.”

Many of these same concerns are relevant to NHIW accounting. Westat utilized a very rigorous sampling technique in constructing their estimate for the EPA, but it took a year to complete (not to mention the fact that it resulted in a value which has derailed our understanding of NHIW in the US for three decades). And not only do all states not have comprehensive studies of industrial waste generation and disposal, even the one that does has changed their methodology over time to limit comparability to itself.

Indirect methods for waste accounting encompass every other estimation method, including material flow analysis, industrial metabolism modeling, waste intensity calculation and

extrapolation, and consultation with experts. The EPA uses a material flow method in their annual official MSW accounting in part due to what they conclude are the insufficiencies of alternatives but also in part because a consistent methodology over multiple decades enables that longitudinal comparability that is important for tracking environmental indicators over time. The EPA also claims that it adjusts materials flow results with data from waste sampling studies.

MSW provides a clear example of the influence that accounting methodology, along with embedded assumptions and dimensions, can have on the accounting result. The EPA's official estimate of MSW generation in 2011 was 227 million Mg (US EPA, 2011). This, as mentioned above, was derived from a sophisticated materials flow model that takes into account "production data (by weight) for the materials and products in the waste stream," adjusting for imports, exports, and product lifetimes (US EPA, n.d.).

Contrasting with the EPA's indirect estimation method is the direct method used in the (roughly) biennial State of Garbage in American study, conducted by *BioCycle Magazine* from 1989–2010 and by the Columbia University Earth Engineering Center (EEC) from 2004–2014. In this research, surveys are sent to "the solid waste management departments in all 50 states and the District of Columbia" inquiring about waste management volumes in those jurisdictions (van Haaren, Themelis & Goldstein, 2010). The most recent survey found that MSW generated in the US totaled 353 million Mg in the year 2011 (Shin, 2014). The difference between the EPA and EEC values has never been definitely explained, but appears to be due almost entirely to the landfill-bound waste tonnage. The EPA estimated that 120 million Mg of MSW was sent to landfill while the EEC estimated 224 million Mg, a full 100 million Mg more.

In her Master's thesis, which was the 2011 State of Garbage in America survey, Dolly Shin speculated on possible reasons for the discrepancy between the EPA and EEC values, including the latter's possible inclusion of non-MSW Subtitle D wastes disposed of at state-regulated landfills and the moisture content of waste. The EEC estimate was further validated by Powell, Townsend & Zimmerman (2015), who very cleverly used data reported to the EPA by landfills subject to the US Greenhouse Gas Reporting Rule to estimate total MSW disposed therein in the year 2012. Their result, 262 million Mg, reflects the same discrepancy with the EPA MSW data as the EEC has.

My work does not address MSW or this specific (but juicy) data gap, but this example does illustrate the effect that accounting method can have on waste estimate. It also points to a phenomenon also seen in the SAIC and IFS results, that measurement at point of disposal yields a larger number than measurement at point of generation. Both SAIC and the EPA's MSW model are effectively point-of-generation observations. SAIC compiled data on waste generation and the EPA's model uses data on production to estimate volumes of materials and products entering the waste stream each year. On the other hand, the IFS and EEC studies interrogated disposal volumes. This is not a rigorous conclusion, as there are many reasons to believe that the two sets of

observations in fact are measuring different things, e.g. waste other than MSW or NHIW and water weight. But in some respects those explanations are irrelevant to the policy context that uses the results of materials accounts in decision making. The near-immediate misinterpretation of NHIW on-site disposal from the IFS as total NHIW generation by the EPA and OTA bears this point out—there is no capacity for nuance in the public understanding of solid waste quantities, and it is incumbent on the accountant to conduct the work as transparently and honestly as possible.

Different waste accounting methods have different degrees of policy relevance, depending on the policy objective. If the goal is to minimize the environmental risk from landfill or other land-based disposal, then the IFS and EEC values are more useful, as they measure the actual tonnage of matter entering the waste management site. At that point, whether or not all of that material was generated by industry becomes irrelevant. But if the objective is to identify the potential for or effectiveness of an industrial pollution prevention or resource recovery scheme, then disposal-based observations can obscure the story. Furthermore, the EEC survey works only because most states already have data collection schemes in support of some other policy goals that the analysts can tap for their own objectives. Direct observation of NHIW at a national scale can be done, as Westat demonstrated, but only with great effort and cost, limiting its repeatability and therefore policy effectiveness. It is possible that having a single, empirical estimate of NHIW disposal from 1985 and no follow-up was actually worse for our understanding of the world of waste than had that study never occurred and we had to rely on indirect estimates that changed from year to year.

While establishing a reliable cradle-to-grave reporting and verification regime for NHIW in the United States is not outside the realm of possibility, as models exist in Japan, Korea, Pennsylvania, and parts of Europe, direct accounting is not feasible at this time. Therefore, inference and indirect observation must be utilized to construct the robust materials accounts necessary for the deployment of effective sustainable materials management strategies.

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3 Methods & Data

This chapter presents A) the methodology developed to answer the research questions posed in this dissertation and B) descriptions of key data sources. The research is a mixed-method, case-study application of general material flow analysis and industrial/socio-economic metabolism principles. The level of analysis is defined at individual industry sectors in the United States for the year 2010, as defined by the North American Industrial Classification System (NAICS). Lacking validated theories about the specific socio-metabolic relationships and drivers of NHIW, generation rates are estimated here using three methods, each relying on independent data sources with independent errors, cross corroborating one another in triangulation. The three methods are: forecasting historical empirical data, constructing industrial materials balance models, and spatial up-scaling of data from the state of Pennsylvania. Results from these estimates are used to triangulate an estimate of contemporary quantity and composition of NHIW at the industry sector level.

3.1 Introduction

The answer to the primary research question of this dissertation—how much non-hazardous industrial waste is generated in the United States?—is to be found via the systematic collection, classification, and analysis of stocks and flows of waste materials, otherwise known as waste accounting. As discussed in Chapter 2, the only accounting paths practically available for this particular material flow in the US involve indirect estimation models and methods.

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” (Leonard, 2010). 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 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 that is one of the original motivators of this dissertation relies in part on figures extrapolated from empirical work performed sometimes a decade earlier (US EPA, 1985). Such models use simple ratios of waste output to industrial production (in mass terms) 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 (1993; 1994; 1998; 1999) leveraged their trademark industrial metabolism approach to estimate NHIW using public records of industrial production and consumption. 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, Barr et al. (2009) demonstrated the feasibility of using sub-national data, specifically the reports from the Pennsylvania Residual Waste program, to estimate national NHIW generation patterns. As in the extrapolations that enabled SAIC (and others) to forecast contemporary figures from historical data, Barr et al. calculated waste intensity factors at the industry sector and scaled them up using the ratio of national to state industrial production (in economic terms).

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, I employ a meta-method in which multiple estimates of the same value 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.

3.1.1 Units

This research is conducted in standard SI units. Many US industry and government agencies publish their data in US customary units, necessitating unit conversion. The vast majority of the data utilized in this work are measured in large mass units, which confusingly are known as “tons” in both systems. Metric tons (sometimes spelled “tonnes”) are equivalent to 10^6 g, or 1 Mg. The unit “ton” has the symbol “t,” but to distinguish metric tons from US customary tons, some

authors use the abbreviation “Mt.” This can itself cause more confusion, as Mt is also the SI unit for a “megaton,” or 10^6 tons. Ayres sometimes uses the abbreviation “MMT” to refer to “million metric tons,” but this is not a standard approach. I have chosen to use the slightly unusual but, I feel, highly precise unit of the megagram, Mg, which is equivalent to the metric ton while avoiding unit confusion. As it turns out, many of the mass flows at the scale of the US economy are measured in the thousands or millions of Mg; occasionally I will use other SI prefixes (Gg = thousand Mg = 10^9 g, Tg = million Mg = 10^{12} g), but in an attempt to maximize clarity, I attempt use Mg except in cases where space is limited (such as tables or figures).

In US-based publications, the use of the term “ton” refers almost exclusively to the “short ton,” equivalent to 2,000 pounds, rather than the more obscure “long ton,” which equals 2,240 pounds (and is found in some historical documents). The conversion is 1 Mg = 0.907 short tons. It is sometimes unclear which ton unit (US or SI) is being used in a document or report. In this case, context clues and corroborative evidence can be sought to distinguish the two. A 10% difference is significant, which both makes it possible and crucially important to diagnose.

With apologies to Gertrude Stein, a ton is not always a ton. That is, the relevant second question (after “how much?”) should be “of what?”. The very discrepancy upon which this research project is based arose in part because that second question was not asked: specifically, SAIC attempted to measure dry waste, while the industrial facilities survey measured wet waste. The inclusion or exclusion of water can lead to vast differences in the result of a study, even if both are measured in tons. There are really three main categories of “wetness” relevant to this context. Dry waste refers either to the mass of the non-water content of a wet waste or to the mass of an already dry waste. The former definition is explained thusly: if you were interested in the potential to use sewage as fertilizer, it is important to know not the total tonnage (or volume) of wastewater that enters the treatment plant, but the total mass of solid material that is theoretically recoverable. The second definition is used if, say, you were to throw out a full bottle of water. In reality, the total mass is almost completely water, but the waste is treated as solid by the handling system.

Wet waste, or more specifically wet-basis mass units, refers to sludgy materials, which have a substantial composition of both solid materials and water. This is a traditional medium of industrial waste, as many wastes were flushed through the factory in process water. Reporting the total tonnage of wet waste can be misleading, as it overinflates the tonnage of the waste material by the included mass of water. Wet-basis mass can be converted to dry-basis mass using a documented figure on water composition of the sludge.

The third category of waste wetness is really only used in the industrial facilities survey, and should not really exist. For some reason, the EPA decided to report data about the discharge of wastewater into on-site surface impoundments in mass, rather than volumetric, terms.

3.2 Estimation methods

The selection of the specific estimation methods used in this research followed a screening study, in which methods were systematically identified and evaluated under a set of criteria, including, essentially, the availability of data.

3.2.1 Screening

Building on the two principles introduced above, the task of indirectly estimating NHIW at the national scale can be done using models from one of two general categories: industrial metabolism,¹⁰ based on the relationship between NHIW and observed industrial economic information; and material flow analysis, based on the relationship between NHIW and other observed material flows. In addition, it is possible, and arguably more common (at least in environmental engineering textbooks), to arrive at an estimate based on literature review and/or interviews, which while potentially illuminating, do not claim the methodological rigor required for the construction of a robust materials account.

Specific estimation methods follow from these general categories. Industrial metabolism-based methods are differentiated from one another by the dimension through which the data source is abstracted from the target, to wit, by time or by space. Time-variant methods use data generated in the past or future, holding all else equal; space-variant methods use data generated in a different jurisdiction (enclosing, like a nation to a state; constituent, like a state to a nation; or independent, like two separate nations), holding all else equal. Reviewing available data, the only time-variant method that is possible is historical forecasting, in which NHIW data that was generated at a national scale but in a past time are forecasted to the present. Two space-variant methods were identified: up-scaling from the state level and cross-scaling from other countries.

Material flow-based methods are less differentiable, but nevertheless two approaches have been identified within this category: materials balance and life cycle inventory analysis. Materials balance methods rely on data reported at the same scale as the target information, i.e. at the national industry scale. Life cycle inventories, on the other hand, are normalized to unit processes, which have been generally assembled from a variety of literature and other sources. Use of these data to estimate large-scale material flows therefore requires the use of physical scaling factors.

To distinguish among these methodological approaches, I considered a broad set of criteria. Ultimately, after considering the priorities and constraints of the project, I arrived at a list of seven,

¹⁰ Ayres and other industrial metabolism scholars often do not separate the material flow principle from the economic endogeneity principle, for they both are essential for understanding the metabolism of an industrial system. I distinguish between the two here because of the increased analytical power provided by considering each principle, at least initially, in isolation.

which are: time and cost efficiency; repeatability from year to year; if the data contains information on waste quantity; if the data contains information on waste composition or category; if the system boundary is or can be adjusted to the US; if the method relies on a dedicated data set; and if raw data is available. The criteria of efficiency, repeatability and waste data quality come from the objectives of the project, the former two about the modeling process and the latter about the outcomes. The remaining criteria have to do with the constraints of material flow estimation. It is important to be able to define the system boundary for the waste account; it is even better if the boundary can be adjusted so as to harmonize the results of multiple estimation methods. The error inherent to estimation techniques can be lessened through triangulation only if the error from the different methods is independent; this constraint demands that each method uses a distinct data set so that both data error and model error are unique to each estimate. Having access to underlying raw data can help with this constraint and that of system boundary adjustability.

Both historical forecasting and spatial up-scaling successfully pass each criterion. The models are efficient, in that the data are generated externally to the modeling process, the effort of which is trivial. They are repeatable, with the result from year to year reflecting that year's changes: historical forecasting uses a constant source waste data set that is transformed using some driver variable that changes year to year. Up-scaling uses new waste data each year as well as new scaling factors. Candidate raw data has information about quantity and composition: the 1985 SAIC study (at a minimum) for forecasting and the Pennsylvania Residual Waste database for up-scaling. Both data represent clear industry system boundaries within the United States. Both data sets are independent and unique to those methods. And the raw data is available for both; the state-level data is actually available in spreadsheet form, while the historical data is tabulated in the report.

The other methods are less clearly excellent candidates. International comparison seems promising, given the fact that the scaling method is very similar to up-scaling from state-level data. As many other countries have active waste data collection programs, both quantity and, at times, composition are available, sometimes at a very high level of detail (although I have not been able to find any sources for raw data, at least in English). The main drawback of this method is the system boundary inconsistency between source and target. International industrial classification systems are different from that used in the United States. Without access to raw data, it is unclear how the two systems would be rationalized to best accommodate any changes in NHIW generation.

Materials balance does not have the system boundary problem as such, as different activities can be included or excluded by design. It has all of the same methodological strengths: efficiency, repeatability, and relies on a unique data set; but the aggregate nature of the data prevents any discussion of waste composition.

Life cycle inventory analysis can provide great detail about waste quantity and composition, but as the data originated from a wide range of literature sources, harmonizing system boundaries

can prove challenging. Furthermore, it is possible that the data used to construct published unit process inventories is also used in other methods.

The results of the screening study are presented in Table 3-1. Based on this evaluation, I have selected three methods for triangulation: historical forecasting, materials balance, and spatial up-scaling. Details of each of these methods and key data sources are presented below. Each method is designed to be applied to a single industrial sector at a time with the goal of estimating NHIW generation for the year 2010. Justifications for this research scope are provided in Section 3.4. The balance of this section introduces the three specific estimation methods deployed in this thesis, including strengths and weaknesses of each and descriptions of key data sources.

Table 3-1. Screening study of NHIW estimation method types

	Efficient	Repeatable	Waste quantity	Waste composition	System boundary	Dedicated data set	Raw data
Historical forecasting	✓	✓	✓	✓	✓	✓	✓
Spatial up-scaling	✓	✓	✓	✓	✓	✓	✓
International comparison	✓	✓	✓	✓/?		✓	
Materials balance	✓	✓	✓		✓	✓	
Life cycle inventory analysis	✓	✓	✓	✓			✓
Interview/literature review			✓	?			

3.2.2 Historical forecasting

At first glance, an overreliance on historical data seems to be the practice that got us into this mess in the first place. After all, it is the continued invocation in the present tense of what is known to be a thirty-year-old NHIW figure (“Each year, approximately 7.6 billion tons [6.9 billion Mg] of industrial solid waste are generated and disposed of at a broad spectrum of American industrial facilities” (US EPA, 2016)) even in the face of subsequent correction and caution that has led to a deep-seated misunderstanding of waste patterns in the US. Nevertheless, when done correctly (i.e., not by acknowledging the provenance of the data but then doing nothing about it), historical forecasting can be a powerful way of extending the applicability of a single observation across many subsequent years.

3.2.2.1 Background

SAIC relied exclusively on historical data in their report on “industrial non-hazardous waste disposal practices” (US EPA, 1985). In some cases, the authors simply reported the data and the year of its collection; in others they forecasted the figures to 1985 by calculating the ratio of waste generation to industrial production in the year of data collection and multiplying that by the industrial production values in 1985.

Similar forecasting methods were used in earlier studies, including some referenced by SAIC. For example, in 1980, the contractor ERCO estimated wood pulping wastes for the year 1978 by extrapolating from “1971 figures based on growth in pulp production” (US EPA, 1980, p. 3-30). As it happens, those 1971 numbers were originally published in a 1974 study by Gorham International (yet another contractor), in which the authors employed a detailed analysis of expected changes to market size and structure, technology, and the regulatory environment to forecast waste generation through the year 1980 (US EPA, 1974). The results from this forecast are approximately 2.5 times that of the extrapolation done by ERCO, highlighting the fraught nature of prediction. It is unclear how much of Gorham’s overestimate was due to an error in the forecasted industrial growth rate versus an error in the forecasted effects of technology, market, and regulatory change on waste production.

3.2.2.2 Method

Irrespective of the fundamental challenges present in forecasting or extrapolation and the varying degrees of complexity in how researchers choose to address them, the same basic model is employed both in past studies and this research:

$$W_n = p_n \sum_i a_{i,n} \frac{w_{i,o}}{p_o}$$

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 , $w_{i,o}$ is the amount of waste type i generated by the industry in the base year, p_o is the production of the industry in the base year, and $a_{i,n}$ is the factor by which the waste intensity changes as a result of exogenous forces (e.g. technology improvements). The ratio w/p is also known as the *waste intensity*.

The factor a_i is defined at the waste type level because different dynamics and exogenous forces affect different waste streams. The contributors to the factor a_i can vary from study to study; ERCO assumed no change from year to year ($a = 1$), while Gorham included a wide range of economic, technological, and regulatory factors. The challenge of quantifying a_i should not be overstated. In a data-scarce environment it is difficult enough to identify relevant factors much less calculate their influence on waste intensity. In the context of triangulation, I have decided to

forego quantifying a , instead suggesting qualitative, directional influences of three classes of driving factors: market structure and size, technology, and regulatory environment.

It is not strictly necessary to use the summation; as the case studies will demonstrate it is often more useful to examine the waste account in a more disaggregated form.

Past research has defined the term p as the physical production of the industry; this suggests that those studies assumed that NHIW scales with physical production of a given industry better than it does with other indicators of industrial activity like economic output or employment. Given the fact that most industrial wastes are in the form of production residuals, this seems to be a sound assumption, and is one that I make as well. I was unable to identify any literature sources that necessarily bear it out, though.

With the model thus formalized and defined, a procedure can be laid out for the study of a single industry sector at the national-scale:

1. Identify the most recent reliable data on NHIW generation; this defines the base year.
The data collected by SAIC in US EPA (1985) provides a backstop, and should be considered an option of last resort. Not only does this study rely heavily on data collected (or modeled) in the 1970s, for many sectors it is incomplete. The longer the time between original data generation and the target year, the much greater the effect of a_i will likely be, making the results of a forecast where a_i is defined qualitatively that much less accurate. If more than one historical data set is available, all should be considered. In fact, comparing forecasts whose base years are more than a few years apart can help to clarify the directionality (if not the magnitude) of the components of a_i . Care should be taken to understand the provenance of any data and precisely what it represents and includes.
2. Collect data on industrial production for the base year and the analysis year (2010).
If possible, this data should reflect the physical production of the industry. Lacking this, revenues or sales measured in constant dollars (i.e. adjusted for inflation) can suffice.
3. Tabulate the qualitative effects of key trends in market structure, technology, and regulation on NHIW generation.
This is the most open-ended step of this method. A broad literature review is likely necessary to collect a complete set of drivers in the three categories. Market structure includes things like product mix and diversity, factory size distribution, degree of consolidation, and mechanization; technology includes raw material mix, production technologies, and environmental control technologies; regulatory environment includes constraints on air, water, and land pollution. These three categories are highly interrelated, so a particular factor may fall into more than one. In many cases, identifying the directional effect of each factor on NHIW generation is itself a small—or not so small—research effort. In cases where the literature is not forthcoming, logical arguments for the directional effect of a particular factor should be

proposed; it is not unreasonable to find arguments for both positive and negative forcings of the same driving factor.

4. Extrapolate NHIW from the base year to the analysis year using the industrial production data and the model above.

The extrapolation should occur at the lowest degree of aggregation, offering the greatest freedom in applying the driving factors. Results can be presented as either over- or under-estimates, depending on the directionality of a_i .

3.2.2.3 Data

As mentioned above, US EPA (1985) offers at a minimum a single (if ancient) waste estimate. In fact, that single reference points to more than one data source for most of the 22 industry sectors it covers, including the Industry Studies Data Base (ISDB), the Pollution Abatement Costs and Expenditures (PACE) surveys, and a broad selection of EPA- and industry-sponsored studies throughout the 1970s and early 1980s.

The ISDB is a compilation of “process-specific information on waste composition, generation rates, and disposal practices” for 16 industries maintained by the EPA starting in 1982 (US EPA, 1985, p. 3-34; 1996a). Sources of information include questionnaires issued under EPA’s inspection authority pursuant to RCRA §3007, “plant visit reports, sampling and analysis reports, and engineering analysis” (US EPA, 1996a, p. 4-4). The database was compiled by SAIC and housed within the EPA’s Office of Solid Waste. SAIC made extensive use of the ISDB in their 1985 report, specifically in the sections on fertilizers and agricultural chemicals, industrial organic chemicals, and plastics and resins manufacturing. Subsequent references to the database can be found in various EPA publications and *Federal Register* notices, though with little added detail. I was unable to find any references to the ISDB after 1996.

PACE was “the only comprehensive source of pollution abatement costs and expenditures related to environmental protection in the manufacturing sector of the United States” (Gallaher, Morgan & Shadbegian, 2008, 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 (US CB, 1984). The physical data were reported by discharge medium for each industry sector; no other details about waste composition were included. The most recent incarnation of PACE (2005) seems to have collected physical data on NHIW generation from survey respondents, but this data set is not part of the report (US CB, 2008). If it were made available, it would likely prove useful to the estimation of contemporary NHIW generation patterns.

Other references used by SAIC included industry-specific studies conducted by the EPA in the years leading up to the report, studies conducted by industry associations, published scholarly literature, and interviews with experts. These same sources, or their contemporary equivalents, are still available for the historical forecasting method described here.

The process of identifying suitable data is necessarily vague. Like the SAIC analysts who compiled the original list, one must cast a wide net, starting with most likely government sources like the EPA, Department of Energy, Department of the Interior, and Census Bureau, and publications of industry trade associations. A good launching off point is the EPA's Industry Sector Notebook project, which point to useful data sources through the mid-1990s. In some cases, an Internet search engine is your best friend; in other cases, turn to your librarian. Both were invaluable in my own research.

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, as evidenced by the sloppy transformation of the responses to the query on on-site waste disposal into an account of waste generation. 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 ISDB), as opposed to a single total waste number (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.

Data on industrial production are 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 Census Bureau-produced *Annual Survey of Manufactures* and *Economic Census* reports include information on production and sales, sometimes in physical units.

As mentioned above, sources for information on changes to the waste intensity as a function of market structure, technology, and regulatory environment can be found through literature search.

3.2.2.4 Discussion

As the first of the three estimation methods, historical forecasting 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 more of 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 bearing out those changes. The disappearance of NHIW from the policy agenda (along with many of the data collection programs that fell victim to the deregulatory wave of the early 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.

The historical forecasting model is built on a convincing model of industrial metabolism, where NHIW-as-process-residual is tightly coupled with industrial production, as measured in physical units. The broad set of drivers identified as influencing waste intensity provides ample flexibility to consider numerous types of changes, while the context of triangulation in which the forecasting is being done removes the need to calculate specific, quantitative factors. On the other hand, the open-endedness of the method does create great room for error, specifically in regards to overlooked factors. For example, despite the above paean to historical industrial system boundaries, the reality is that today's industries do 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 in fact be well off the mark.

3.2.3 Materials balance

A materials balance is the most elegant and abstract of the three methods employed here. At its core is a single physical law—that 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.

3.2.3.1 Background

The materials balance approach for calculating industrial pollution is inextricably tied with the scholarship and legacy of Robert Ayres. In 1970, he published with his then Resources for the

Future (RFF) colleagues Allen Kneese and Ralph d'Arge *Economics and the Environment: A Materials Balance Approach*, which expanded on an article published the previous year on the flows of materials, including wastes and industrial residuals (in gas, liquid, and solid form), in an economy, stating, “we find it useful initially to view environmental pollution and its control as a materials balance problem for the entire economy. The inputs to the system are fuels, foods, and raw materials which are partly converted into final goods and partly become waste residuals” (Ayres & Kneese, 1969, p. 284).¹¹ The diagram of materials flows in the economy that accompanied that article (and reproduced only marginally less crudely in the 1970 book) would eventually become the highly refined industrial metabolism model and operationalized materials balance approach for characterizing a wide variety of aspects about the material flows and environmental impacts of industrial activity (Ayres et al., 1989; Ayres, 1994).

Ayres oriented his prolificacy towards the NHIW accounting problem repeatedly throughout the 1990s. Faced with the inconsistency between the two published EPA NHIW figures, Ayres & Ayres¹² crafted materials balance models for most of the waste-generating industries in the US economy for the year 1988 (1993; 1994). This approach, which synthesizes published production and consumption data, process information, and models of material transformation processes, was framed as an “indirect” alternative to the conventional bottom-up (or survey-based) approach to waste accounting. Unlike the bottom-up approaches, materials balance was shown to be able to distinguish well between wet and dry wastes, account for wastes from “non-point sources,” and be efficiently repeated on a routine basis. The analysis for the year 1988 was vastly improved in a 1999 publication by the same authors. One year prior, Ayres & Ayres released *Accounting for Resources, 1: Economy-wide Applications of Mass-Balance Principles to Materials and Waste* (1998), an extraordinary expansion and refinement of the method and application to the year 1993.¹³

Back in the 1970s, Ayres’s RFF colleagues had continued the research into the dynamics, drivers, and economics of industrial residuals. While Ayres’s industrial metabolism research often

¹¹ Nearly an identical quote can be found in Kneese, Ayres & d'Arge (1970), p. 7. In the 1969 article (footnote 9), Ayres & Kneese acknowledge but a few esoteric antecedents to their approach: an unpublished 1967 draft of a Northwestern University doctoral dissertation by an F. Smith, an unpublished manuscript suggesting a “pollution matrix,” and an earlier ecological application by Ayres. The only antecedent that has withstood any test of time is Kenneth Boulding’s “spaceship economy” concept, also acknowledged by Fischer-Kowalski (1998) in her “intellectual history of materials flow analysis.” For more reading on the history of this concept from the industrial ecology perspective, see Fischer-Kowalski’s full two-part article (1998; Fischer-Kowalski & Hüttler, 1998) and/or subsequent book chapter on the same subject (2002). For the history from the economics perspective, see Pethig (2003). Both pay equal homage to Ayres & Kneese’s seminal contribution.

¹² The second Ayres in many of the references is Leslie W. Ayres, Robert’s wife and frequent collaborator.

¹³ Although the revised 1988-basis study was published one year after the 1993-basis study, it was actually written four years earlier, the product of a 1994 National Academy of Engineering workshop. It seems to simply have taken NAE a long time to publish the volume.

tended towards the aggregate, RFF's industrial residuals research program went the other direction, involving great detail at the individual plant level (Bower, 1975). This research program ultimately produced a large number of studies, including applications of the methodological approach to, among others, the same three industry sectors covered in this dissertation: pulp and paper, iron and steel, and petroleum refining (Kneese & Bower, 1979).

The breadth of scholarship that has built on Ayres's materials balance insight is staggering; few other thinkers in history can be credited with having generated the intellectual foundation of what would become a distinct field of study, in his case, industrial ecology. But the specific application of materials balance to waste estimation has remained largely the domain of the Ayreses alone, until now.

3.2.3.2 Method

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 (1998) have done this work; 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 ($\text{waste} = \text{in} - \text{out}$) 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.

3.2.3.3 *Data*

As explained by Ayres & Ayres (1998), 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.

Relevant U.S. data is published by multiple agencies. Agriculture data, including forestry, is published by the U.S. Department of Agriculture and U.S. Forest Service. Data on minerals and metals is handled by the U.S. 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 U.S., useful data about the U.S. can be found via 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.

3.2.3.4 *Discussion*

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—while extraordinary that it is even possible, and credit is due to the data analysts and statisticians who make it possible—facilitates 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” (1994, 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 or more 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 I have defined that physical law eschews 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.

3.2.4 Spatial scale-up

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.

3.2.4.1 Background

Up-scaling is a standard practice in any survey method. Any time a sample is used to infer information about a population, scaling methods are employed. No extant estimate of NHIW that is based on a direct observation method successfully covered every single facility that generated waste. The EPA Industrial Subtitle D Facilities Survey, the study out of which came the 6.9 billion Mg figure for NHIW, was in fact a phone survey of 18,051 unique facilities out of a total 149,151 establishments that were identified as belonging to one of the 17 industry sectors of interest in that study (US EPA, 1987). The results from the survey were scaled up based on the ratio of the number of sampled facilities to the total number of facilities in the population within each industry. The past use of the ISDB to estimate NHIW as described above also represents a scale-up procedure, using the ratio of production volume of facilities represented in ISDB to national production volume, again at the industry level (US EPA, 1985).

In both of these cases, care was taken to ensure representativeness of the sample to the population. In the first case, the analysts stratified the sample by size (represented by number of employees); it is not clear how SAIC (who originally compiled the ISDB) managed it, but they did “[assume] that waste generation rates are proportional to production rates and that the ISDB ... facilities are representative of the overall industry” (US EPA, 1985).

The spatial up-scaling method used here is a refinement of one developed by Barr et al. (2009). 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]” (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 Mg 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” (p. 21).

3.2.4.2 Method

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:

$$W_{US} = \frac{r_{US}}{r_{PA}} \times \sum_i w_{i,PA}$$

Up-scaling resembles historical forecasting in that empirical data observed in a particular analytical frame are transformed to another by some ratio of activity in the latter to activity in the former. The major difference is that the up-scaling method lacks the change factor, inasmuch as we assume, like Barr et al. did, that the industrial activity and waste generation rates in Pennsylvania are both representative of national-scale conditions. With this assumption in hand, we proceed through the following steps:

1. Select and clean raw PARW data

As will be discussed below, the PARW database is a messy one. Facilities that report in years n and $n+2$ may not report in year $n+1$. Even if they do report in multiple subsequent periods, the categories and amounts of wastes reported vary wildly. And there are inconsistencies in simple things like self-reported industry classification code. Although the guidelines for reporting are very clear, there does not seem to be much state oversight of the program, and the minimum penalties for mis- or non-reporting are merely \$300 (25 Pa. Code § 287.413(e)).¹⁴ Through my interaction with the database, I came up with a procedure for cleaning the data:

- a) Filter the database by desired industry code (either SIC or NAICS, depending on year of report). Check for facilities reporting under a higher aggregation level—these should be included after checking whether or not the facility is in the particular industry segment of interest (an Internet search works well here, as do EPA or Census Bureau sources).

¹⁴ As per 25 Pa. Code § 287.412(c), “each day of continuing violation shall be considered a separate violation,” so if a reporter truly did not report in a given biennial period, the PA Department of Environmental Protection could theoretically sue for two years or more of missed reports. But I doubt the DEP would expend its limited resources on such a course of action.

- b) Isolate the unique reporter ID numbers from the list created in step (a). Filter the database by this list. This step captures data reported by facilities of interest under incorrect classification codes (a common occurrence in the database resulting from simple transposition or single digit errors).
- c) Examine frequency of reporting by each facility. This provides a general sense of the year-to-year reliability of the data.
- d) Correct for missing or mis-entered data. Isolate time series of reported data by facility and medium (not by waste type—the reality is that from year to year, facilities report the same waste under different waste codes). When data changes by an excessive amount (around an order of magnitude or more) or is missing, interpolate using reported waste generation from the surrounding years.

After this cleaning process, the database can be examined for waste generation per industry sector by reporting period, waste code, medium of discharge, and generator. The biennial report data contains a great deal more information than just these dimensions, but they are not used here.

2. Qualitatively characterize the state industry vis-à-vis the national industry

Although I have selected to withhold a change factor from this method, it nonetheless behooves the analyst to know as much as possible about the representativeness of sample data when using it to estimate characteristics of a population. The goal is less to identify the type of directional insights that we were going for with the forecasting analysis, and more to just better understand the idiosyncrasies of the state industry as it relates to its national counterpart.

3. Identify scaling factors

Candidates for scaling factors must fulfill two criteria: 1) they must be available for the industry at both state and national levels; and 2) they must have a defensible metabolic relationship with NHIW generation.

In its *Annual Survey of Manufactures* (ASM) and semi-decadal *Economic Census* (EC), the U.S. Census Bureau publishes data on employees, value of shipments, value added, and numerous other indicators at state and national levels for all industries. It is unknown if one of these measures of industry size is a better proxy for waste output than the others; industrial metabolism suggests that physical output from the industries would be preferable, but that information is often not available at the state level, hampering its utility as a scaling factor. Industrial employment seems a reasonable proxy as it is immune to short-term variability of market prices, except that the global trend in manufacturing has been towards mechanization, leading to a secular increase in industrial labor productivity (Holman, Joyeux & Kask, 2008). The other two indicators are closely related. Value of shipments is the revenue received from sales. Value added is the value of shipments minus the “cost of materials, supplies, containers, fuel, purchased electricity, and contract work” (ASM). Indirect relationships between waste

production and both financial indicators can be proposed. Value of shipments is tied directly to factory output (and market prices for products), although “value added is considered to be the best value measure available for comparing the relative economic importance of manufacturing among industries and geographic areas” (ASM). All three scaling factors, each telling a unique story about the relationship between Pennsylvania and the country, are used here.

To maximize the robustness of the estimation method, scaling factors are calculated for all industry subsectors, if relevant to the case at hand. State and national data on employees, value added, and shipment value at the subsectoral level (5- and 6-digit NAICS code level) are available annually until 1997 and semi-decadally thereafter.¹⁵ To estimate scaling factors at the subsectoral level for the even PARW reporting years after 1997 that do not coincide with the publication of an EC, data from proximate Censuses are transformed based on the scaling factors for the entire industry (4-digit NAICS code) published annually in the ASM. As annual changes to 5-digit subsectors are different from annual changes to 4-digit sectors, the value of estimated scaling factors will be different depending on the selected basis year.

Consider the notional diagram in Figure 3-1. Here, economic characteristics of a subsector *aa* (black dots) are observed at the beginning and end of a time period, while the full sector *A* (dark gray) is observed annually. One option for filling in data for missing years would be to linearly interpolate between the two observations of *aa*, leading to the black dotted line. However, it is reasonable to assume some non-linear motion of *aa* because of the observations of *A*. On the other hand, *aa* is observed to decrease more than *A* over the time period, so it must not track precisely. Using the relative motion of *A* applied to both observations of *aa*, it is possible to calculate a reasonable uncertainty band for the missing years. This procedure can be repeated for all three economic scaling factors, the lowest and highest out of which become the extremes of the scaling factor range.

4. Calculate up-scaled waste tonnage
Multiply state-level waste data by the range of scaling factors.

¹⁵ Through 1996, the ASM published Pennsylvania and national data for industry subsectors. Starting in 1997, when NAICS superseded SIC, the ASM only included data on 4-digit codes, with data on 5- and 6-digit codes reserved for the EC, released only on years ending in -2 or -7.

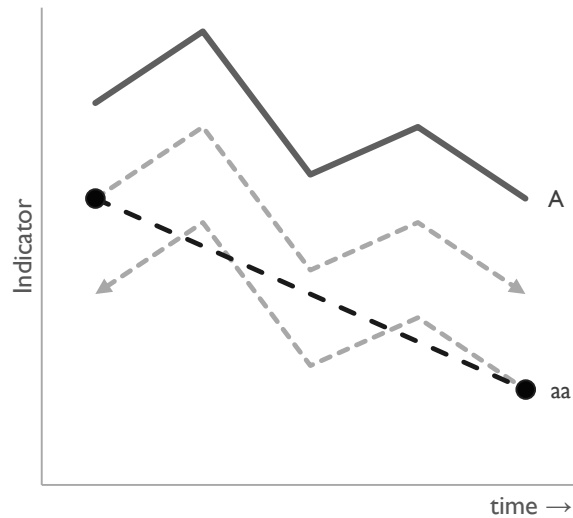


Figure 3-1. Schematic of the technique used to interpolate between infrequent sub-sectoral observations using a time series of observations of the full sector.

3.2.4.3 Data

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 one ton per year that includes: the waste code, tonnage, medium of discharge (solid, liquid, sludge, or gas), the industry code most closely describing the activity that generated the waste, and details of disposal. The state DEP hosts the most recent three reports (in the form of Excel spreadsheets) on its website; earlier data was made available by Adrian Horotan, one of the authors of the original study to propose the method (Barr et al., 2009).

The database is large, on the order of 10,000 entries per reporting year, and messy, as described above. Over the course of the 20+ year history of the residual waste program, the reporting requirements seem to have shifted, specifically regarding the reporting of process wastewater. According to the 2014 reporting instructions, “Process wastewater (R420, including R421) that is discharged to a POTW or via an NPDES permit DOES NOT NEED TO BE COUNTED [emphasis in original] in determining if your site met the reporting threshold of 13 tons.”

3.2.4.4 Discussion

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 the

target year, 2010, provides experimental control for time effects better than any of the other methods used in this research. The change factors identified in the historical forecasting method—technology, markets, and regulation—are all functions of time. Using data reported in the year of interest holds all of those factors constant. 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. In fact, Pennsylvania played an important role in the original establishment of all three industries focused on here! 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)” (NAICS Association, 2016). 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. Barr et al. (2009) found numerous instances of mis-coded waste streams. There are likely many that went uncaught. Also, 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.

3.3 Triangulation

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 I 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. I 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. This principle has famously been employed in land survey for many centuries.

In social science, triangulation is a term sometimes used for the very approach taken in this research. According to Bryman (2004), “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.” 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.”

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, or forecasting 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. The specific methodology is illustrated in Figure 3-2.

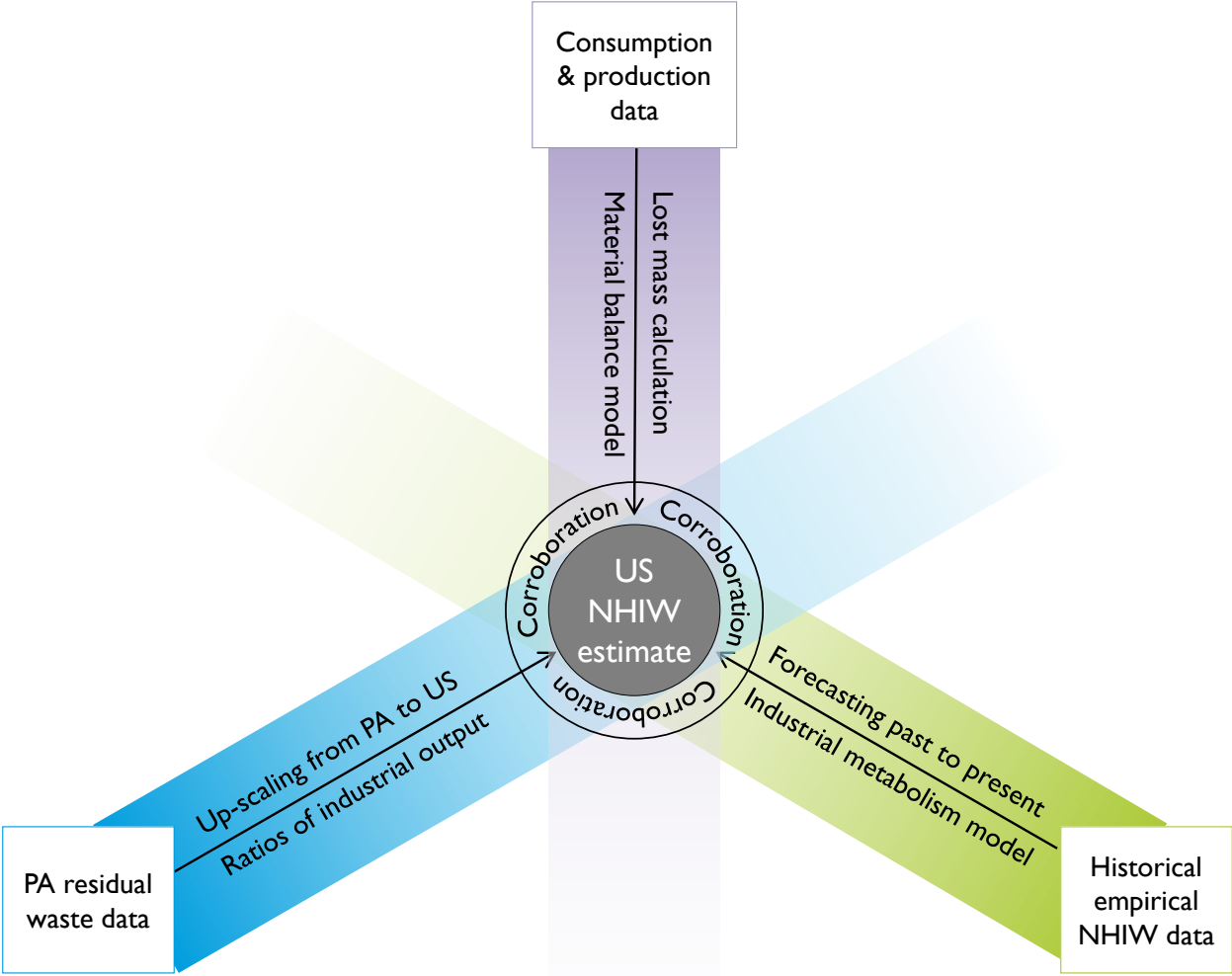


Figure 3-2. Triangulation methodology

3.4 Industry case study selection

Although the ultimate goal of the method developed here is to assemble a waste account for the United States as a whole, the path to doing so is through industry-by-industry case studies. Unlike municipal solid waste accounts, which are distinguished mainly by material, product, and end of life pathway, and hazardous waste accounts, which focus on method of disposal (among other things), NHIW accounts distinguish waste by industry source. Extant NHIW accounts also include information about waste type and disposal scenario, but for the purposes of this research, defining the system boundary at the industry level enables comparability among estimation method results.

The specific industries studied in this dissertation should be selected according to a number of criteria. The cases should be different enough so that each provides new information as to the viability of the estimation method and the triangulation proposal as a whole. There should be similarities too, so that the differences that emerge from applying the triangulation might be explained (providing a sort of rough experimental control). And since the results from this dissertation will be the first entries in a new contemporary account of NHIW generation in the US, the industries selected should be expected to be important contributors to that waste flow.

Viability is also an important criterion. For the purposes of this research, industry sectors should be avoided that are too new to have much historical data on NHIW generation (i.e. semiconductor manufacturing), too underrepresented in Pennsylvania (i.e. also semiconductor manufacturing), or too complex and fragmented to be effectively modeled using materials balance (i.e. equipment manufacturing). This clarification suggests that the specific triangulation approach used here is actually insufficient to accomplish the ultimate goal of assembling a complete NHIW account, although there is reason to believe that the vast majority of NHIW can be accounted for this way.

Determining the ideal level of aggregation for industry classification is another important decision. The two prevailing industry classification schemes, SIC and NAICS, provide a basic hierarchy for this process, but the classifications are done based on economic terms, not material flow terms, and so the same levels of aggregation are not necessarily appropriate across industry sectors. The industry sectors as defined in US EPA (1985) and US EPA (1988) are displayed in Table 3-2, as are the SIC code and its NAICS approximation and the rankings of each industry in both of the studies in terms of tonnage of waste. The 1985 study included 22 sectors and the 1988 study included 17 sectors. The definitions the sectors that overlapped was consistent in both studies.

Table 3-2. Industry sectors included in historical NHIW studies in the US; SIC codes and their approximate NAICS equivalents; and the industries' rankings in the SAIC (US EPA, 1985) and Subtitle D (US EPA, 1988) surveys. "--" indicates sector was not surveyed.

	SIC	NAICS (approx.)	Rank	
			1985	1988
Electric power generation	4911	2211	4	3
Electrical machinery and electronic components	36	334-335	22	–
Fabricated metal products	34	332	16	–
Fertilizer and other agricultural chemicals	2873-2879	3253	3	10
Food and kindred products	20	311-312	10	6
Inorganic chemicals	2812-2819	32512-32518	6	4
Leather and leather products	31	316	21	17
Lumber and wood products; furniture and fixtures	24, 25	321, 337	18	–
Machinery, except electrical	35	333	17	–
Organic chemicals	2865, 2869	32511, 32519	1	13
Petroleum refining	29	324	12	9
Pharmaceutical	2831-2834	3254	15	–
Plastics and resins manufacturing	2821	3252	5	8
Primary iron and steel	3312-3321	3311-3312, 33151	2	2
Primary non-ferrous metals	3330-3399	3313-3314, 33152	9	12
Pulp and paper industry	26	322	8	1
Rubber and miscellaneous plastic products	30	326	13	15
Selected chemicals and allied products	2822, 2824, 2851, 2891	3255	–	11
Soaps; other detergents; polishing, cleaning and sanitation goods	2841-2842	3256	20	–
Stone, clay, glass, and concrete products	32	327	7	5
Textile manufacturing	22	313	19	7
Transportation equipment	37	336	14	16
Water treatment	4941	2213	11	14

Based on this list, I selected three industries for exploration in this dissertation: pulp and paper, iron and steel, and petroleum refining. The main similarity among the three is that as primary materials industries, they sit far upstream on the value chain. Put another way, they all consume an unrefined material and produce a refined material that is used to make products. This is in contrast with industries that manufacture products to sell to consumers. These materials processing industries are generally those that will produce the most process residuals that can be utilized beneficially. The refining process is also one that can be represented in materials balance in

a more or less straightforward manner. This keeps the analytical focus on the triangulation rather than on the material flow model.

The three selected industries also largely meet the criteria of viability. They are all old industries, central to the United States's industrialization, and have been grappling with their waste and environmental impacts for decades. They are also well represented in Pennsylvania, in fact the early histories of each of these industries in the United States plays out in a large part in that state. Finally, they can be readily modeled as materials balances, even if, as we will see, that technique may not be able to say very much about NHIW for all three sectors.

The industries vary in their waste generation rates. Iron and steel ranks as the second highest generator in both past studies, which is a strong indicator that it deserves close attention, even if those two studies are ultimately proved wrong. Pulp and paper was found to be the largest on-site disposer of NHIW in the 1988 reference but just eighth in the SAIC report. Allen & Behmanesh (1992) tackled this particular gap with materials balance logic, but left a lot of precision to be desired. Petroleum refining was about halfway down both of the lists. This suggests the industry is not a large waste generator. I include it here in order to evaluate the effectiveness of the methods for smaller industry sectors.

The list in Table 3-2 provides a blueprint for an economy-wide characterization of NHIW after the completion of this dissertation. The NAICS code equivalents of the sectors studied by the EPA reports cover nearly the entire manufacturing section of NAICS (31-33), with the exceptions of: textile product mills (314), apparel manufacturing (315), printing (323), other chemical product manufacturing (3259), and miscellaneous manufacturing (339).

The target year for analysis was selected to be 2010. This was the most recent year for which there was reliable data at the time I began the research. Today, it would be possible to create accounts for years up until 2014.

In the course of the three sector studies that follow, more detail about the individual estimation methods, data sources, and triangulation meta-method is presented. In particular, Chapter 4, which covers the pulp and paper industry, serves as the primary demonstration case. The chapter lays out many specifics of the application of the methods introduced here and positions the methods in broad literature and historical contexts. Chapters 5 and 6 largely assume the reader is familiar with the methodology and key concepts and terms.

At the start of each chapter is an introductory characterization of the industry subject, including historical trends and current performance of economic activity, geographic distribution, and physical production. I also include descriptions of key processes, technologies, and where possible multiple options for industrial waste classification. These dimensions cover the breadth of possible drivers of NHIW relevant to the different estimation methods, whether or not the results hinge on a specific insight presented in the introduction.

4 Pulp & Paper Manufacturing

More than two billion of the total seven billion metric tons of NHIW estimated by the EPA in the mid-1980s was attributed to the pulp and paper industry, making it thought to be the single largest NHIW-generating industry in the country. The results from the three estimation methods tell a vastly different story for the year 2010. Forecasting yields 12.10–12.33 million Mg; materials balance 8.49–14.66 million Mg; and spatial up-scaling 3.7–6.4 million Mg. Using triangulation, it can be claimed that the industry generated between 9.8–13.2 million Mg of wastewater treatment sludge, coal and wood ash, and miscellaneous wastes in 2010.

4.1 Introduction

The origins of papermaking date to the year 105 CE, when Chinese Han Dynasty agriculture minister Cai Lun manufactured the first useful paper from a pulp of mulberry wood, bamboo, grass, hemp, and silk rags (see Figure 4-1) (Goedvriend, 1988).¹⁶ Over subsequent centuries, this useful material—and knowledge of how to make it—spread throughout the world,¹⁷ with new sources of pulp and papermaking processes developed along the way. The industry in its modern form is a product of the industrial revolution in Europe, which enabled the mass production of standardized, high-quality paper through the mechanization of the papermaking process¹⁸ (see Figure 4-2) and chemical pulping of wood—specifically the kraft sulfate process.¹⁹

¹⁶ Archaeological remains from the first century BCE include evidence of proto-paper made from plant fiber and rags. One can easily envision fibers released from clothes washed on rocks in the river collecting in a “sheet downstream, which could be lifted off and dried” (Goedvriend, 1988, p. 38).

¹⁷ Papermaking, along with printing, gunpowder, and the compass, are sometimes dubbed as the “Four Great Inventions” of ancient China (“Do we need,” 2008). These technologies, along with many others, were closely held, taking hundreds of years for them to be spread to other parts of the world, even with the significant economic, cultural, and martial contact that was occurring at the time. Paper was brought out of China along the Silk Road; stories tell of a Chinese prisoner of war captured during the Battle of Talas in 751 CE (thought to have taken place near the present day border of Kazakhstan and Kyrgyzstan) who disclosed the secrets of papermaking to his Arabian captors, giving rise to a paper industry that spanned the Islamic world (Sass, 1998, p. 145). The technology arrived in Europe via Moorish Spain in the 12th century, made its way through the continent to Great Britain by 1494 (Goedvriend, 1988), and finally was brought to North America in 1690 (Weeks, 1916, p. 3).

¹⁸ Although pulping had become mechanized using water power when it reached the Arab world, it took until 1799 for papermaking to receive similar treatment at the hands of Frenchman Louis-Nicolas Robert (Goedvriend, 1988). Robert’s design was refined multiple times, most notably by Henry Fourdrinier, whose name the class of machines still bears. Other designs followed, such as the “Yankee” cylinder machine, which enabled product diversification (Tschudin, 2006, p. 11).

¹⁹ Despite Cai Lun’s prophetic use of mulberry bark in his original recipe, most of the paper manufactured through the 18th century was made from rags (Goedvriend, 1988). Constraints stemming from a reliance on this waste product motivated numerous attempts to develop alternative pulping methods, including some as early as 1695

One result of rapid industrialization of papermaking has been considerable environmental degradation in the form of air and water pollution and solid waste throughout the paper life cycle. The characteristic “rotten egg” smell permeating the air around paper mills is that of the dimethyl sulfur and other reduced sulfur compounds from kraft pulping, which while eye-watering are relatively benign compared with the more environmentally troubling industrial emissions of SO₂, N₂O, and VOCs (US EPA, 2002). Water pollution from pulp and paper mills famously contaminated rivers across the United States during the 20th century (Mechenich, 1980; McFarlane, 2012; Ortmann, 1909). While many of the waterways destroyed by mills have been restored, land-disposed hazardous and toxic solid wastes remain persistent problems for the industry (Sumathi & Hung, 2004). And looking upstream, sourcing raw materials for wood pulp can lead to deforestation and negative impacts from forest monoculture practices (“Roundtable,” 1997; Pikel, 1968).

In the popular consciousness, much of the environmental impact from paper comes from its disposable nature, with paper products comprising more than a quarter of all municipal solid waste generated in the United States at present (US EPA, 2013). This large tonnage, combined with the recyclability of waste paper, has made it a target for increased recovery and reuse, efforts which have resulted in waste paper making up more than half of the total diverted tonnage. Despite the focus placed on reducing the landfill disposal of paper products, the solid waste generated in the production of those products has received substantially less attention.

This chapter presents the application of the triangulation approach proposed in this thesis to the pulp and paper industry in the United States, focused on the year 2010. As the first of the three industry case studies, extensive background and review is provided for each of the three estimation methods. Important background and motivational information is also provided throughout the chapter.

based on re-pulped waste paper, foreshadowing today’s secondary paper market. The first wood pulping process was simple mechanical grinding, developed in the early 19th century in Germany. But even with steam pretreatment, the high lignin content of mechanical wood pulp led to paper with substandard performance compared with rag paper. In 1851, it was discovered that lignin and other undesirable fractions could be removed by cooking the pulpwood with caustic soda (sodium hydroxide, NaOH) (Sass, 1998, pp. 141–143). Chemical recovery processes were developed soon after. An alternative chemical pulping method based on sodium sulfate instead of sodium hydroxide was developed in 1884. The resulting pulp was found to be stronger than soda pulp, and so was called *kraft*, the Swedish (and German) word for “strong.” Kraft pulp was also darker than soda pulp, requiring new and more aggressive bleaching treatment before it could gain market position (Sixta, 2006a, p. 5–6). In response, sodium chlorite and chlorine dioxide bleaching processes came onto the market during the first half of the 20th century. Throughout this period, other competing pulping technologies were developed, distinguished themselves based on specific physical and chemical properties of the resulting wood pulp. The most significant of these alternatives is the acid sulfite process, first developed in 1857 and continually refined and improved to the present.

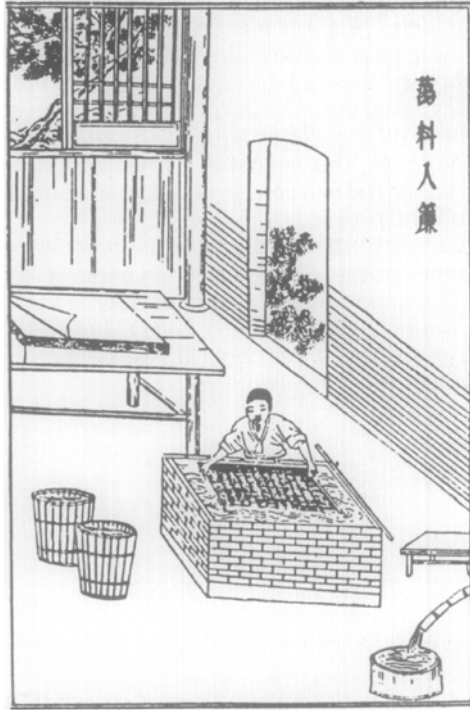


Figure 4-1. "Chinese paper making" (Goedvriend, 1988)

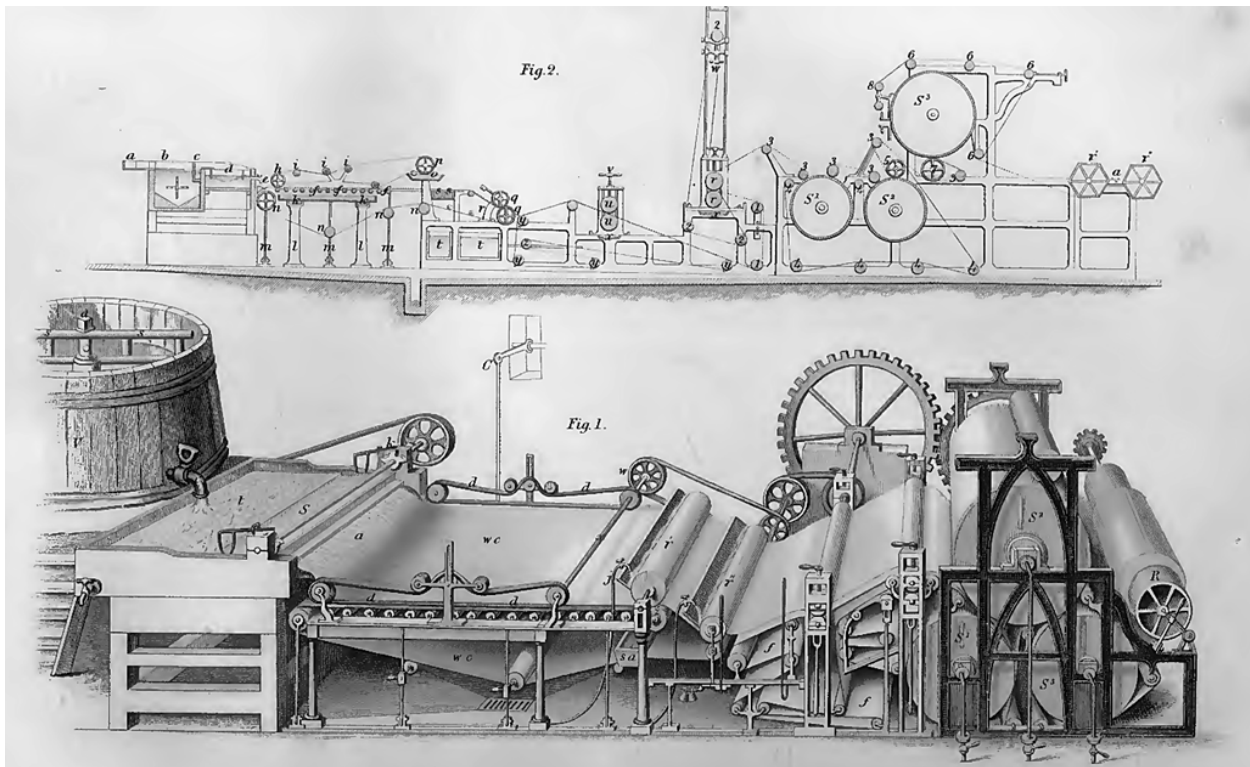


Figure 4-2. Early paper making machine (Tomlinson, 1854, p.364b)

4.1.1 Motivations

The pulp and paper industry is an important subject for the estimation of non-hazardous industrial waste generation for a number of reasons. First, according to the official EPA statistics (from the mid-1980s), the industry produced nearly 30% of all NHIW generated in the country—two billion Mg—making it the largest single contributor by a wide margin, despite in that year contributing less than 5% of the manufacturing sector’s value added to the U.S. economy (US EPA, 1988; US BEA, 2015). On the other hand, the 1985 SAIC literature review estimate of NHIW ranks the industry eighth—8.6 million Mg, 2.2% of that source’s total (US EPA, 1985). The disparity between these two estimates is the largest of any sector.

The paper industry occupies a notable place in the decades-long search for the elusive figure at issue here. In their early effort to rationalize the two EPA estimates with materials balance logic, Allen & Behmanesh (1992) used estimates of nation-wide paper production and paper mill water consumption to argue that the difference observed between the two estimates must stem from the inclusion or exclusion of vast quantities of process wastewater. This argument seemed to hold water for other major sectors. It also reinforced anecdotal evidence that the earlier estimate focused on dry mass while the latter was dominated by waste materials disposed in surface impoundments, which are aqueous environments.

Relevant waste data is available for the paper industry that is lacking for most if not all other major materials sectors in the United States. The credit for this should be placed at the feet of the National Council for Air and Stream Improvement (NCASI). NCASI was established in 1943 as the National Council for Stream Improvement (of the Pulp, Paper, and Paperboard Industries), Inc., with an objective to coordinate and conduct industry-wide research into “improving the quality of effluents and wastes discharged into the surface waters of the country” and developing new technologies for the “recovery and utilization of material” lost during processing (“Organization and activities,” 1944).

The organization was also responsible for collecting, analyzing, and disseminating data relevant to these goals. Within two years of its establishment, NCASI was engaged in utilizing “data concerning the character of streams and the discharge of wastes ... for the purpose of determining the relative responsibility for pollution of the pulp and paper industry, municipalities and other industries on the watersheds concerned” (Gehm, 1945, p. 783). This research, which relied on data both “available and ... forthcoming,” (ibid.) involved soliciting quantitative and qualitative information from individual companies and public records and would foreshadow subsequent NCASI studies with similar goals, albeit evolving as public environmental concerns grew to include air pollution (hence the organization’s name change) and solid waste.

From the outset, NCASI and its relationship to both individual firms and other industry associations was presented as a model for other industry sectors interested in “passing from individualized and small group research on manufacturing wastes and stream pollution to an

integrated national program” (Gehm, 1945, p. 782). At the time of its establishment, only two other sectors had similar industry-wide programs: steel and dairy (Heukelekian et al., 1945). Although in the decades immediately following NCASI’s formation similar organizations were established, few if any that I have been able to identify regularly and voluntarily collect, analyzes, and publishes data on non-hazardous waste generated by the industry it supports. In this, pulp and paper is unique. That NCASI provides public access to multiple, detailed, facility survey-derived estimates of NHIW spanning the time horizon of this research positions the paper industry as close to a validation case as is possible given the context of this project.

4.1.2 Pulp and paper sector in the US

In the United States, the pulp and paper industry is classified as NAICS subsector 322—Paper Manufacturing, which superseded SIC major group 26—Paper and Allied Products. This subsector contains two industry groups: 3221—Pulp, Paper, and Paperboard Mills; and 3222—Converted Paper Product Manufacturing. This research focuses exclusively on 3221. Any references to the “pulp and paper industry” refer to mill rather than converting activities (the latter refers to the transformation of raw paper and paperboard stock into products like boxes, envelopes, etc.). NAICS 3221 is in turn comprised of four six-digit sub-codes, as indicated in Table 4-1.²⁰ At this level, the sectors remain highly aggregated across a great variety of products. The 2012 NAICS index entries for the relevant industry codes are tabulated in Table 4-2, and communicate the diversity of products from the modern pulp and paper industry.

Table 4-1. Crosswalk between NAICS and SIC for the US pulp and paper industry (US CB, 2014)

<u>NAICS</u>	<u>SIC</u>
322: Paper Manufacturing	26: Paper and Allied Products
3221: Pulp, Paper, and Paperboard Mills	
322110: Pulp Mills	261: Pulp Mills
322121: Paper (except Newsprint) Mills	262: Paper Mills
322122: Newsprint Mills	
322130: Paperboard Mills	263: Paperboard Mills
3222: Converted Paper Product Mfg.	265: Paperboard Containers and Boxes
...	267: Converted Paper and Paperboard Products, except Containers & Boxes
...	

²⁰ The difficulty of using NAICS codes to draw conclusions about physical manufacturing processes emerge here, as many paper mills also engage in at least some limited converting processes. A single NAICS code is assigned to each firm based on the activity that brings in the largest fraction of that firm’s revenue, which does not necessarily correspond to the activity that generates the most waste.

Table 4-2. 2012 NAICS Index entries for NAICS 3221 (US CB, 2013)

322110: Pulp	<i>This category includes just pulp-only mills. Integrated mills that manufacture both pulp and paper or board are classified under 32212(1/2)—Paper Mills and 322130—Paperboard Mills.</i>
<ul style="list-style-type: none"> • deinking pulp • groundwood pulp 	<ul style="list-style-type: none"> • pulp from bagasse, linters, rags, straw, wastepaper, or wood
<hr style="border-top: 1px dashed #000;"/>	
322121: Paper	
<ul style="list-style-type: none"> • absorbent paper • asphalt paper • bond paper • book paper, coated • bostons paper • building paper • cigarette paper • construction paper, school and art • cotton fiber paper • diapers, disposable • facial tissues • felts, asphalt • glassine wrapping paper • groundwood paper, coated • kraft paper stock 	<ul style="list-style-type: none"> • looseleaf fillers and paper • napkins, table • office paper (e.g., computer printer, photocopy, plain paper) • paper towels • sanitary napkins and tampons • sanitary paper • saturated felts • sheathing paper • tablets (e.g., memo, note, writing) • tar paper, building and roofing • tissue paper • toilet paper • towels, paper • writing paper
<hr style="border-top: 1px dashed #000;"/>	
322122: Newsprint	
<ul style="list-style-type: none"> • groundwood paper, newsprint • groundwood paper, wallpaper base • newsprint paper 	<ul style="list-style-type: none"> • paper, newsprint and uncoated groundwood
<hr style="border-top: 1px dashed #000;"/>	
322130: Paperboard	
<ul style="list-style-type: none"> • binder's board • bostons board • cardboard • chipboard (i.e., paperboard) • coated board • container board • folding boxboard • kraft liner 	<ul style="list-style-type: none"> • leatherboard (i.e., paperboard based) • milk carton board • paperboard (e.g., can/drum stock, container board, corrugating medium, folding carton stock, linerboard, tube) • setup boxboard • wet machine board

4.1.2.1 Physical production

The physical output of the industry has been in decline since peaking in the late 1990s. In 2010, wood pulp was produced in a quantity of approximately 50 million Mg, down from its peak of nearly 61 million Mg in 1995 (Howard & Westby, 2013). Collected waste paper is used as a secondary fiber source at a quantity of 28 million Mg in 2010. The share of primary to secondary pulp has been declining from 3.5 in 1980 to 1.7 in 2010 as recovered paper use has declined slower than has the production of wood pulp (Figure 4-3).

The production of paper and paperboard products has followed a similar trend (Figure 4-4). Down from its peak of 89 million Mg in 1999, the industry produced 32 million Mg of paper and 43 million Mg of paperboard in 2010. The share of paper had held more or less steady between 45–50% for decades; in the mid-2000s it began to plummet and is below 40% as of 2014 (SAUS). This trend can be understood by looking at the trends of specific paper products (Figure 4-4). The only two product segments to be experiencing growth are tissue and paperboard, while every other product is in decline (SAUS).

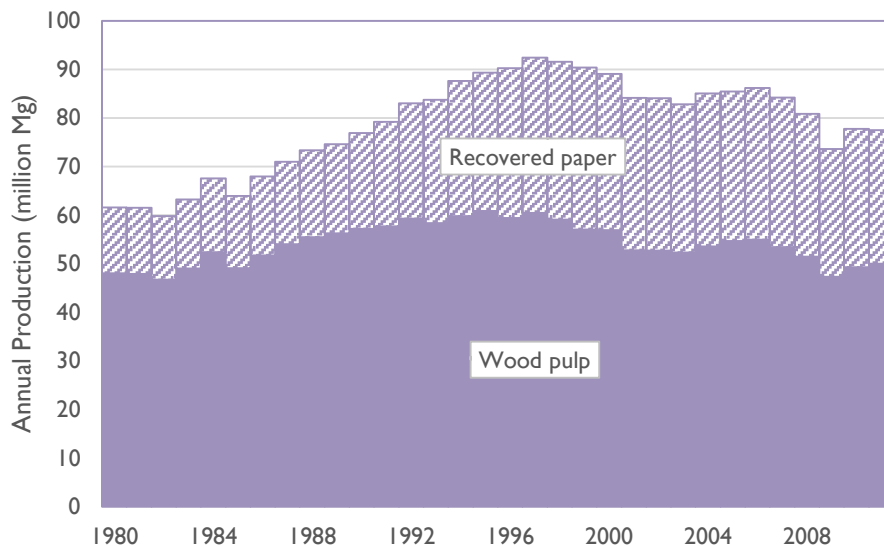


Figure 4-3. Annual production of wood pulp and consumption of recycled paper in the United States, 1980–2011. Wood pulp includes dissolving pulp used in the chemical industry. (Howard & Westby, 2013)

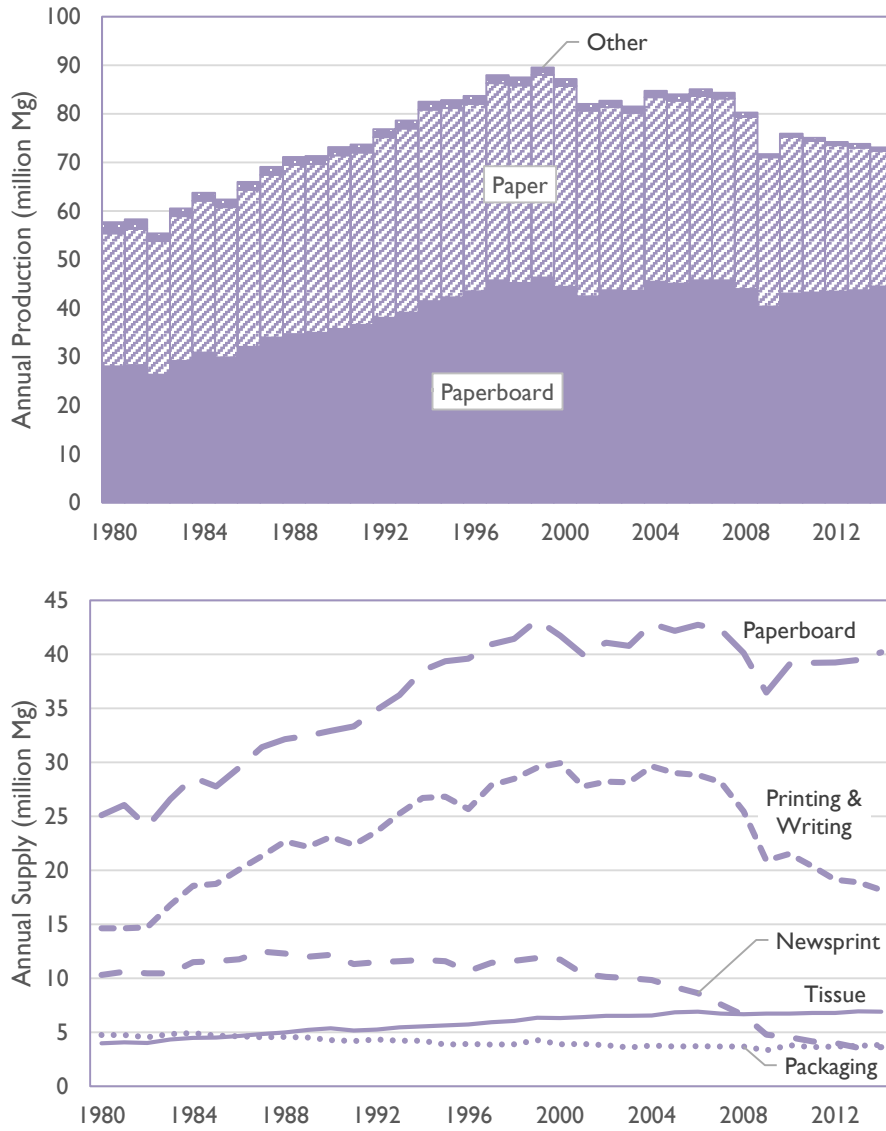


Figure 4-4. Annual production (top) and effective supply (production + imports – exports) (bottom) of the US pulp and paper industry, 1980–2014. (SAUS)

4.1.2.2 Economic indicators

The economic statistics of the industry also bear out the overarching trend of an industry in decline: number of employees²¹ (Figure 4-5), number of mills (Figure 4-6), and value added²² (Figure 4-7). Each of these figures displays the statistic for paperboard, paper, and pulp, corresponding to five-digit NAICS codes (except for # mills, which also includes the paper/newsprint split) and its SIC equivalent for years before 1997. Note that the SIC-NAICS transition was a major reorganization of national recordkeeping, and statistics cannot be compared across systems. Data is displayed before 1997 to highlight directionality in the trends and to reinforce the incompatibility of SIC- and NAICS-basis statistics.

The decline in employment in the industry and number of active mills indicate trends towards consolidation and mechanization as a strategy to deal with declining output. Value added (revenue less expenses) seems to have roughly stabilized, however, in real dollar terms.

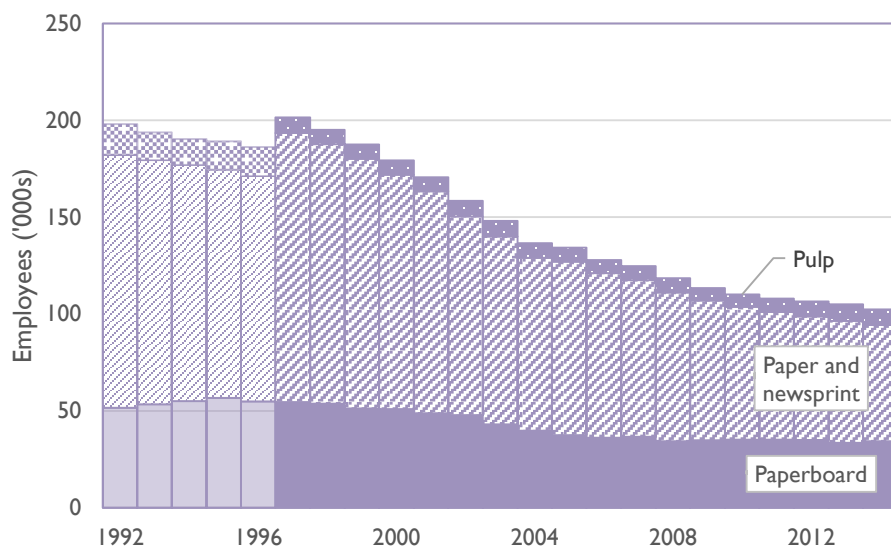


Figure 4-5. # of employees in the pulp and paper industry, 1992–2014 (SIC left, NAICS right) (ASM)

²¹ These data are extracted from two regular Census Bureau products: the Annual Survey of Manufactures (ASM) and the Economic Census (EC). The latter is issued every five years, ending in -2 and -7; the ASM on all other years.

²² Value added is reported in the ASM in nominal values. These values were deflated to 2010 dollars using the Producer Price Index for each five-digit NAICS code, published by the Bureau of Labor Statistics.

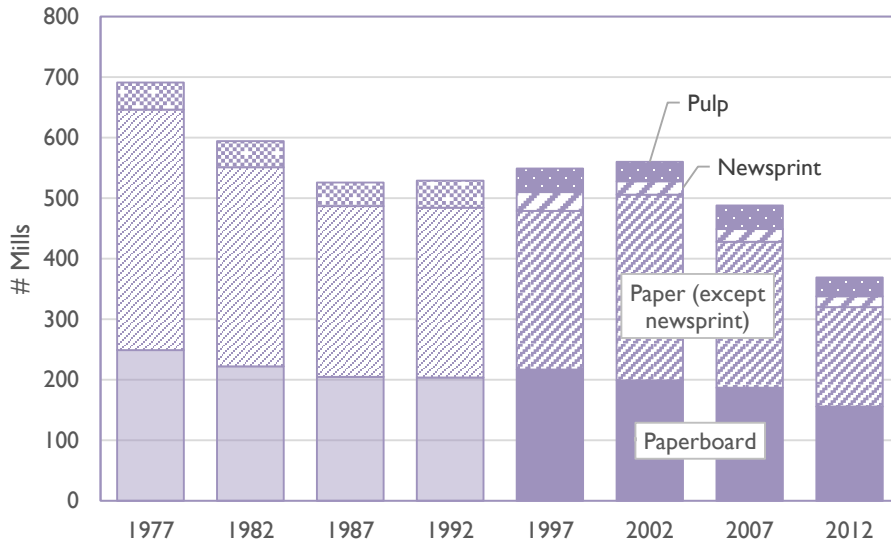


Figure 4-6. # of mills in the pulp and paper industry, 1977–2012 (SIC left, NAICS right) (EC)

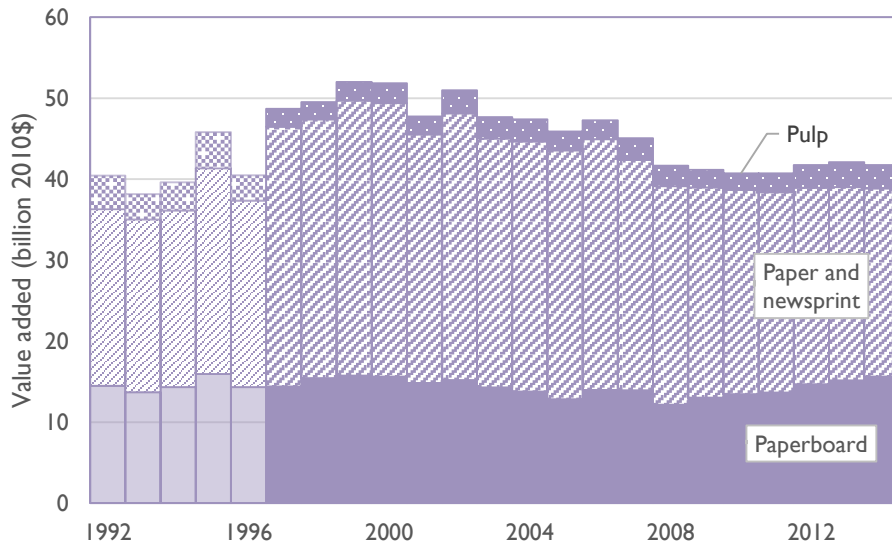


Figure 4-7. Value added, 1992–2014 (in billion 2010 \$) (ASM)

4.1.2.3 Geographic distribution

The paper industry is not evenly distributed around the country. It is located mainly in parts of the country heavily wooded with pulpwood (Figure 4-8). The states with the largest fraction of the national paper industry (by value added) in 2010 are Alabama, Pennsylvania, Wisconsin, Georgia, South Carolina, and Louisiana. Maine's paper industry has been in rapid decline, nationally and as a fraction of the state's total industry base (Figure 4-9).

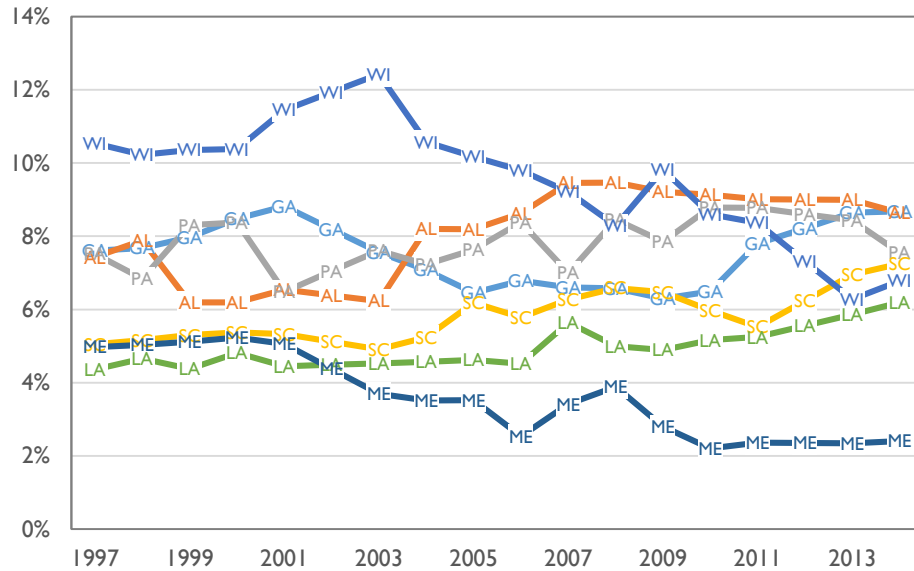


Figure 4-8. State paper industry as fraction of national paper industry (value added,ASM)

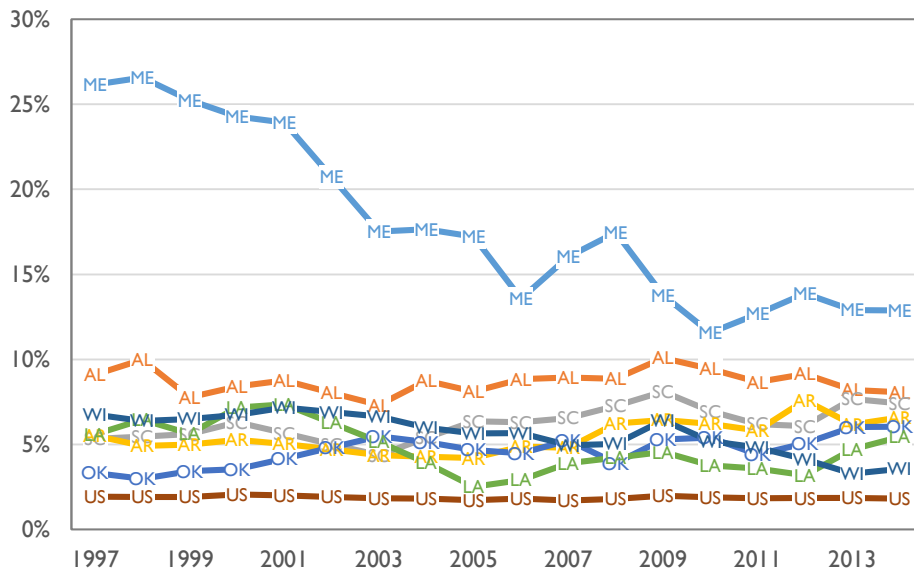
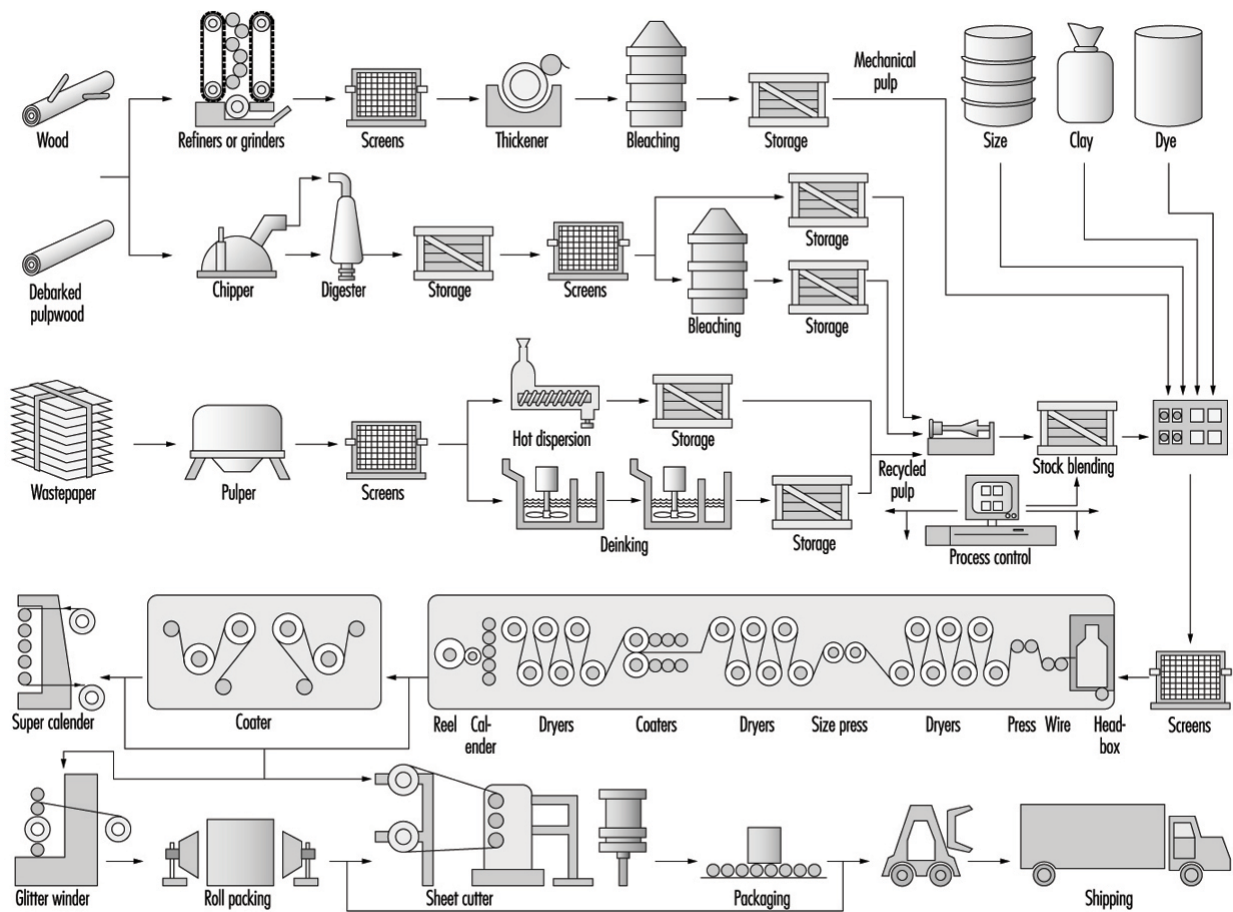


Figure 4-9. State paper industry as fraction of state total industry (value added,ASM)

4.1.3 Overview of pulp and paper making; sources of NHIW

The basics of papermaking still closely resemble those used by Cai Lun two millennia ago. Simply put, a watery mixture of fibrous materials, e.g. cellulose, cotton, or recovered paper, is laid on a screen, drained, pressed, and dried. Along the way, any number of other materials and processes can be applied, yielding paper products with widely varying characteristics. A schematic of processes in the pulp and paper industry is presented in Figure 4-10. Solid wastes from this industry include refining residuals, that is, inevitable byproducts from an industrial process that takes an input and separates desirable from undesirable fractions; process losses; and environmental control sludges.



Source: Adapted from Weidenmüller 1984.

Figure 4-10. “Illustration of process flow in pulp and paper manufacturing operations” (Teschke & Demers, 2011)

4.1.3.1 Primary wood pulping

Primary pulp begins as wood. Wood is composed primarily of three types of organic molecules: cellulose, hemi-cellulose, and lignin, as well as a small amount of other organic and inorganic compounds like resin and ash. The specific fraction of each of these compounds in wood varies with species and with location within the tree, bark having different composition than heartwood, for example (Koch, 2006). Lignin, which gives trees and other plants their mechanical structure, is somewhat problematic for papermaking.²³ Chemical processes for creating high quality pulp tend to dissolve this material, leaving the cellulosic matter behind. Paper made from pulp with a high lignin content is known to age rapidly and get brittle, in part because lignin disrupts hydrogen bonding between cellulosic fibers that contributes to paper's pliability (Sixta, 2006a, p.8).

After arriving at the mill, air-dried pulpwood is debarked and pulverized into chips. Additional wood is purchased from lumber mills in the form of chips, cuttings, and sawdust. The wood chips and other *furnish* materials²⁴ are then fed into a series of chemical, semi-chemical, or mechanical steps that ultimately produce pulp (US EPA, 2002).

The simplest pulping techniques are mechanical ones (illustrated on the top row of Figure 4-10), which physically grind and screen wood furnish to produce pulp using either grinder stones²⁵ or refiners (grooved disks). Depending on the source of furnish and desired pulp characteristics, pre-treatments with either heat or chemicals can be used to facilitate pulping. The various mechanical pulping processes have different energy efficiencies and environmental impacts, but all convert a very large fraction of furnish into pulp, yielding a correspondingly small amount of pulping waste (US EPA, 2002, p. 24). Because of its short fiber length and high lignin content, mechanical pulp is of comparatively low quality and is used mainly for paper with short lifetimes: e.g. newsprint, tissue paper, and molded fiber products²⁶ (ibid., p. 7). Ongoing technological innovation continues to improve the properties—and thus market usefulness—of mechanical pulp (Sixta, 2006a, pp. 12–13).

The dominant primary pulping processes use chemical digestion to liberate cellulose fibers from the wood matrix (second row, Figure 4-10). There are two main techniques in current use: kraft (sulfate) and sulfite. The kraft process digests wood chips in a solution of sodium sulfide (Na_2S) and sodium hydroxide (NaOH)—this is known as “white liquor.” Produced pulp is sent for

²³ Interestingly, lignin also causes problems in the ethanol debate. It is trivial to produce ethanol from cellulose (i.e. corn sugar); the trick has been trying to economically produce ethanol from the woody agriculture waste that is mainly lignin.

²⁴ Furnish is the industry term for “the blend of fibrous materials used to make pulp” (US EPA, 2002, p. 19).

²⁵ Pulp produced by grinder stones is called “stone groundwood pulp.” Why that instead of “stone-ground wood” is somewhat perplexing, although no more so than much of the other bizarre industry jargon. After all, it is *stone-ground flour*, not *stone groundflour*.

²⁶ Molded fiber products include egg cartons and those green baskets that fruit and berries are sometimes sold in.

screening and further treatment, while a mixture of delignification residues and process chemicals (now in the form of sodium sulfate (Na_2SO_4) and sodium carbonate (Na_2CO_3)) called “black liquor” is processed for energy and chemical recovery. Concentrated black liquor is burned for energy recovery in an oxygen-poor environment, incinerating the lignin residues and reducing the sodium sulfate. The molten inorganic materials left over are then dissolved in water, producing a mixture of mainly Na_2S and Na_2CO_3 known as “green liquor” (Tran & Vakkilainen, nd).

Green liquor is then fed to a causticizing plant, where lime (CaO) has been “slaked” with water (H_2O) to produced calcium hydroxide ($\text{Ca}(\text{OH})_2$). Slaked lime is combined with sodium carbonate in the liquor to recover sodium hydroxide and produce calcium carbonate (CaCO_3). The calcium carbonate (also known as “lime mud”) is then burned to regenerate lime, completing the chemical recovery cycle (Figure 4-11). This is not a completely closed loop, requiring the periodic input of some pulping chemicals and lime (US EPA, 2002).

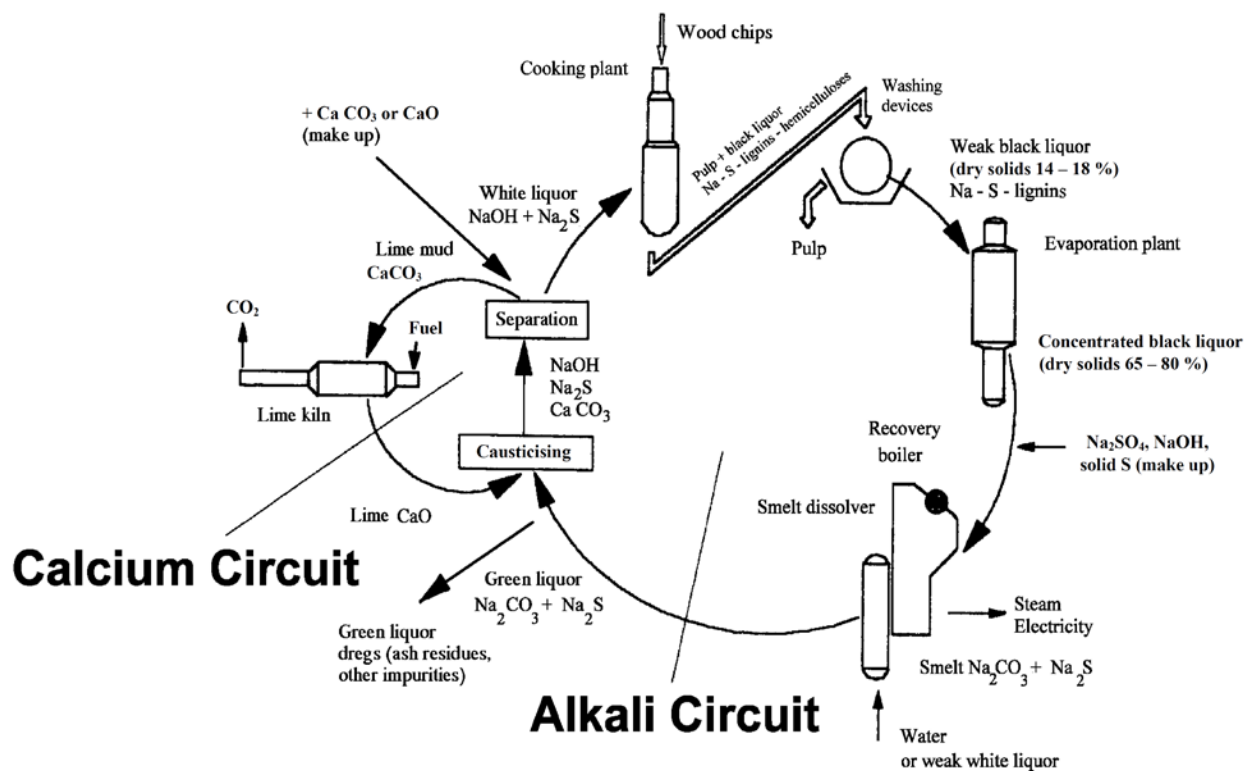


Figure 4-11. Kraft chemical recovery process schematic (Suhr et al., 2015, p. 205)

The sulfite process utilizes any of a number of similar compounds of sulfite and calcium, magnesium, sodium, or ammonium. These compounds—like calcium bisulfite ($\text{Ca}(\text{HSO}_3)_2$)—decompose in solution into sulfurous acid (H_2SO_3) and other salts which attack the lignin molecules (Sixta, 2006b).

Chemical pulp tends to be very high quality, with long, durable fibers that are desirable for writing paper and paperboard (cardboard) (US EPA, 2002). However, its superior properties are due in part to the absence of lignin, which means that a large fraction of the input material (roughly 50%) is discarded in pulping. The importance of sulfur compounds to both sulfate and sulfite pulping processes exposes air and water systems around mills to the risk of sulfur contamination. Additionally, bleached pulp often requires further aggressive chemical treatment, exacerbating the environmental hazard of these processes.

Semi-chemical processes involve combinations of chemical and mechanical processes. By applying multiple techniques in sequence, desired pulp characteristics can be achieved with lower temperatures, pressures, and amounts of aggressive chemicals. Semi-chemical processes have a pulp yield between those achieved by mechanical and chemical processes. A summary of key characteristics of pulping techniques is presented in Table 4-3.

Table 4-3. “Summary of major pulping processes” (Briggs, 1994).

Process	Treatment		Pulp yield (%)
	Chemical	Mechanical	
Mechanical			
Stone groundwood	–	Grinder	93–95
Refiner mechanical	–	Disk refiner	93–95
Thermo-mechanical	Steam	Disk refiner	80–90
Chemi-thermo-mechanical	Na_2SO_3 or NaOH	Disk refiner	80–90
Chemi-mechanical	Na_2SO_3 or NaOH	Disk refiner	80–90
Semichemical	Na_2SO_3 Na_2CO_3 , and/or NaOH	Disk refiner	70–85
Chemical			
Kraft (sulfate)	NaOH + Na_2S	–	45–55
Sulfite	$\text{Ca}(\text{HSO}_3)_2$ + H_2SO_3	–	40–50
Magnefite	$\text{Mg}(\text{HSO}_3)_2$ + H_2SO_3	–	45–55

4.1.3.2 Secondary (recovered paper) pulping

Pulp from recovered paper now makes up a considerable fraction of the global pulp market. Waste paper is recovered from municipal recycling programs, office buildings, and cuttings or breaks in paper production.²⁷ Municipal recycling programs yield a recycled paper flow that is of low quality, especially since many municipalities now collect all recyclable materials—paper, plastic, metal, and glass—in a single receptacle, which leads to contamination of the paper waste with liquids and other substances from the containers. The highly automated facilities that separate fully commingled municipal recycling can lead to further contamination of the recovered paper. Shattered glass mixed in with bales of recovered paper has been a problematic issue for the recycled paper industry, for example (Sacia & Simmons, 2006). Even with clean secondary paper sources, as is recovered from offices and other commercial establishments that contract their own recycling rather than going through municipal services, there are contaminants that interfere with the production of good-quality pulp, namely ink and various plastics and glues such as those on envelopes.

Secondary pulping uses mainly mechanical processes, although pulping chemicals are sometimes added to facilitate the process. Contaminants, debris, and impurities are removed during pulping using various techniques, including centrifugal force and floatation. The plastics and glues, sometimes called “stickies,” are removed using talc and other flocculants. Deinking is accomplished with the addition of surfactants and heat. The contaminants and de-inking sludge, along with fiber lost in the re-pulping process, make up a majority of NHIW in secondary pulp production. Secondary pulp used to be consumed exclusively in the production of low-quality paper, but improved repulping, de-inking, and bleaching technologies, combined with increasing demand for recycled-content paper has led to its use throughout the range of paper products (Putz, 2006).

4.1.3.3 Bleaching

The brilliant white color that is associated with office paper is enabled by the bleaching step in pulp production; without it, primary paper would be the color of cardboard and secondary paper a drab gray. Bleaching also increases the softness and absorbance of paper. Bleaching chemicals are still largely based on chlorine, although there has been a major shift away from the use of elemental chlorine (Cl_2) towards environmentally safer alternatives like chlorine dioxide (ClO_2)

²⁷ Waste paper generated within the mill is known as *broke* or *mill broke*.

and hypochlorites.²⁸ Non-chlorinated alternatives include sodium hydroxide (NaOH), oxygen (O₂), ozone (O₃), and hydrogen peroxide (H₂O₂) (US EPA, 2002).

4.1.3.4 *Papermaking*

The papermaking process continues with “stock preparation,” in which raw pulp is screened, bleached, and dried (if shipped off-site) or blended (if consumed in-plant) and mixed with various additives that give the finished paper desired qualities. Additives include dyes, fluorescents, fillers, sizings, and visual and/or textural substances. Dyes adjust the coloring of the paper. Fillers, like calcium carbonate, clays, and talc, are added as a low-cost replacement for fiber to increase paper bulk and to enhance various properties, including opacity, smoothness, and printability. *Size* or *sizing* refers to substances (like alum) that increase the hydrophobicity, and therefore the durability, of the paper.

The basic mechanics of papermaking are simple: pulp is deposited on a screen from which water is removed using passive (gravity) and active (suction) means; the slurry is pressed into a thin sheet, which then is dried and pressed further with heated rollers. Finished paper is coated with more dyes, filler, and sizing substances, and rolled onto spools. Related processes are used to produce a broad range of paper products. A major differentiating factor among products is thickness: tissue paper is among the thinnest products, followed by newsprint, writing and office papers, and finally paperboard. Although there tends to be market segmentation among these producers of different types of papers, the distinction between board and paper is often just one of thickness. Many paper mills also convert raw paper stock into paper products like envelopes, corrugated cardboard, and boxes.

4.1.3.5 *Non-hazardous industrial wastes*

Waste from papermaking includes fiber lost during the slurry drying process, lost filler chemicals, and cuttings or sub-quality product (broke). A summary of key processes, inputs, and outputs in gaseous, liquid, and solid media is presented in Figure 4-12. A more detailed summary, focused just on solid wastes, can be found in Table 4-4.

²⁸ Non-chlorine-based bleaching techniques are given the following designations: elemental chlorine free (ECF) and total chlorine free (TCF). The majority of current bleaching techniques seem to use ECF processes; TCF and elemental chlorine (Cl₂)-based processes collectively make up a small market fraction (US EPA, 2002).

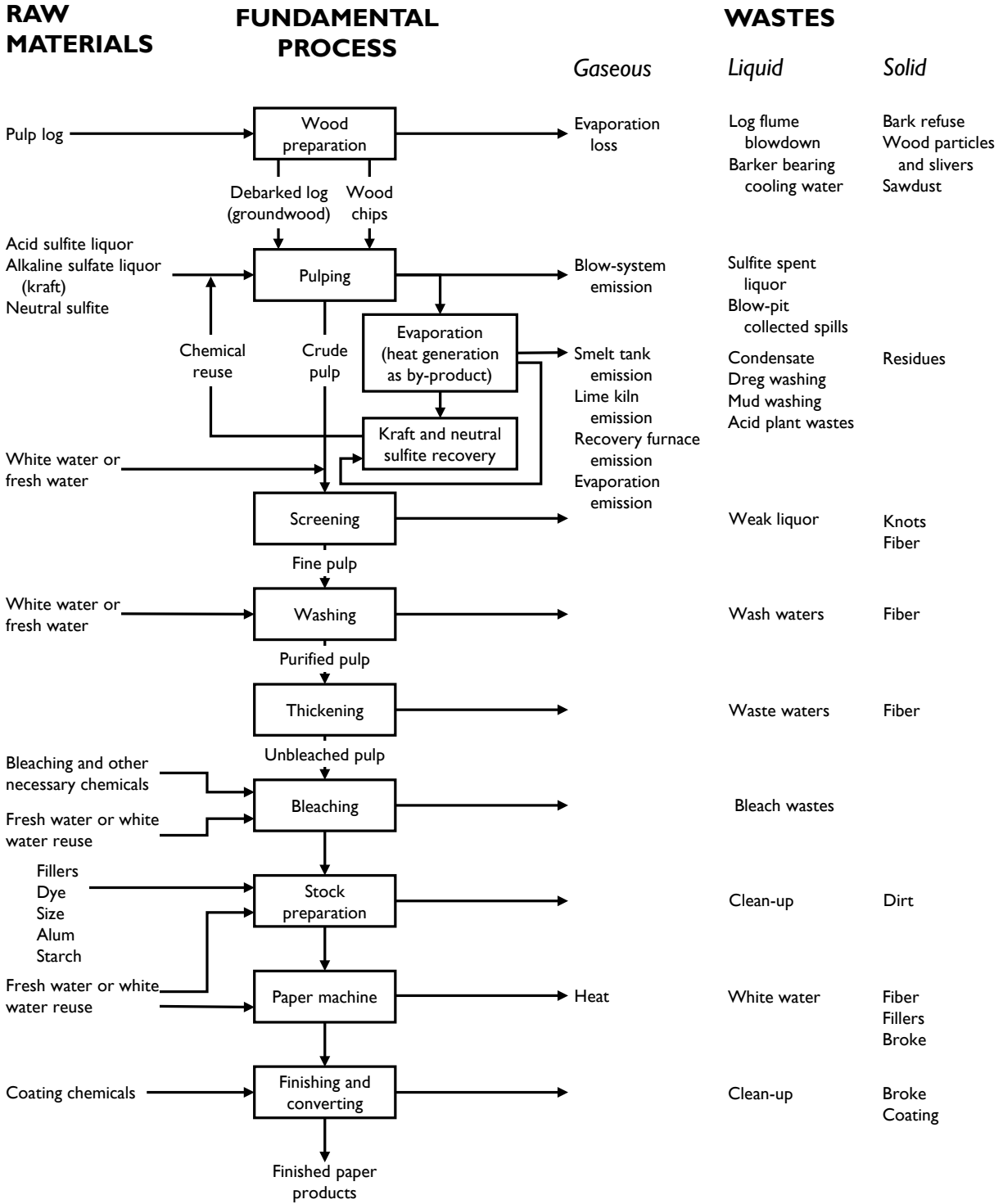


Figure 4-12. “Simplified diagram of fundamental pulp and paper processes,” with characteristic gaseous, liquid, and solid wastes (Nemerow & Agardy, 1998, p. 452).

Table 4-4. Processes and solid wastes in pulp and paper manufacturing (from Wallendahl, 1995, pp. 519, 523, 525)

Process step	Process activities	Solid wastes
I. Pulping of Wood		
1: Wood yard	<ul style="list-style-type: none"> Barking Chipping Storage 	<ul style="list-style-type: none"> Dirt and debris Hog fuel
2: Pulping	<ul style="list-style-type: none"> Cooking Defibration Washing Screening 	<ul style="list-style-type: none"> Knots and rejects Fiber loss
3: Bleaching	<ul style="list-style-type: none"> Delignification Brightening Cleaning 	<ul style="list-style-type: none"> Cleaner rejects Fiber loss
4: Pulp Dryer	<ul style="list-style-type: none"> Forming and pressing Drying 	<ul style="list-style-type: none"> Fiber loss
5: Chemical Recovery	<ul style="list-style-type: none"> Evaporation Combustion Chemical regenerant 	<ul style="list-style-type: none"> Dregs, grits Lime and mud Scale and inert materials Filtration residue
6: Utilities	<ul style="list-style-type: none"> Water supply Effluent Process cooling Energy 	<ul style="list-style-type: none"> Water treatment sludge Primary effluent sludge Secondary effluent sludge
II. Recycled-Fiber Processing with Deinking		
1: Receiving	<ul style="list-style-type: none"> Storage Conveying 	<ul style="list-style-type: none"> Paper Wire
2: Pulping	<ul style="list-style-type: none"> Coarse screening and cleaning 	<ul style="list-style-type: none"> Tramp metal Dirt, plastic, rope
3: Deinking	<ul style="list-style-type: none"> Flotation or washing 	<ul style="list-style-type: none"> Deinking sludge Fiber rings Fillers, coating
4: Cleaning and screening	<ul style="list-style-type: none"> Forward cleaners Fine screens Reverse cleaners 	<ul style="list-style-type: none"> Dirt sieves Plastics
5: Washing		<ul style="list-style-type: none"> Fiber loss
6: Bleaching	<ul style="list-style-type: none"> Bleach tower(s) Bleach extractors and washers 	<ul style="list-style-type: none"> Fiber loss
7: Storage or pressing and shipping		<ul style="list-style-type: none"> Fiber loss
8: Effluent treatment		<ul style="list-style-type: none"> Sludge
III. Paper and Paperboard Manufacturing		
1: Stock preparation	<ul style="list-style-type: none"> Refining Cleaning, screening Broke handling Wet-end additives 	<ul style="list-style-type: none"> Rejects Broke
2: Forming and pressing	<ul style="list-style-type: none"> White water system Forming Pressing Vacuum pumps 	<ul style="list-style-type: none"> Wet end broke
3: Drying	<ul style="list-style-type: none"> Steam drying Gas dryers Size presses 	<ul style="list-style-type: none"> Dryer broke
4: Coating and screening	<ul style="list-style-type: none"> Coating preparation Coating application Coater drying 	<ul style="list-style-type: none"> Coater broke Coater material
5: Finishing and packaging	<ul style="list-style-type: none"> Rewinders Roll handling Packaging Sheeters 	
6: Effluent treatment		<ul style="list-style-type: none"> Sludge, TSS

4.2 Historical forecasting

The first of the three estimation techniques used here is historical forecasting. In essence, lacking contemporary observation or measurement of NHIW, we can rely on historical figures forecast to the present via some tracking indicator that has a definable relationship with NHIW quantity and composition. Because NHIW is largely a residual waste of a physical process, that indicator variable is simply the physical production of the industry: tons per year of pulp, paper, and paperboard. Deceptively simple, the validity of this method hinges on consideration of both the conditions surrounding the acquisition of the historical figures as well as the effects of important industry changes.

In this section, care is taken to present the context in which historical NHIW figures were collected or calculated. The forecasting itself is straightforward and interpretation that considers qualitative changes in technology, market conditions, and regulatory environment follows.

4.2.1 Background & historical context

Waste from the American pulp and paper industry has been a subject of interest long before federal environmental law dramatically changed permissible levels of air, water, and land pollution, forcing a step change in industrial activity. The 1921 report of the Federated American Engineering Societies' Committee on Elimination of Waste in Industry, which dropped a planned study of the pulp and paper industry "for lack of time and funds" (CEWI, 1921, p. v), nevertheless stimulated the industry's attention to its own sources and types of waste (Skinner, 1939). Although the CEWI focused exclusively on "economic wastes," by 1939 the paper industry had expanded its perspective to include the environmental consequences of its wastes. Motivations for the study of pulping and papermaking wastes included the losses of economically valuable raw materials, the environmental impacts of disposal, and, relatedly, the expectation that laws regarding stream pollution—laxly enforced at the time—would inevitably be made more stringent.

Skinner acknowledged the importance and value of good measurement of pulp and paper mill waste in order to bound the problem ("[W]aste sulfite liquor ... contains roughly half of the original wood ... The production of sulfite pulp in the world is in the neighborhood of 8,000,000 tons annually, which means that almost an equivalent amount of solid material in solution is going to waste."), identify opportunities for waste reduction ("A survey made in 1927 indicated a total of 6 to 7 million dollars worth of white water losses that should be recovered and utilized."), and track progress over time ("A study ... of thirty-nine mills in Wisconsin indicated a reduction of 60 per cent in the fiber losses from 1931 to 1937. This improvement is indicative of the progress which has been made throughout the industry.") (pp. 1332–1334).

In this pre-EPA era, the term "industrial waste" referred often to effluents that today would most likely be categorized as wastewaters rather than as solid wastes. As our purpose is to

understand the solid waste outputs of industry, this dissonance could be problematic. The waste sulfite liquors and fiber wastes with which Skinner (1939) was primarily concerned were of interest because of their solid fractions and because of the high environmental availability of the aqueous medium of disposal. Accordingly, much of the measurement and reporting of wastes from the paper industry distinguished between total waste (measured volumetrically in gallons) and solids (measured in mass units). Warrick (1947) reports on a 1946 survey of 68 Wisconsin mills that yielded perhaps the first near-comprehensive waste account of a state's paper industry: "solids loss" per ton of production of five paper (book, tissue, wrapping, bond, and glassine) and four pulp (rag and de-inked, kraft, sulfite, and groundwood) products. These losses vary significantly among products—with rag and de-inked pulp generating the most Total Suspended Solids and sulfite pulp the most Total Soluble Solids—but also among mills making the same products, a variability that highlights a problem of using average waste intensity figures in waste accounting and forecasting (Warrick, 1947, p. 672).

By the mid-1960s, effluents and wastes from the paper industry had been extensively characterized, in a large part due to NCASI's research and data collection activities, despite the rapid growth of the industry and increasing diversity of its product offerings (Gehm, 1965). But a transition from a largely (if accidentally) comprehensive approach to the study of industrial waste towards one that would ultimately support the federal government's medium-based environmental regulatory framework was underway, the consequence of which would be a fragmented understanding of industrial waste. Shortly after the establishment of the EPA but before the passage of the Clean Water Act the EPA Office of Research and Monitoring initiated a detailed study of "the treatment of liquid effluents produced from the manufacture of pulp, paper, and related products" (US EPA, 1973a; 1971a; 1971b; 1971c).²⁹ The resulting report served as the most state-of-the-art documentation of such effluents and treatment processes and included an encyclopedic account of relevant quantities and compositions, including of suspended solids and wastewater sludges.

Shortly thereafter, the Office of Solid Waste Management Programs commissioned Gorham International, Inc. to develop a "study of solid waste management practices in the pulp and paper industry" (US EPA, 1974b). This is the first study of its kind. While the 1973 report on industrial wastewater built on a strong legacy of related research, "prior to [that] time, the industry's solid waste management activities had not been viewed as a single entity, and the small amount of available information dealt with specific cases and was scattered throughout the trade literature" (p. 1). The Gorham report relied on a combination of industry process modeling, literature review, and five in-depth case studies representative of the diversity of the pulp and paper industry to characterize the solid waste outputs of the industry for the year 1971. By calculating the

²⁹ The lead author the final report from the contractor was none other than Dr. Harry Gehm, founding Technical Advisor of NCASI.

intensity of waste generation (kg/Mg) for each waste category and pulp and paper product in that year and the effect of market size and structure, technology, and regulatory requirements on those intensities, the authors were able to estimate waste generation over the range 1958 to 1980 (Figure 4-13).

In 1971, the majority of the waste output was in the form of bark. This is an important observation because, as a purely solid waste (i.e. not one that could be conflated with wastewater), bark had rarely shown up in previous industrial waste studies. Other waste streams—ash (from incineration of coal and bark), wastewater treatment sludge, and recycled paper waste—were also present in substantial quantities. This study presumed large effects from increasingly stringent environmental regulations expected in the ensuing decade. The elevated cost of wastewater disposal would make increased resource recovery more economically viable, driving overall waste intensities down even with total industry production projected to increase.

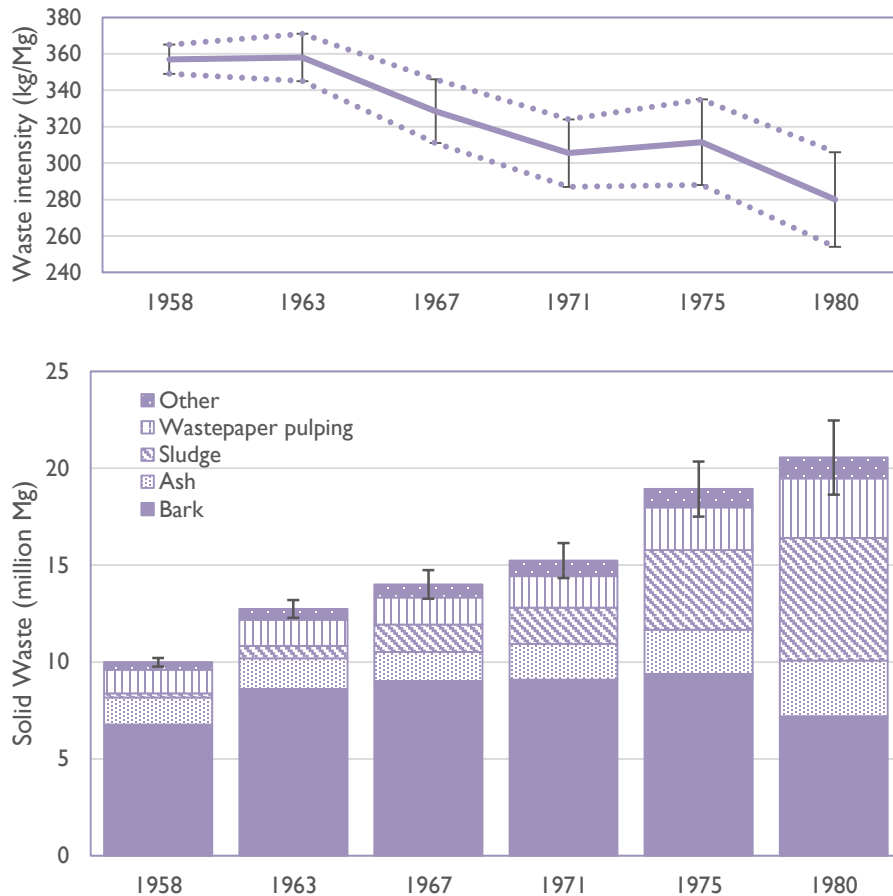


Figure 4-13. Waste intensity (top) and total solid waste generation (bottom) from the pulp and paper industry. Years 1975 and 1980 were forecast. (US EPA, 1974b)

The projections used by the researchers were based on trends still affecting the industry. Bark wastes were projected to decrease as mills used more and more of it for fuel. Ash increases were due primarily to the growth of the industry and its energy demand. Massive increases in sludge disposal were projected because of tightening regulations around water and air pollution. Forecasted increases in the collection and use of recycled paper are also reflected in the waste data.

The study concluded that, for the most part, the pulp and paper industry produced very few wastes that are “toxic, hazardous, or extremely difficult to handle” (US EPA, 1974b, p.141). Hazardous waste laws such as RCRA (still two years in the future) would likely have little effect on this industry, but air and water pollution controls would, largely due to their effect on sludge generation. Resource recovery from sludge would therefore be an appealing strategy to offset increasing costs of pollution control. As sludge quantities and compositions remained an outstanding source of uncertainty in the 1974 Gorham study, uncertainty that would be exacerbated by forecast error, ongoing survey efforts were called for (Joyce, Webb & Dugal, 1979). Subsequent studies validated the 1974 report’s projection of future growth in sludge generation because of tightening air and water pollution controls (Dyer & Mignone, 1983, p. 221).

In the meantime, the passage of RCRA in 1976 provided the EPA with the statutory authority and resources to study current waste patterns and practices in similar detail to that which air and water pollution had received. Following the promulgation of initial regulations regarding non-hazardous waste disposal facilities under RCRA subtitle D, the EPA contracted Energy Resources Company, Inc. (ERCO) to conduct detailed analyses of the “issues of non-hazardous waste disposal for ... four industries,” including pulp and paper for the year 1978 (US EPA, 1980, p. ii). This study built on the previous Gorham report, in fact using many of the same sources, models, and assumptions, but expanded the detail considerably.

ERCO concluded that the industry’s 1978 solid waste was made of wastewater treatment sludge (2,217,000 Mg dry weight), wood wastes (2,000,000 Mg), ash (1,360,000 Mg wet weight), chemical pulping recovery wastes (610,000 Mg), and pulp rejects (460,000 Mg). This total (6,647,000 Mg) is about one third of the total projected by Gorham for 1975–1980. The difference is due most likely to a divergence of reality from Gorham’s projections but also to a difference in wet/dry measurements of sludge and ash. The ERCO report was the last study of the pulp and paper industry before the 1985 SAIC report that partially motivates this research, and is in turn heavily referenced in that report. Since neither ERCO nor Gorham conducted industry-wide surveys in the course of preparing their reports,³⁰ there is an important empirical dimension missing from their conclusions, and possibly contributed to EPA’s later decision to discard the 1985 SAIC estimate in favor of their own 1988 survey result.

³⁰ NCASI (1979) published a survey of waste generated in 21 kraft pulp mills in 1979, but this was used only minimally in the ERCO study.

4.2.2 Baseline

The baseline of the forecasting analysis is the latest reliable and available waste account. The pulp and paper industry is uniquely positioned in this case due to NCASI's ongoing environmental evaluation of the industry. For most other industry sectors, the last available data on non-hazardous waste comes from the 1985 SAIC report (US EPA, 1985) and the 1988 US EPA *Report to Congress*, the same two reports that motivate this research. Because of the availability of more recent survey results (NCASI, 1992; 1999), we can expect the results from this forecasting exercise to be more accurate than it would have been otherwise. It also gives us a limited ability to gauge the reliability of the forecasting method, which had been thrown into question by the vast gulf between the Gorham forecast and ERCO estimate for the late 1970s (US EPA, 1974b; 1980).

SAIC's task was to mine the available literature to construct an assessment of solid waste in industry. As ERCO had done this very task merely five years previously, SAIC relied heavily on ERCO's analysis for the overlapping industries, pulp and paper included. In fact, SAIC did not even attempt to generate what would have been a contemporary estimate, instead amending ERCO's 1978 estimate with 2.2 million Mg of wastepaper rejects, a figure from the 1974 Gorham report that ERCO had pointedly declined to include in their own round-up of waste figures.

NCASI conducted two industry-wide surveys of solid waste generation: focused on 1988 (NCASI, 1992) and 1995 (NCASI, 1999). The latter report was based on a survey of 285 facilities "representing approximately 70% of that year's U.S. pulp and paper production" (NCASI, 1999).³¹ For each product, waste intensities were calculated for wastewater treatment residuals, ash, and miscellaneous solid residues and applied to the remaining 30% of the industry to arrive at a total estimate of 13.25 million dry Mg of solid waste in 1995.³² The baseline estimates from SAIC, NCASI, and the EPA are presented in Table 4-5.

4.2.3 Forecast

The tracking indicator used to conduct the forecast is "waste intensity:" kg waste / Mg product. This is the same method used in every study referenced above that attempted to present an estimate of waste generation, even those that were reporting survey results. NCASI (1999), the most sophisticated and comprehensive survey of the bunch, calculated median waste intensities at a detailed product and waste category level to incorporate mills that were not included in survey results. Many of the extant studies attempted sophisticated forecasting based on expected or observed shifts in production. Gorham (US EPA, 1974b) also quantified the expected effects of

³¹ The 1999 NCASI report also raised some issues with methodology and conclusions of the 1992 report, limiting its use here.

³² This was reported as 14.6 million dry (short) tons.

economic, technological, and regulatory trends in their forecast. Here, I use a simple forecast, whereby waste is calculated as a function of total industry paper and paperboard production (Figure 4-4). Results from this forecast show a surprising agreement between the totals from the 1978 SAIC (via ERCO) estimate and the 1995 NCASI estimate, with the 1988 NCASI estimate coming in somewhat lower (Figure 4-14). However, looking deeper into the data, the agreement looks more tenuous, with few of the waste categories in both forecasts in agreement (Table 4-6).

Table 4-5. Baseline estimates of NHIW from the pulp and paper industry, in million Mg.

	1978 (US EPA, 1985)	1985 (US EPA, 1988)	1988 (NCASI, 1999)	1995* (NCASI, 1999)
Wastewater sludges	2.22		4.20	5.29
Coal and bark ash	1.14		2.55	2.55
Miscellaneous waste			4.00	
Wood wastes	2.00			0.80
Chemical recovery wastes	0.61			1.66
Pulp rejects	0.46			0.86
Waste paper rejects	2.20*			1.07
Other				0.96
Total	8.63	2,042.00	10.75	13.20

*1995 data are recorded at a more detailed level. Chemical recovery wastes include: “green liquor dregs,” “lime mud,” “lime slaker grit,” and “raw process water treatment residuals.” Pulp rejects include “virgin” and “secondary fiber pulping rejects.” Waste paper rejects include “broke not recycled in mills” and “paper mill rejects.” Other includes “general mill refuse” and “other.”

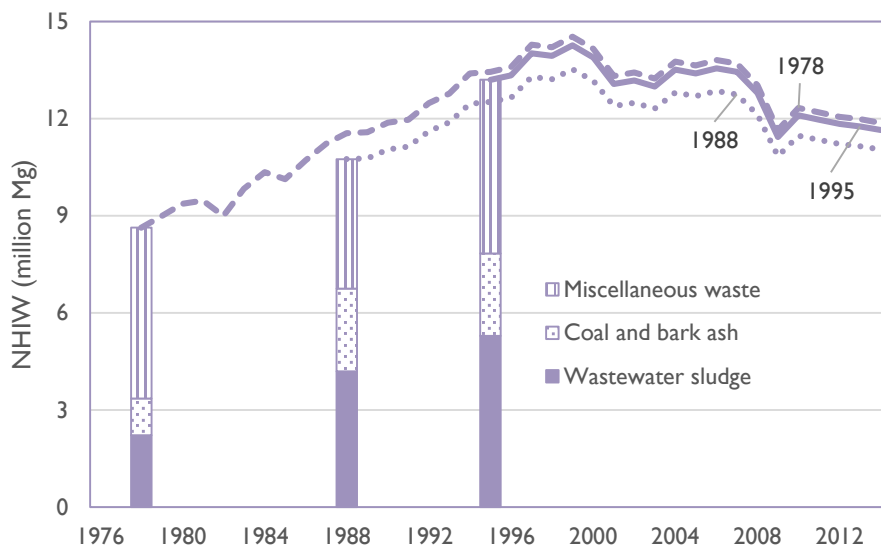


Figure 4-14. Forecast of NHIW generation in the pulp and paper industry from three estimates using time series of total production of paper and board

Table 4-6. NHIW generation from the US pulp and paper industry in 2010 (million Mg) based on 1978 and 1995 estimates and total paper and board production over time.

	2010	
	(1978)	(1995)
Wastewater sludges	3.17	4.85
Coal and bark ash	1.63	2.34
Wood wastes	2.86	0.74
Chemical recovery wastes	0.87	1.52
Pulp rejects	0.66	0.79
Waste paper rejects	3.14	0.98
Other	n/a	0.88
Total	12.33	12.10

4.2.4 Discussion

The differences between the two forecasted estimates can be partially explained by qualitative (directional) changes in technology, market/economic factors, and regulatory requirements. Because of the linear nature of the forecasting technique, the proportions of waste represented within each forecast (i.e. 1978 vs. 1995 basis) are the same as in the source. Differences in the 1978-2010 forecast and 1995-2010 forecast are a result of changes to waste outputs between 1978 and 2010. These are not the only possible explanations, but are some that are defensible from the literature review and from NCASI's (1999) explanation of changes from 1988 to 1995.

The observed increase in wastewater sludge generation is due to restrictions on water and air pollution, requiring more and more solid material to be scrubbed out and disposed. An increase in ash is due to an increase in on-site power generation of both coal and wood waste, as well as, possibly, improved fly ash capture. This is related to the decrease in wood wastes; superior on-site energy production makes economical use of hog fuel. Chemical recovery wastes have increased possibly because of a shift in product mix towards more kraft pulping, increased chemical recovery efforts (which would lead to increased disposal of related solids, rather than seeing it all go down the drain), or more stringent water pollution restrictions. Pulp rejects have increased because of increased use of recycled paper. The large change in waste paper rejects might be a result of improved processing and screening of waste paper, but more likely the original Gorham estimate of waste paper rejects (2.2 million Mg) was wrong, as ERCO originally suspected but SAIC added back into the estimate. It is also likely that the different data collection methods used in the 1978 and 1995 studies have accounted for similar wastes in different categories.

4.3 Materials balance

Materials balance of the pulp and paper industry holds a notable place in the multi-decadal search for an accurate estimate of non-hazardous industrial waste. Specifically, Allen & Behmanesh (1992) used a rudimentary materials balance logic to demonstrate that the two prevailing estimates of NHIW—392.6 million Mg from the 1985 literature review performed by SAIC for the U.S. EPA and 6,900 million Mg from a 1986–1987 telephone survey of industrial Subtitle D facilities (US EPA, 1988)—not in as much conflict as they appeared to be. By looking closely at the industry with the largest absolute gap in reported waste output between the two studies, which happened to be the pulp and paper industry, the authors argued that both estimates (8.6 million Mg from 1985 and 2,043 million Mg from 1986–7) could be accurate if the former represented just the dry fraction of solid wastes while the latter included a considerable volume (and therefore mass) of dilute wastewater. Referencing a source that claimed a single large mill consumed 110–150 million gallons of water per day, or 45 million Mg/year, the two billion Mg of NHIW in the form of dilute wastewater could be conceivably generated by 20–30 large mills. This type of simple materials balance logic, also applied to a fraction of the chemicals industry in the article, brings legitimacy to the SAIC study that had been discarded almost immediately by industrial materials policymakers. It also reinforces the assertion that the majority of the 6.9 billion Mg of NHIW reported in 1988 and again by the US OTA (1992) is predominately dilute wastewater, demanding a closer look to determine the solid waste fraction.

In this section, the materials balance method is applied to the pulp and paper industry to determine solid waste generation rates. I begin with a review of the literature, focusing on three models of the industry with distinctly different levels of analysis. Then I propose a refined model based on the literature and available data but tailored to estimating solid residuals generation. A summary of all of the waste estimates from materials balance methods concludes the section.

4.3.1 Literature

The use of materials flow analysis to study the pulp and paper industry is not uncommon. As with all process industries, material and energy flow models have been used to identify opportunities for improved energy performance (AIChE, 2006), cleaner production (Žarković, Rajaković-Ognjanović & Rajaković, 2011), and water reuse (Byers et al., 2003, p. 4-15). In addition, various material flow analysis techniques have been used to study the dynamics of material and energy inputs to paper manufacturing in the U.S. (Ruth & Harrington, 1997), the U.K. (Sundin et al., 2001), and India (Beukering & Duraiappah, 1998); as well as the integration of a pulp and paper mill into industrial symbiosis (Sokka et al., 2011).

Materials balance methods are of particular use in estimating industry-wide residuals generation because the mass conservation constraint enables insight without empirical

observation. As such, they have been applied at multiple levels of analysis of the industry. At the lowest level of analysis, or highest data resolution, are detailed industrial process models, such as those used in the Resources for the Future industry residuals studies (Bower, 1975). These models are technically complex, and therefore usually limited in scope to a single integrated mill, although model parameters can be varied to represent a variety of mill technologies and configurations.

Occupying a medium level of analysis are models of pulp and paper production like that at the center of an “environmentally-balanced industrial complex” (Nemerow, Farooq & Sengupta, 1980). This model does not have as high resolution as the detailed process models, and is abstract enough to be able to represent a large fraction of the entire industry.

At the highest level of analysis, the pulp and paper sector is embedded in a broader forest products industry (Ayles & Ayles, 1993). At this level of analysis, material flows are aggregated together to such a degree enabling government statistics to be used to infer missing mass flows.

The following subsections present examples of studies at each of these three levels of analysis and the estimates of non-hazardous industrial waste production that each yields.

4.3.1.1 Resources for the Future Industry Residuals Study, 1971

The third study of the Resources for the Future (RFF) industry residuals management research program examined the “very complex pulp and paper industry, look[ing] at eleven residuals, five discharged to the atmosphere, four discharged to water courses, and two solids” (Russell & Vaughan, 1976, p. xvi). The study was conducted in order to understand “the basic technologic, physical, and economic interrelationships among the two basic types of residuals—materials and energy, and the three states of the former—liquid, gaseous, and solid” (Bower, 1975, pp. 276–277).

Bower continues: “an adequate industry study requires the calculation of almost complete materials, electric energy, and heat balances for the production processes involved” (p. 283), which, in the case of the pulp and paper study relied on “outside consultant expertise in the technology of the industry to develop materials balance and flow diagrams for the various processes in the industry, information not available anywhere in the published—or even in unpublished—literature” (p. 282).

The pulp and paper study approached the generation of residuals as a function of raw material type, pulping process, bleaching sequence, papermaking process, converting operation, and the quality and characteristics of the desired product (Bower, Lof & Hearon, 1971, p. 608). To accomplish this task, the researchers developed an integrated simulation model of the industry, spanning from forestry to wastepaper collection and recycling (Bower, 1975, pp. 318–319). They

then observed the output of the model (i.e. the simulated residuals generation) as input parameters were varied among realistic options.³³

Published results are limited to the cases of newsprint (Bower, Lof & Hearon, 1971, p. 614) and tissue (napkin) paper products (Kneese & Bower, 1979, pp. 65–67), with a considerable variety of other input parameters. Results are summarized in Table 4-7. In general, newsprint production is less residual-generating than is tissue paper production. Calcium and ammonium base sulfite pulping create a tremendous amount of liquid residuals (mainly in the form of dissolved organic solids), much more than the output of the now dominant kraft sulfate process. Sulfite pulping cases also tend to create the most solid residuals, exceeding solid waste from kraft pulping by 2.3 times, according to Bower, Lof & Hearon (1971, p. 617). Reliance on wastepaper rather than softwood pulp (the simulation default feed material unless wastepaper is designated in the model) also decreases solid residual production.

More specific and quantitative conclusions could have been drawn from the use of the simulation model. Residuals in all three media are presented here because, although the focus is explicitly on solid waste, the RFF studies were performed at the very beginning of the era of industrial environmental transformation in the United States. The EPA had been founded a mere ten months before the Bower, Lof, & Hearon study was published in October 1971, and Clean Water Act and Clean Air Act regulatory programs would not start influencing industry behavior for many years to come. As a result of environmental regulations, many of the residuals modeled by RFF as gaseous or aqueous would be required to be scrubbed out of those media and disposed as solid waste. So, although this model preceded an important regulatory sea change, the results are potentially useful nonetheless. On the other hand, the somewhat narrow snapshot of pulp and paper industry operations represented by the published simulation model results limit the representativeness of the residuals generation ranges.

Table 4-7. Range of modeled outputs from the RFF pulp and paper industry residuals study; residuals in gaseous (G), liquid (L), and solid (S) form, in units of kg residual/Mg air-dry paper. (Bower, Lof & Hearon, 1971, p. 614; Kneese & Bower, 1979, pp. 65–67)

Residual	Newsprint			Tissue		
	Min	Median	Max	Min	Median	Max
G	0.0	11.5	16.1	0.0	34.2	76.8
L	113.2	178.3	335.6	88.7	278.7	2017.6
S	11.0	15.5	28.0	13.3	39.9	70.6

³³ The inclusion of economic factors in the model enabled the researchers to draw some conclusions not only about the costs of current residuals management but also the potential future costs of increased environmental regulations (e.g. Bower, 1975, p. 307). This is outside the scope of this dissertation, although it is fascinating research.

4.3.1.2 Environmentally-Balanced Industrial Complex, 1977

Nemerow's extensive work developing models of "environmentally-balanced industrial complexes" (EBICs) offers another approach to industrial-scale material balance. Nemerow, Farooq & Sengupta (1980) first presented a model of an industrial complex centered on a 1,000 (short) ton per day (907 Mg/day) sulfite pulp and paper mill in 1977. The objective of their complex was, similar to industrial symbiosis, to identify complementary industrial processes that can effectively eliminate pollution from papermaking. Through a network of various plants, the model complex produces five products for sale on the open market in addition to fine paper: low grade wrapping paper, paperboard, pressed hardboard, vanillin, and road binder.

The "balanced" criterion of the EBIC requires material flows throughout the complex to be quantified. Various composition factors are used by Nemerow, Farooq & Sengupta, although their sources are not referenced. For example, the authors claim that fiber losses in paper production equal 1.68% of production (which are claimed as the only losses from papermaking); sulfite liquor is generated at a rate of 300 gal/ton (1.25 m³/Mg), 11% of which is dissolved solids; and bark is discarded from a pulp mill at a rate of 15% of production. Other factors, including some drawn ostensibly from Nemerow (1978) are used for the remainder of the EBIC material balance, and are not relevant for this study.

Working backwards from desired paper output of 907.2 Mg, fiber losses from papermaking total 15.2 Mg. Pulp input to the papermaking process must therefore equal 922.4 tons. With a sulfite liquor generation rate of 1.25 m³/Mg, a dissolved solids concentration of 11%, and a liquor density equivalent to that of water (1 kg/m³), dissolved solids in sulfite liquor total 126.9 Mg. The stated bark waste generation rate assumption of 15% yields 138.4 Mg of bark, sent to energy recovery. Generation rates in units of kg/Mg paper produced are shown in Table 4-8. Inputs to the sulfite pulping process are pulpwood, recycled groundwood pulp fines, and sulfite pulping chemicals: calcium hydrogen sulfite (Ca(HSO₃)₂) and sodium bisulfite (NaHSO₃), from primary and secondary sources.

Table 4-8. Waste outputs from the 1,000 Mg/day pulp and paper mill at the center of an environmentally-balanced industrial complex (Nemerow, Farooq & Sengupta, 1980, p. 66).

Waste type	(Mg)
Papermaking wastes	16.8
Sulfite liquor sludge	139.9
Bark	152.5

The Nemerow material balance reviewed is limited and flawed. Pulping and papermaking chemical inputs are mentioned, they are not given any mass, and, as mentioned earlier, most of the waste factors used in the balance are not robustly sourced. Furthermore, it appears as if the figures have not been updated since initial publication in 1980 (actually 1977, when the model was presented at a conference in Calcutta, India). This is despite attempts by the authors to acknowledge the transition from sulfite to kraft sulfate pulping, a transition that has come with considerable changes to industrial material inputs and outputs. If anything, the technological change has been dealt with by simply and incompletely switching the "i" for the "a" in parts of the diagram as it has been repeatedly republished in Nemerow 1995, p. 116), Nemerow & Agardy (1998, p 209), and Nemerow (2007, p. 435), without making any changes to the material balance. Interestingly, Nemerow does develop a qualitative model of an EBIC based on a kraft mill (2007, p. 439), but does not offer a material balance.

In a related study, inputs and outputs are presented for a 1,000 Mg/day integrated kraft sulfate pulp and paper mill (Tewari & Nemerow, 1982, p. 357-359). Presumably these figures are given in the spirit of defining the *potential* for waste reuse and raw material substitution by an EBIC, similar in spirit to this dissertation research. The authors drew their values from five sources: two EPA reports from the mid-1970s and what appear to be three pulp and paper industry textbooks from the 1950s. So, while the numbers are out of date (and not mass-balanced), they offer yet another estimate of waste production. The figures are reproduced in Table 4-9.

The solid waste fraction from energy recovery incineration is ash, the non-incinerable fraction of wood biomass made up mainly of various oxides of calcium, potassium, magnesium, etc.

Table 4-9. Inputs and waste outputs associated with a 1,000 Mg capacity integrated kraft pulp and paper mill. From Tewari & Nemerow (1982, p. 357).

Inputs	(Mg)	Waste Outputs	(Mg)
Wood chips	2,200	Total solids in wastewater ³⁴	370
Caustic soda	200	Bark	160
Sulfur	40	Fines	160
Lime	30	Sawdust	50
Chlorine	50	Inert matter	40
Chlorine dioxide	4	Others	5

³⁴ The source article lists multiple wastewater constituents, but it is unclear whether or not "Suspended Solids" (45.5 Mg) and/or "Color" (136.4 Mg) are included within the category "Total Solids."

4.3.1.3 *Industrial Metabolism, 1993*

Ayres & Ayres (1993; 1998) examine the paper industry as a component of the extended forest products industry, alongside forestry and lumber and wood products (excluding furniture). Given the essentiality of wood to pulp and paper production, it comes at little surprise that Ayres & Ayres's material balance is dominated by wood of different uses and, crucially to the full material balance, different water content values, with very small non-wood constituent flows. By the time the wood reaches the pulping process, it has been air dried to 15% water content (down from 48% contained in raw wood biomass but not "oven dry," which requires heating to achieve). The inputs and outputs for the two relevant industrial processes, pulping and papermaking, and wood fuel incineration for of Ayres's subject year of 1993 are listed in Table 4-10. The constraint of the material balance method is in force; inputs and outputs in each of the three process stages are equal (pulping = 158.8 million Mg, papermaking = 86.4 million Mg, wood fuel = 333.9 million Mg), sometimes contradicting source data or other corroborative sources referenced by the authors.

The interdependencies of these three industrial process steps are somewhat apparent from the input and output data: the woodpulp that makes up the primary saleable output of pulping operations is nearly all consumed by papermaking; Ayres estimates that 0.5 million Mg of woodpulp "was diverted to net exports, inventory changes, and 'dissolving grade' cellulose for the chemical industry" (p.59). Similarly, the lignin wastes from pulping are shown to be consumed in entirety in combustion for energy recovery.

The chemical requirements for both pulping and papermaking add complexity to Ayres's material balance model. Pulping chemicals that are not recovered are required to be replaced: in 1993 this value is estimated to be 8.1 million Mg. (This statistic is one that exposes conflict in the material balance. Ayres notes that pulp mills can recover upwards of 99.5% of the sodium hydroxide, sodium sulfide, and other chemicals used in the kraft and related processes, but consumption data from USGS Minerals Yearbooks of these same chemicals suggest a much lower recovery rate. Ayres does not offer an explanation.) The chemicals that require replacement are mostly lost in wastewater (counted in the "sludge" category in Table 4-10) or incinerated along with the rest of the black liquor.

On the other hand, papermaking chemicals are all embodied in the products, at least according to the model. This includes filler clays, and whiteners and dyes. Ayres's estimate of chemical inputs to the entire pulp and paper industry for both subject years, 1988 and 1993, is reproduced in Table 4-11.

The solid waste fraction from energy recovery incineration is ash, the non-incinerable fraction of wood biomass made up mainly of various oxides of calcium, potassium, magnesium, etc.

Table 4-10. Summary of the inputs (L) and outputs (R) from the Ayres & Ayres (1998, p. 56) material balance of the pulp and paper industry in the US for the year 1993 (million Mg).

INPUTS		OUTPUTS	
Pulping			
Pulpwood		Woodpulp	57.6
Roundwood to pulp	106.8	Lignin wastes (15% H ₂ O)	88.0
Lumber mill residue	38.2	Sludge	13.2
Pulpwood net from imports/inventory	5.7		
Chemicals	8.1		
Papermaking			
Woodpulp	57.1	Paper and paperboard products	82.8
Other fiber	0.2	Internally recycled waste	3.6
Chemicals	3.7		
Waste paper			
Recycled paper	21.8		
Internally recycled waste	3.6		
Wood fuel			
O ₂	166.2	CO ₂	228.5
Roundwood fuel	57.2	Ash	2.2
Lumber mill residue	22.5	H ₂ O	103.1
Pulp plant residue	88.0	heat	

Although the industry-scale of Ayres's models necessitates many gross estimates (which I do in my models as well!), it nonetheless is not inappropriate to point out holes in the model. In particular, it is curious that the model excludes material balances in the repulping of recycled wastepaper. He acknowledges that the chemical inputs to papermaking (kaolin filler, predominantly) are lost in repulping, yet this mass is somehow not within the boundaries of the system.

Table 4-11. Estimates of chemical requirements of the U.S. pulp and paper industry in 1988 and 1993, as reported in Ayres & Ayres (1998, p. 60). All numbers in thousand Mg.

Chemical		1988	1993
Sulfuric acid	H ₂ SO ₄	826	304
Sulfur	S	8	27
Lime	CaO	1,140	1,190
Magnesium hydroxide	MgO	150	253
Caustic soda	NaOH	2,400	2,390
Chlorine	Cl ₂	1,500	950
Oxygen	O ₂	--	290
Hydrogen peroxide	H ₂ O ₂	--	120
Sodium chlorate	NaClO ₃	200	828
Sodium chloride	NaCl	340	115
Sodium carbonate	Na ₂ CO ₃	110	140
Sodium sulfate	Na ₂ SO ₄	240	180
Kaolin	clay	3,960	3,460
Titanium dioxide	TiO ₂	243	350
Aluminum sulfate	TiO ₂	300	300
Total	Al ₂ SO ₄	11,417	10,897

4.3.2 Model structure and data

The materials balance model of the pulp and paper industry presented here is based mainly on the model by Ayres & Ayres (1998) discussed above. Following their lead, this model is informed more by general descriptions of inputs and outputs than by a detailed characterization of the chemical and physical transformations that occur within each industrial sector. Nevertheless, with knowledge of the industrial processes, inevitable conflicts among data sources might be able to be explained, if not reconciled.

Data for this material balance comes primarily from two government sources: the U.S. Department of Agriculture (USDA) Forest Products Laboratory (FPL) and the U.S. Geologic Survey (USGS); the former aggregates various data about the pulp and paper industry (much of which originates in the American Forest & Paper Association's (AF&PA) statistical publications), while the latter publishes the *Mineral Commodity Summaries* (MCS) and the *Minerals Yearbooks* (MYB). Guidance on where to look for data came from the *Statistical Abstract of the United States* (SAUS) and the original Ayres & Ayres paper (1993) and book (1998).

The literature informing construction of material flow accounts explicitly state that the conceptual model (i.e. processes/activities and flow categories) should be constructed without considering data availability (Brunner & Rechberger, 2004). In these formalizations, only through analytical iteration does data availability inform model parameters. In reality there is often a much

more muddled process of model formulation that includes data availability early in the process. Here, data availability is fundamental to model form; particularly in the case of chemical inputs, the assumption is made that government sources of data have identified the major mass flows into the pulp and paper industry, and therefore whichever substances are identified by the sources are those that are included in the model.

As explained above, Ayres & Ayres model the pulp and paper industry as part of a larger forest products industry. Here, I focus on four activities of the pulp and paper industry and exclude the upstream forest and wood products sectors. The four activities are: Pulping, Papermaking, Wood Fuel, and Re-pulping. The model, highlighting major material flow pathways, is illustrated in Figure 4-15.

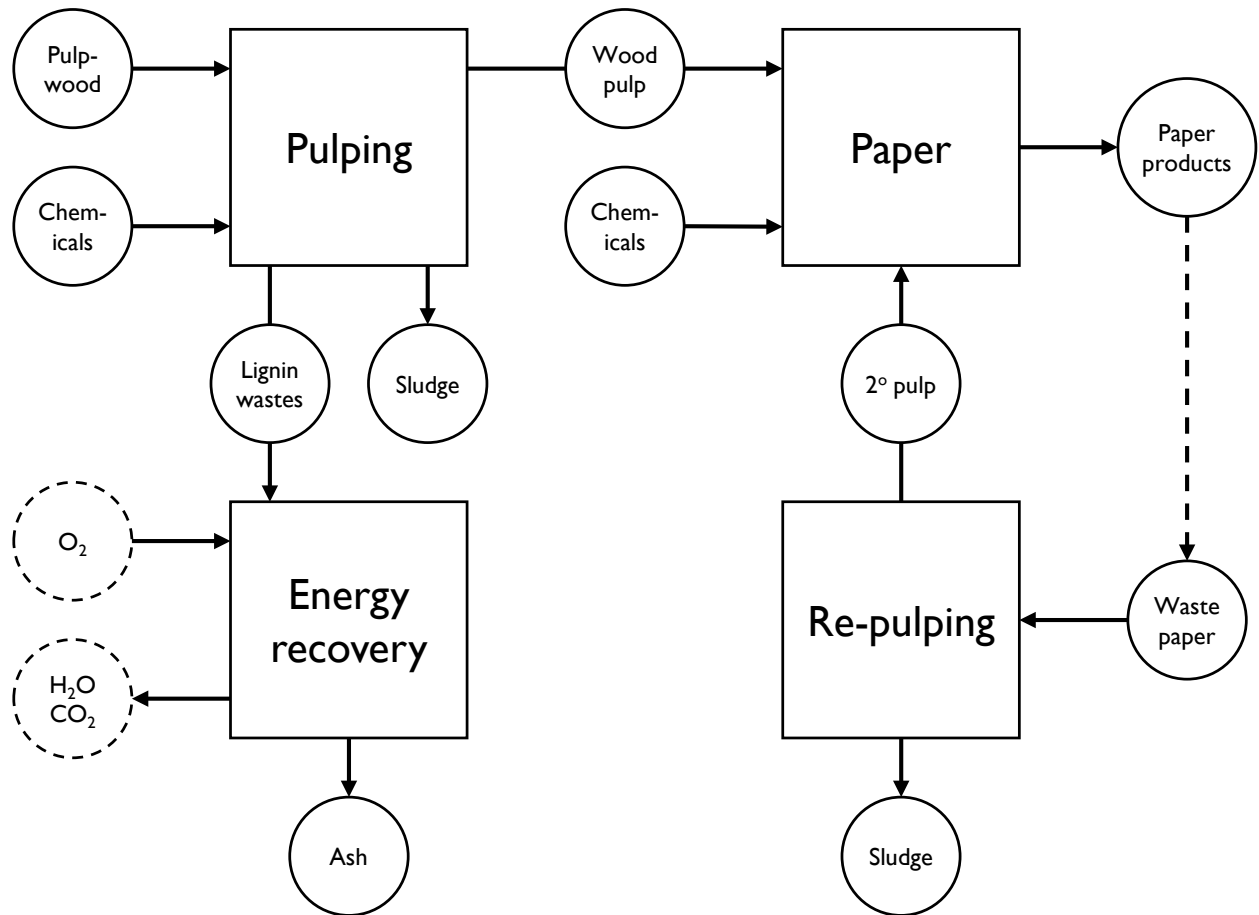


Figure 4-15. High-level model of the pulp and paper industry used in the material balance.

4.3.2.1 Pulping

The primary inputs to pulp mills are pulpwood and chemicals. Pulpwood inputs include bolts and logs³⁵ of softwoods and hardwoods as well as pulpwood chips, slabs, cores, sawdust, bark, and other mill residues. Virgin pulpwood is chipped before pulping, and unsuitable parts of the logs, such as bark, are burned for heat energy.

Pulp mills recover a large fraction of the chemicals used for pulping, so new consumption is limited to replacing lost pulping chemicals and adjusting for production volume. Given that the kraft sulfate process dominates the chemical pulping industry, input chemicals are overwhelmingly the kraft process chemicals sodium hydroxide (NaOH) and sodium sulfide (Na₂S) and their precursors, soda ash (sodium carbonate, Na₂CO₃) and sodium sulfate (Na₂SO₄); and the lime (calcium oxide, CaO) used in the recovery of the process chemicals.

Other chemical inputs are used mainly for pulp bleaching. There are many bleaching technologies; bulk material inputs for bleaching seem to include: chlorine (Cl₂), sodium chloride (salt, NaCl), sulfuric acid (H₂SO₄)³⁶ and sodium chlorate (NaClO₃).³⁷

The outputs of pulping are finished pulp, extractives, and pulping wastes. Pulping wastes can be divided into an organic fraction that is the non-cellulose components of input pulpwood (lignin, hemicellulose, resins, etc.) and an inorganic fraction that is made up of pulping and bleaching chemicals (see the lists above; various other chemical species are generated in liquor recovery and air and water pollution control processes). The organic content of the waste is incinerated as part of the liquor recovery process (also producing heat used to power the mill), leaving all unrecovered chemical content and incineration ash for final disposal.³⁸ A very small fraction of outputs are extractive by-products such as turpentine and tall oil.

A detailed diagram of the pulping process material balance model expanded in subsections below is given in Figure 4-16.

³⁵ A “bolt” is a processed tree trunk less than eight feet in length; a “log” is the more commercially acceptable length, > 8 ft. (Bousquet 2001).

³⁶ It is somewhat unclear the main uses of sulfuric acid and elemental sulfur in pulping; various sources suggest its use as a precursor chemical in sulfite pulping, while others suggest a similar role in bleaching. Thankfully, this method does not require precise knowledge of the function of each input material, since all inputs must become outputs.

³⁷ Chemical inputs to pulp and papermaking are too numerous to list. One particularly comprehensive example can be found here: <http://www.paperonweb.com/chemical.htm>

³⁸ It should be reminded here that this model does not indicate actual waste disposal practices of the industry. The “lost mass” method can only illuminate the fraction of inputs that are left as residuals; whether they are in fact scrubbed from air emissions or water pollution requires different research methods.

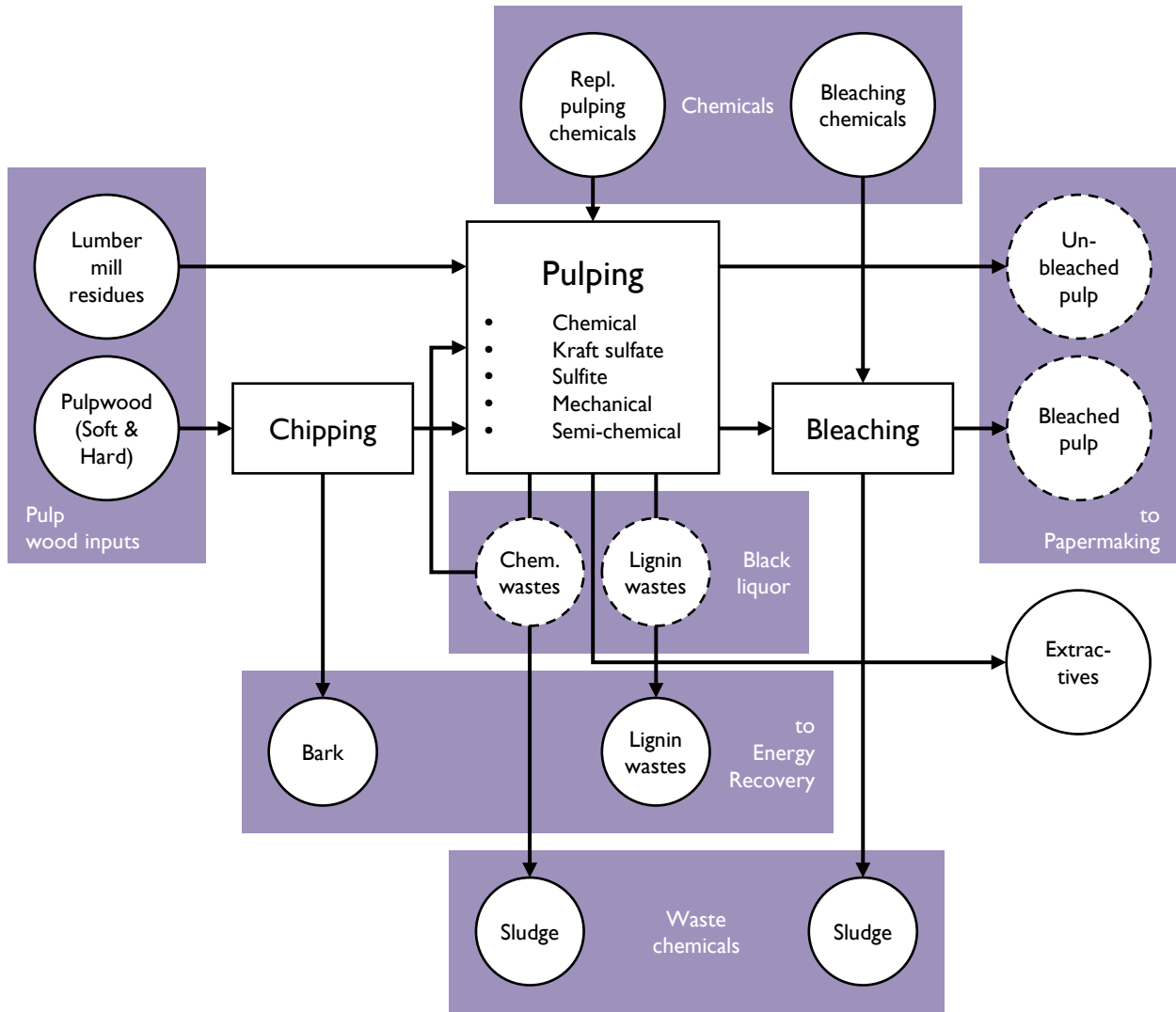


Figure 4-16. Detailed conceptual material balance for pulp production from wood, with inputs and outputs categorized

4.3.2.1.1 Pulpwood input

Timber data in the United States is reported almost exclusively in volumetric terms, rather than in the mass terms that would facilitate this materials balance.³⁹ Pulpwood consumption in units of cords is reported in Howard & Westby (2013, pp. 53). A standard cord is “a unit of measure for stacked bolts of wood, encompassing 128 cubic feet of wood, bark, and air space” (US FS 2013).

The simplest way to use the reported volume of pulpwood inputs would be to use estimates of wood density (mass/volume) to convert cords to kg. Estimates of this type abound; it is important to clarify details such as wood species, moisture content, and even quality of stacking (Worthington & Twerdal 1950). Just-felled timber, or “green wood,” has a very high moisture content; Ayres & Ayres use a figure of 48% moisture content of green wood.⁴⁰ Air-dried wood, which is the status of pulpwood when it arrives at a pulp mill and (often) the basis in which volumetric data is reported,⁴¹ has a moisture content between 15–25% (FPL, 1999, p. 4; Howard & Westby, 2013, p. 32).⁴²

Haynes (1990, p. 262) reports average values of mass per standard cord of air-dried (15% moisture content) softwood and hardwood for the year 1986. Converted to SI units, these values are 1.27 Mg/cord softwood and 1.45 Mg/cord hardwood. These conversion factors are roughly corroborated by other data sources. The Forest Products Laboratory (1999, p. 20) reports the average weight of 2.36 m³ of 36 species of hardwoods and 35 species of softwoods at 25% moisture content. That seemingly arbitrary volume was selected as it corresponds to 1,000 board feet, another industry-specific unit that is equal to the volume of a board one foot square and one inch thick. Strangely, a thousand board feet seems to be the same volume as a cord of timber—remember, the volume of a cord is 128 ft³, but that only contains 80–85 ft³ of actual wood (US FS, 2013). Since 1,000 board feet equals 83.33 ft³, maybe there is some logic to this system after all! The FPL (1999) data report a range of 934–1,944 kg/cord for hardwood densities and 865–1,625 kg/cord for softwood densities. DeWald, Josiah & Erdkamp (2005) also corroborate these figures.

³⁹ See Ayres & Ayres (1998, pp. 65–66), endnote #2 for their take on this vexing problem.

⁴⁰ The timber industry uses a measurement of moisture content based on oven-dried (or “bone-dry”) mass of wood. Green wood moisture content is reported as $(m_{\text{green}} - m_{\text{oven-dried}})/m_{\text{oven-dried}}$ (Reeb 1997). It is therefore common to see moisture content measurements in excess of 100%, since 100% simply means that 50% of the mass of the green wood is moisture. It is highly likely that Ayres & Ayres do not use this idiosyncratic measurement, instead opting for a more rational approach of reporting on the fraction of the actual thing being measured (i.e. $(m_{\text{green}} - m_{\text{oven-dried}})/m_{\text{green}}$).

⁴¹ Shrinkage is not an inconsequential concern from drying: oven drying can shrink green timber up to 7.4% in the radial dimension and up to 11.7% in the axial direction (FPL 1999).

⁴² Due to the confusion over the “moisture content” measurement, it is unclear if those figures are on an air-dry or oven-dry basis. At these low moisture content percentages (15–25%) the differences in the two measurements ($(m - m_{\text{oven}})/m_{\text{oven}}$), $(m - m_{\text{oven}})/m$) is small. Non-water content (or “oven-dry mass,” the conserved figure for this material balance) varies 2.3% using the two measures at 15% moisture content and 6.3% at 25% moisture content.

The FPL published data (Howard & Westby, 2013) for pulpwood consumption is the annual sum of consumption in pulp mills of softwoods, hardwoods, residues, and net imports. The data is reported in two different tables in the report (Table 24, p. 53; Table 50, p. 81), and although the accompanying spreadsheet formulas indicate Table 50 linked to Table 24, the numbers diverge for the most recent years (2006–2011). No explanation for the divergence has been found (data from Table 24 was used here). Using the conversion rates from Haynes (1990), the consumed pulpwood can be converted from thousand cords (as reported) to Mg. Values for residues and net imports are assigned the same ratio of hardwood/softwood as domestic production of pulpwood (this becomes important in later material balance steps). The resulting mass flow is illustrated in Figure 4-17.

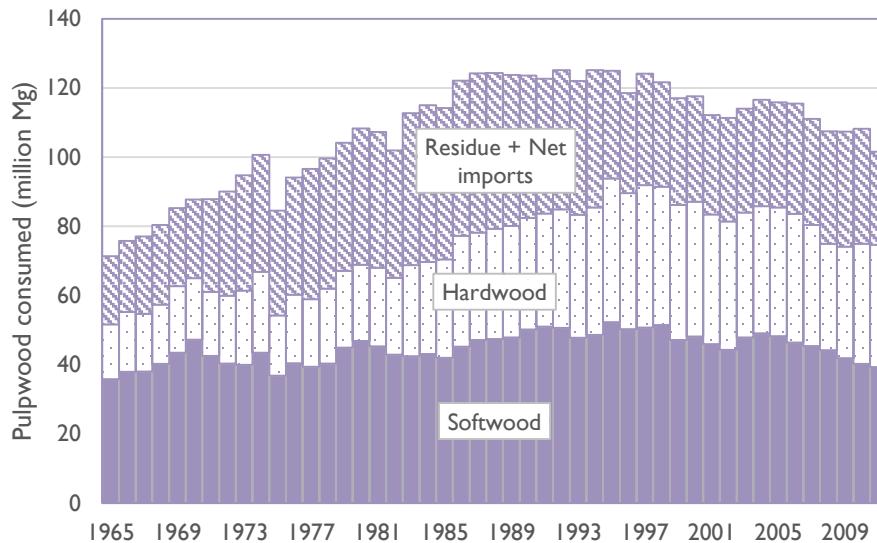


Figure 4-17. Pulpwood consumed in pulp mills in the U.S., 1965–2011 (million Mg). Pulpwood volumes (in thousand cords) from Howard & Westby (2013, p. 53); volumetric conversions from Haynes (1990, p. 262).

According to this estimate, consumption of pulpwood peaked in 1992 with 125.2 million Mg; coincidentally this is just one year removed from the Ayres & Ayres (1998) subject year. Their estimate of pulpwood feed for the year 1993 is 150.7 million Mg, 23.5% greater than my estimate of 122.0 million Mg. The reason for the difference is not readily apparent, in part because Ayres & Ayres are not as transparent with their raw data sources and conversion factors as they could have been. The earlier version of the FPL report that Ayres & Ayres relied on (Howard, 1997) did publish different numbers than the 2013 version: Howard (1997, p. 37) reports 1993 pulpwood consumption in U.S. mills of 103,592,000 cords, while Howard & Westby (2013, p. 53) report

consumption of just 90,996,000 cords for the same year. This 13.8% difference may be exacerbated by the use of different volumetric (cords to mass) conversion factors. For example, my conversion factors exclude bark content, while the Ayres' conversion factors may include it. Consider: if bark is generated at a rate of 40–56 kg (dry) / m³ incoming wood (US EPA, 1980, p. 3-27), the reported 1993 consumption of roundwood at pulpmills in the United States of 62,410,000 cords (226,200,000 m³ at 1 cord = 128 ft³ = 3.62 m³)⁴³ would yield 9–12.5 million Mg of bark, sufficient to satisfy the difference observed between the Ayres & Ayres and my own estimates of pulpwood consumption, after acknowledging the disparity in the source data. Therefore, the values in Figure 4-17 represent mass post-chipping, while Ayres & Ayres (1998, pp. 59–61) acknowledge the flow of bark from pulpwood for use as “hog fuel.”

A final characteristic of the input pulpwood that influences the material balance is the chemical composition of the wood. Wood is made up of cellulose, a variety of hemicellulose compounds, lignin, extractives, and ash, the relative compositions of which are species-dependent. According to one source, ranges for wood constituents are: cellulose (40–50% oven-dry weight), hemicelluloses (25–35%), lignin (18–35%), extractives (4–10%), and inorganic ash (<1%) (Pettersen, 1984, pp. 58, 68). Values for typical soft- and hardwoods used in pulping and papermaking are shown in Table 4-12.

Table 4-12. Average values of the primary constituents of common pulpwood species as a percent of dry wood weight. From Sjöström & Westermarck (1999, p. 3).

Constituent	Softwood	Hardwood
Cellulose	37–43%	39–45%
Hemicelluloses	20–30%	17–35%
Lignin	25–33%	20–25%
Extractives	2–5%	2–4%
Ash	< 1%	< 1%

⁴³ The full volumetric conversion of 1 cord = 128 ft³ is used here (rather than the wood content-corrected conversion of 80–85 ft³) because that is the standard in which the bark conversion estimate is (probably) reported. Yet another example of the absurdity of using volumetric rather than mass measurements.

4.3.2.1.1.1 Pulping chemicals

Chemical inputs to pulping are technology dependent. It is widely reported that the kraft sulfate pulping technology overwhelmingly dominates the market for virgin pulp. By the turn of the 21st century, kraft pulp mills made up 98% of total chemical pulping capacity in the United States (US DOE, 2005, p. 29), generating 82% of all virgin pulp (US EPA, 2002, p. 8). Sulfite chemical processes generated just 2%, semichemical processes 6%, and mechanical processes 10%.

Given that mechanical pulping requires few chemicals, pulping chemical inputs are therefore mainly the replacement chemicals for the dominant kraft sulfate process: sodium sulfide (Na_2S) and sodium hydroxide (NaOH) and/or their precursors, as well as the lime compounds used in the kraft recovery process. (Sulfite pulping uses sulfurous and related acids (H_2SO_3), while semichemical processes use sodium sulfite (Na_2SO_3) and sodium carbonate (Na_2CO_3), among other chemicals.) Lacking reliable information on chemical recovery rates, I rely entirely on shipments and consumption data from government statistical offices.

Data is published by two agencies. Information on shipments of chemicals to the pulp and paper industry is collected and published by the U.S. Geological Survey in their annual *Minerals Yearbooks* and *Mineral Commodity Summaries*. These reports are intended to provide a nation-wide (and in some cases global) overview of the size and dispensation of vital mineral resources. The list of minerals is extensive, having grown considerably since first published in 1933.⁴⁴ In recent years, government funding cuts have led to a reduction in the breadth and depth of research and publication of the USGS and other government statistical agencies.

One might expect supply-side data to be on the high end of available estimates for chemical consumption by the industry, since it is in the form of mineral or mineral compound precursors to process chemicals. In some cases, the publications are clear about the composition and quality of the shipments, but not always.

On the demand side, the U.S. Census Bureau publishes a semi-decadal *Economic Census* (EC) (in years ending in two and seven). This is an extraordinarily varied data source, with information derived from a survey of nearly four million business throughout the United States and its territories. As such, data quality is sometimes questionable, and the Bureau is quite conservative in disclosing information that could possibly be thought of as threatening firms' competitive positions. Furthermore, as is the case with much of the data that is used by industrial ecologists to evaluate material flows, there is greater confidence and resolution in the financial figures than in the reported mass figures, but identifying appropriate conversion factors is a fraught challenge in itself.

⁴⁴ Previous publications, including *Mineral Resources of the United States*, have been published regularly since the middle of the 19th century.

The *Economic Census* reports data at the six-digit NAICS code level. There are four industry sectors at this level that are within the pulp and paper industry (3221) as scoped here: 322110–Pulp mills, 322121– Paper (except newsprint) mills, 322122–Newsprint mills, and 322130–Paperboard mills. The latter three categories include standalone as well as integrated mills (where both pulp and paper are manufactured on-site).

The USGS reports data for the following pulping and related chemicals: lime, sodium sulfate, soda ash, and sulfuric acid. The *Economic Census* reports data for lime and sodium hydroxide (there is a row for “other sodium compounds,” but it is perennially empty). These data are presented in Table 4-13 and Figure 4-18.

The *Economic Census* data is somewhat inconsistent from year to year. Not only does the 2007 Census not report any input flows due to disclosure concerns, but data from integrated newsprint mills (where pulping and papermaking occurs in the same facility) is lacking for all recent years.

A question remains of if the values for consumption of sodium hydroxide reported in the Economic Census somehow incorporate the shipments of other sodium compounds reported by the USGS. It does not make a large difference; the NaOH values reported by the EC are considerably larger than the shipments reported by the USGS.

As mentioned above, it is at present impossible to reconcile these input values with the industry assertion of 95–99.5% chemical recovery (Ayres & Ayres, 1998, p. 62). It is possible that these rates refer only to normal, steady-state operation, with considerable losses occurring during process upsets such as shutdown or startup, when flows “exceed recovery and available storage capacity” (Dyer & Mignone, 1983, pp. 207–8).

4.3.2.1.1.2 Bleaching chemicals

Quantifying bleaching chemicals follows a similar method, with similar drawbacks, to the pulping chemicals quantification above. Like pulping, there are many bleaching technologies in use. The traditional method of chlorine bleaching was dominant for much of the 20th century, but due to environmental concerns with chlorine bleach, other chemicals such as “sodium chlorate and methanol (for conversion into chlorine dioxide), sodium hydroxide (for extraction), hydrogen peroxide, oxygen, ozone, sodium hypochlorite, and a number of organic chemicals for new processes” have become popular substitutes in the industry (US EPA, 1994, pp. 32–33).

The *Economic Census* and USGS each publish data on two bleaching chemicals: chlorine and sodium chlorate in the former and salt and sulfuric acid in the latter. These data are presented in Table 4-14 and Figure 4-19.

Table 4-13. Pulping chemical inputs to the pulp and paper industry, 1997–2012. (EC; MYB; MCS)

Chemical ('000 Mg)		Year				Source
		1997	2002	2007	2012	
Lime	CaO, Ca(OH) ₂	1,321	902 ⁱⁱ	-- ⁱ	987 ⁱⁱ	EC
		976	868	859	890	USGS
Sodium hydroxide	NaOH	2,493	1,612	-- ⁱ	1,263 ⁱⁱ	EC
Sodium sulfate	Na ₂ SO ₄	84	54	33	-- ⁱⁱⁱ	USGS
Soda ash	Na ₂ CO ₃	143	104	91	81	USGS

(i) Data withheld in source

(ii) Excludes inputs to integrated newsprint mills

(iii) Data collection for sodium sulfate was terminated in mid-2011.

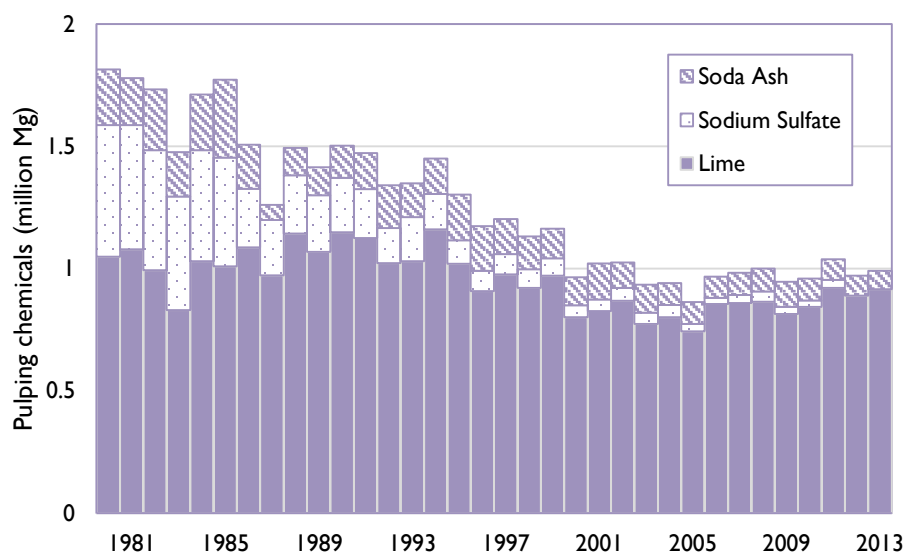


Figure 4-18. Pulping chemical inputs. (MYB; MCS)

Table 4-14. Pulp bleaching chemical inputs.

Chemical ('000 Mg)		Year				Source
		1997	2002	2007	2012	
Chlorine	Cl ₂	559	145 ⁱ	25 ^{i,ii}	-- ⁱⁱⁱ	EC
Sodium chlorate	NaClO ₃	1,036	1,040 ⁱ	865 ^{i,iv}	905 ⁱ	EC
Salt	NaCl	107	93	61	61	USGS
Sulfuric acid	H ₂ SO ₄	334	122	245	168	USGS

- (i) Excludes inputs to integrated newsprint mills.
- (ii) Excludes inputs to integrated paper and paperboard mills.
- (iii) Data withheld in source.
- (iv) Excludes inputs to pulp mills.

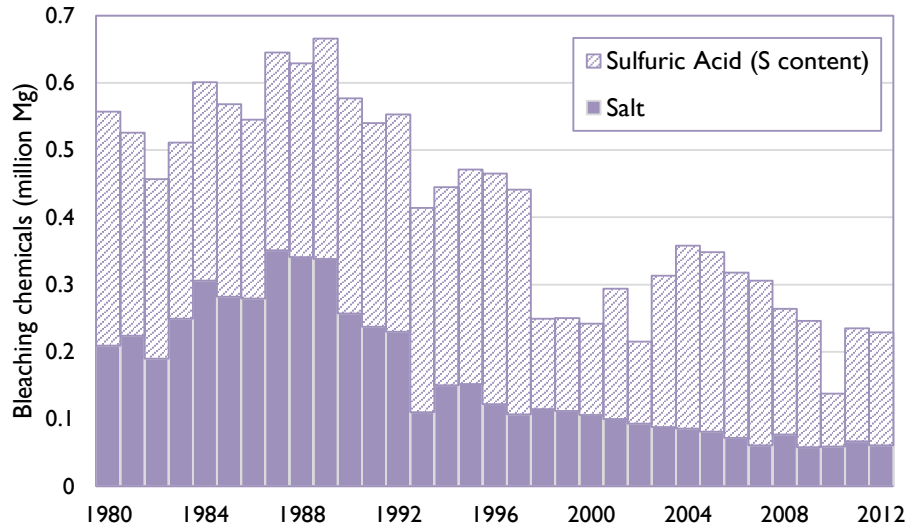


Figure 4-19. Pulp bleaching input chemicals, 1980–2012.

Although I have segmented the pulping and bleaching chemicals according to their main probable use in the industry, often these chemicals are used for both purposes. For example, sodium hydroxide (NaOH) is used both in the kraft process and in chlorine-free bleaching processes (US EPA, 2002, p. 31). Additionally, the chemical transformations that occur within pulping and bleaching enable slightly more complex interactions to occur. The 1994 *Minerals Yearbook* (p. 1) for sodium sulfate illustrates an interesting substitution process:

“Of the 120 kraft pulp and paper mills in the United States, only about 12 continue to use sodium sulfate in the Kraft pulping process. These mills have switched to using chlorine dioxide for the bleaching process that generates its own byproduct sodium sulfate. Pulp mills have converted to oxygen-based chlorine dioxide because of environmental problems associated with chlorine-based bleaching agents, which have been the traditional bleaching compounds used.”

4.3.2.1.2 Pulping outputs

The outputs from pulping are wood pulp (of various grades), extractives (turpentine and tall oil), pulping wastes, and bleaching wastes. In this model, wood pulp goes on to papermaking processes, pulping wastes proceed through chemical and energy recovery processes, yielding wastewater treatment sludge and incinerator ash, and bleaching wastes end up as wastewater treatment sludge.

4.3.2.1.2.1 Wood pulp

Data on wood pulp production is published by the Forest Products Laboratory (Howard & Westby, 2013, p. 80). Their data set, reproduced in Figure 4-20, is assembled from numerous sources, including the U.S. Census Bureau *Current Industrial Reports* series (publication of which has been terminated as of 2012), the UN Food and Agriculture Organization database, and AF&PA statistical publications.

4.3.2.1.2.2 Extractives

The “extractive” compounds contained within pulpwood are often economically (and sometimes environmentally) attractive byproducts of pulping, particularly during the kraft process. Terpenes, the chemical basis of turpentine, are volatilized from pulpwood during early stages of pulping when pulpwood chips are heated. Tall oil fatty acids are recovered from black liquor (kraft sulfate process wastes).

At present no direct data has been found tabulating by-product production from the pulp and paper industry. Nonetheless, various indirect methods can be used to bound an estimate or, in the spirit of this dissertation, provide insight into the by-product recovery potential for extractive compounds.

Three sources of information are at hand: data from the FPL tabulating total forest chemical products produced in the United States (although not distinguishing between primary production and by-product recovery from pulping), the chemical composition of pulpwood indicating the dry fraction of extractive compounds, and potential recovery rates of the compounds from the literature. Howard & Westby (2013, p. 90) aggregate information from the *Naval Stores Review* and the Pine Chemicals Association of tall oil fatty acids, turpentine, and rosins produced annually in the United States (Figure 4-21).⁴⁵ These data indicate that annual total production of forest chemical products has been between 650,000 and 700,000 Mg for the past decade, with tall oil making up approximately half that tonnage and turpentine another 10–11%.

Henricson (2004) reports that potential yield of turpentine from pine wood in kraft pulping is 2–15 kg/Mg pulp and tall oil 20–40 kg/Mg pulp. Based on the wood pulp production data from Howard & Westby (2013, p. 80), these ranges translate into extractives recovery potentials illustrated in Figure 4-22. These potentials exceed reported production to a considerable degree: tall oil potentials are in recent years between 3 and 6 times that of reported production; turpentine between 1.25 and 11 times that of reported production.

Chemical composition analysis of pulpwood shows that extractives make up 2–5% of the dry mass of pulpwood (Sjöström & Westermark, 1999, p. 3). Figure 4-23 presents the range of extractive chemical content in pulpwood consumed in U.S. pulp mills using the oven-dry fraction of consumed pulpwood (see Section 4.3.2.1.1) assuming a 15% moisture content. The Figure also presents the total range of recoverable turpentine and tall oil from Figure 4-22. The ranges overlap in a realistic, if highly optimistic manner, with the low end of the chemical composition estimate overlapping convincingly with the middle of the range of potentially recoverable chemicals.

From this analysis, it appears numerically feasible for the forest chemical products reported by the FPL to arise from pulp by-product recovery, and for tall oil, it may indeed be the case, as recovery from black liquor appears to be the primary, if not only, source of the chemicals (Wansbrough, n.d.). Turpentine, on the other hand, is produced mainly by tapping pine trees for their resin (Coppin, 1995, p. 65). No robust estimate is possible for the contribution of pulp mills to the total production of this chemical, but assuming a small fraction of the already small production tonnage, it is reasonable to consider this material flow insignificant.

⁴⁵ Turpentine is originally reported in volumetric units. Conversion to mass units is done using a density of 868.2 kg/m³ (from http://www.simetric.co.uk/si_liquids.htm).

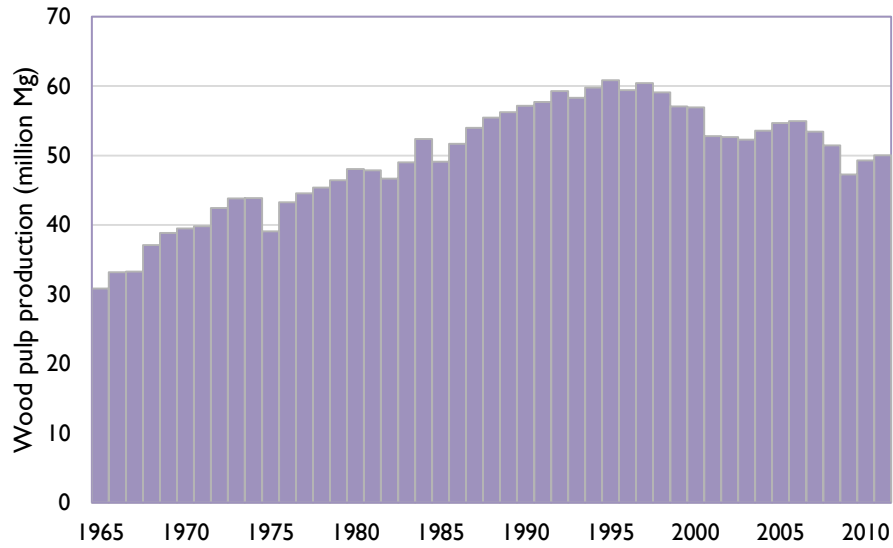


Figure 4-20. Wood pulp production, 1965–2011 (Howard & Westby, 2013, p. 80)

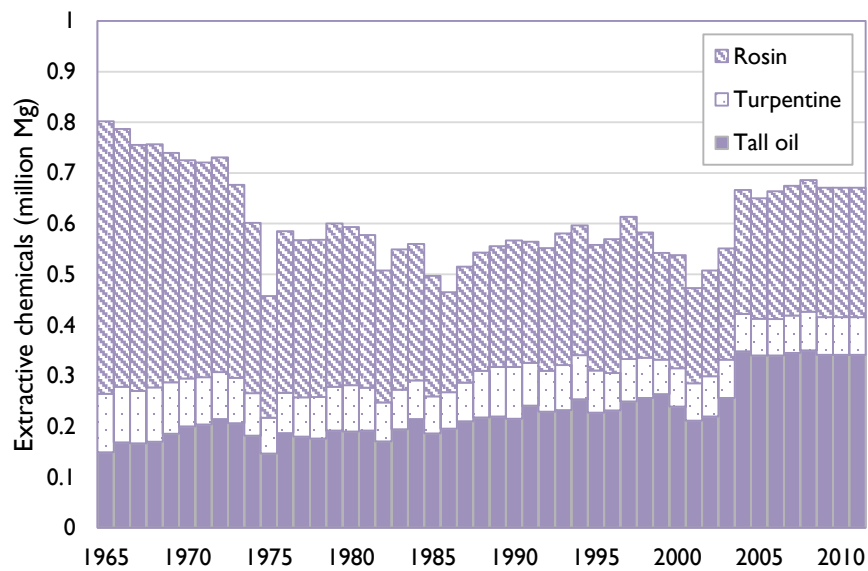


Figure 4-21. Forest chemical products in the US, 1965–2011 (Howard & Westby, 2013, p. 90).

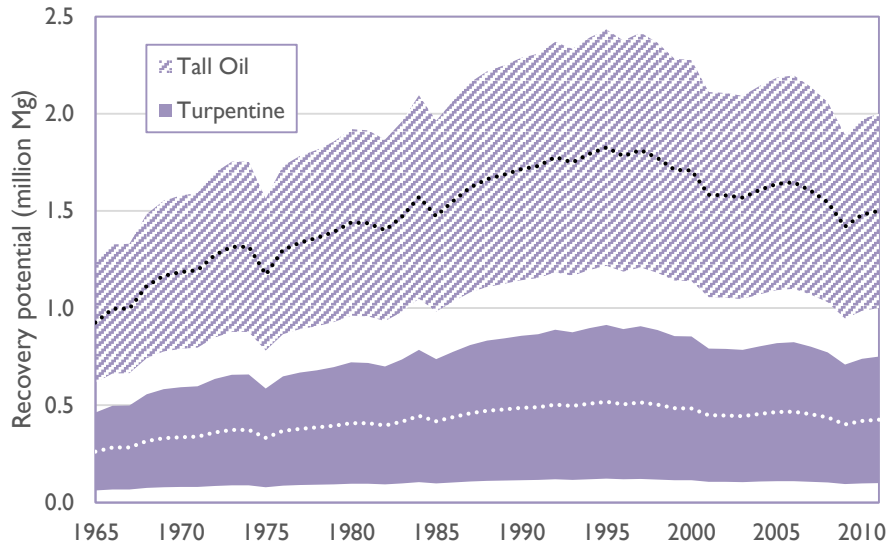


Figure 4-22. Recovery potential ranges of turpentine and tall oil from kraft pulping processes in the United States, 1965–2011, based on wood pulp production figures from Howard & Westby (2013, p. 80) and recovery estimate ranges from Henricson (2004).

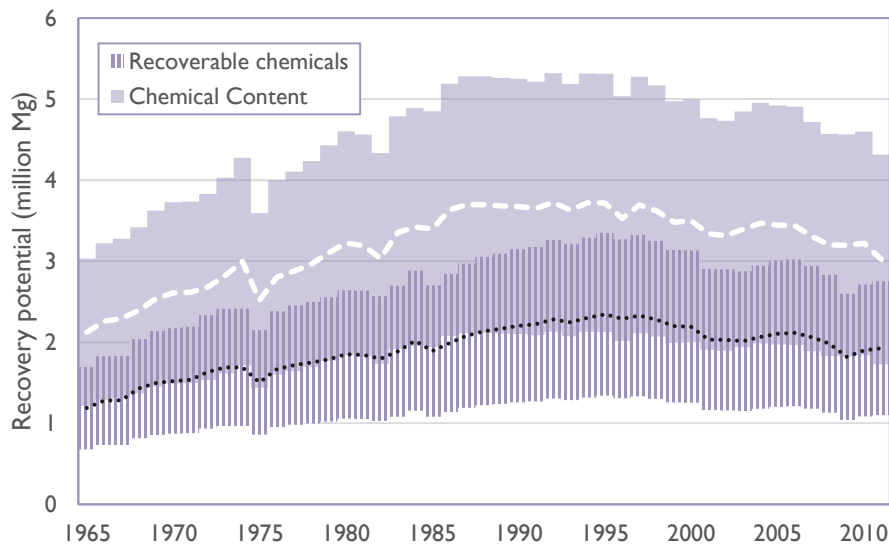


Figure 4-23. Chemical content and potential recovery rates of extractives from pulpwood in the United States, 1965–2011. Content estimate ranges from Sjöström & Westermark (1999, p. 3) and the calculation of pulpwood consumption in the United States in Section 4.1.2.1.1. “Recoverable chemicals” is the sum of the ranges from Figure 4-22.

4.3.2.1.2.3 Pulping wastes

Following Ayres & Ayres (1998), pulping wastes are distinguished into organic (lignin) and inorganic (chemical) fractions. The difference between pulpwood consumption (Figure 4-17) and pulp (Figure 4-20) yields an estimate of the lignin portion of the pulping waste. Differences in moisture content between the pulpwood in and pulp out mean that the wood content of pulping wastes has a higher than air-dry moisture content. Wood pulp is sold using an air-dried standard of 10% (90% oven-dry fiber, 10% moisture) (TAPPI, 2003, p. 1), compared with the 15–25% moisture content of air-dry pulpwood. Although it is not confirmed in the Howard & Westby (2013), it is likely that the data reported by the FPL in Figure 4-20 also uses the 10% moisture standard. Subtracting the oven-dry content of wood pulp and the tall oil production figures from the oven-dry content of pulpwood yields the lignin and hemicellulose (lignin, for short) content of pulping wastes displayed in Figure 4-24. The remaining mass in the pulping material balance is the excess moisture content of the pulpwood that goes out with the considerable volume of process water.

The transition to oven-dry units here is notable because this waste flow is the first purely derived mass flow in the model. Previously, moisture content was noted but mass flows left in the economically-relevant units in accordance with the data sources. This waste stream gets sent to energy recovery, where only the dry fraction is used for fuel.

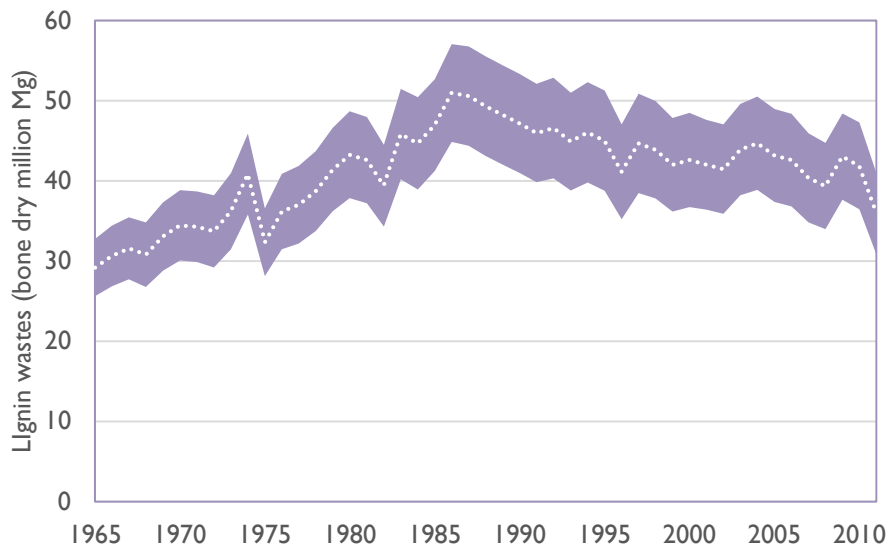


Figure 4-24. Wood wastes from wood pulp production, 1965–2011, in oven-dry million Mg of lignin and hemicellulose compounds. Calculated as the difference between oven-dry inputs of pulpwood and oven-dry outputs of wood pulp. Upper and lower bounds result from conceivable air-dry moisture content of pulpwood between 15% and 25%, respectively.

The fraction of input pulpwood that leaves the pulp mill as waste—roughly 30–45%—is a function of the pulp yields of the various pulping technologies in use. Pulp yield refers to the oven-dry fraction of pulpwood that is converted to saleable pulp, and ranges from upwards of 95% for purely mechanical pulping, 70–85% for semichemical processes, and as low as 40–55% for sulfite and kraft chemical processes (see Table 4-15) (Briggs, 1994). The low yields of chemical pulping are due to that technology’s production of pulp composed nearly entirely of cellulose content, a requirement for high-quality paper. Kraft and sulfite processes dissolve the lignin and hemicellulose constituents in the wood, which make up somewhere between 37–65% of the dry mass of pulpwood, species depending (see Table 4-12).

Lacking detailed information about the evolution and distribution of pulping technologies, it is not possible to recreate robust estimates of lignin waste for the entire time series. The most recent data available, from 2000, reports that kraft pulping commanded 82% of the market, mechanical pulping 10%, semichemical 6%, and sulfite chemical pulping just 2% (US EPA 2002, p. 8). Applying these percentages to the decades before and after the year 2000, they can be used to check the material balance developed thus far. Starting with the reported production of wood pulp from Howard & Westby, 2013, p. 80), converted to oven-dry mass, the pulp flow is segmented into the four dominant pulping technologies using the market fractions reported in Table 4-15. Consumed pulpwood is derived by calculating the amount of wood required to yield reported quantities of pulp, given the ranges in pulp yield for each technology in Table 4-15, as in:

$$\text{pulpwood}_{\text{oven-dry, low}}(t) = \sum_i \text{pulp}_{\text{oven-dry}}(t) \times \frac{\text{market fraction}_i}{\text{pulp yield}_{\text{high}, i}}$$

$$\text{pulpwood}_{\text{oven-dry, high}}(t) = \sum_i \text{pulp}_{\text{oven-dry}}(t) \times \frac{\text{market fraction}_i}{\text{pulp yield}_{\text{low}, i}}$$

where i refers to each of the four dominant pulping technologies. (High yields are used to estimate the lower bound of pulpwood consumption because the pulp yield factor is in the denominator.) Lignin wastes are estimated by subtracting reported pulp production from the total estimated consumed pulpwood. All calculations are performed using oven-dry mass units. The results, compared with estimates of pulpwood and lignin wastes derived in previous sections (converted to oven-dry mass), are presented in Figure 4-25. The two methods—pulp yield and reported pulpwood—seem to reasonably agree despite the use of a single year’s market fraction of pulp production.

The other component of pulping waste is made of spent and lost pulping chemicals. Ayres & Ayres (1998) simply use input chemical flows as a proxy for output flows, citing the mass balance principle in so doing. Although the complex chemistry associated with kraft liquor recovery and wastewater treatment in pulp mills makes this substitution a factually dubious one, it is untenable to develop a superior approach at the level of analysis of this model. Therefore, I too consider inflows as proxies for chemical sludge outflows from pulping.

Table 4-15. Ranges of pulp yields and market fractions for the year 2000 of major pulping technologies. Yields from Briggs (1994, Table 8-1) and market fractions from US EPA (2002, p. 8).

Pulping process	Pulp yield	Mkt fraction (2000)
Mechanical	93–95%	10%
(Chemi)-thermomechanical	80–90%	
Semichemical	70–85%	6%
Chemical		
Kraft sulfate	45–55%	82%
Sulfite	40–50%	2%

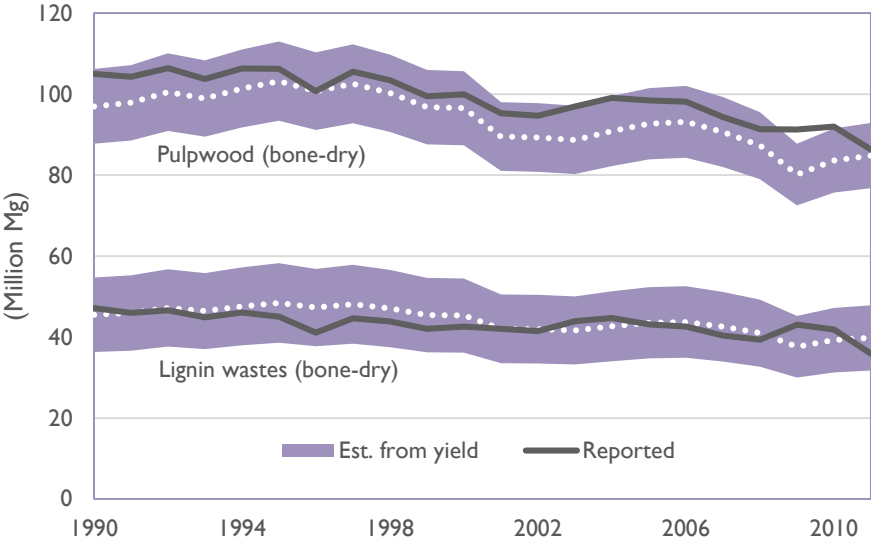


Figure 4-25. Estimates of pulpwood in and lignin waste out, 1990–2011, based on documented market fractions and pulp yield, overlaid with reported material flows derived from US FS data.

4.3.2.1.2.4 Bleaching wastes

As with the chemical sludge portion of pulping wastes, bleaching wastes are largely compounds at the tail end of complex chemical reactions: primarily bleaching and treatment of air and water pollution. Following Ayres & Ayres (1998) and the all-mighty law of conservation of mass, bleaching chemical inputs are used as proxies for bleaching sludge wastes.

4.3.2.2 Papermaking

The second activity of this material balance model is papermaking. Here, primary and secondary pulp is combined with chemical inputs to yield a variety of paper and paperboard products. Differences in mass between inputs and outputs are possibly attributable to material loss during papermaking, but in this model more likely due to data irregularities.

4.3.2.2.1 Inputs

4.3.2.2.1.1 Pulp inputs

The pulp that is used in papermaking is largely virgin wood pulp. There is an international trade in pulp; at the beginning of the time series the United States was a net importer, but in 1987 became a net exporter, a position that has been maintained except for during the years 1999–2006 (Howard & Westby, 2013, p. 80). A substantial amount of secondary pulp derived from waste paper is also used in papermaking. Other non-wood pulp feedstocks are effectively insignificant portions of the material flow into the papermaking industry. Fibrous materials consumed in papermaking are presented in Figure 4-26. Data originally came from the AF&PA, although pulp consumption figures seem to represent effective consumption (production + imports – exports) rather than observed consumption.

4.3.2.2.1.2 Chemical inputs

Data on the chemical inputs to papermaking is considerably better documented than data for pulping and bleaching chemicals. The Economic Census and the USGS publications report on the consumption of chemicals for paper “sizing,” coating and filling, and other purposes⁴⁶ (see Figure 4-27 and Table 4-16). Sizing “makes the native fiber network hydrophobic and thus prevents or reduces the penetration of water or other aqueous liquids into the paper.” (Auhorn, 2006, p.83). Sizing agents include alum (aluminum sulfate, $Al_2(SO_4)_3$), rosin, and starch. The largest category of papermaking chemicals (in this model) are additives for filler and coating. Fillers were originally

⁴⁶ The reports do not categorize the chemicals in this manner; I made this categorization based on the most likely uses of the chemicals, from the literature.

added to writing paper to “increase the weight of the sheet and to improve the writing properties,” but now serve multiple purposes, including improving optical properties, surface smoothness, printability, dimensional stability, and paper permanence (Laufmann, 2006, p. 33). Major fillers and coating additives include precipitated calcium carbonate (PCC, CaCO_3), kaolin and ball clays, titanium dioxide (TiO_2). Talc has multiple uses in papermaking, including as a filler but also as a pitch control agent (ibid., p. 45). Pitch refers to a variety of detrimental, sticky substances that contaminate the papermaking process, including rosins and extractive compounds from wood pulp and glues or melted plastic from wastepaper pulp (Auhorn, 2006, p. 132). Alum is also used as pitch control alongside its role as a sizing agent (ibid., p. 134). Glues, adhesives, and synthetic resins have various uses for finishing paper products.

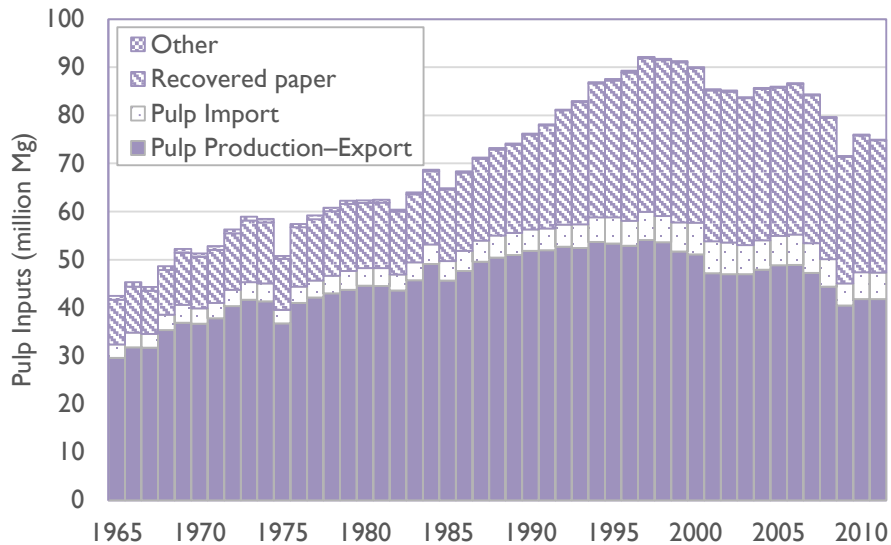


Figure 4-26. Fiber consumed in papermaking, 1965–2011. (Howard & Westby, 2013, pp. 77, 80)

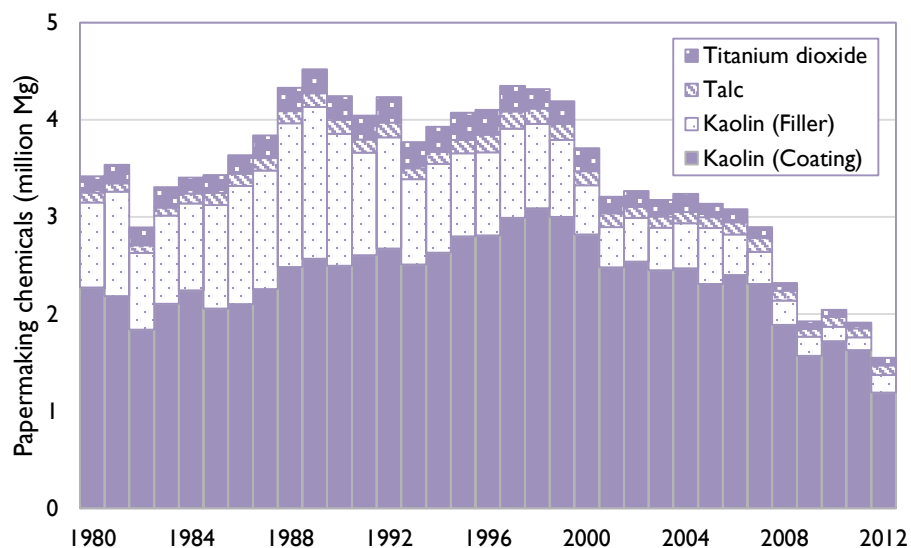


Figure 4-27. Papermaking input chemicals, 1980–2012. (MYB)

Table 4-16. Papermaking chemical inputs summary, 1997–2012. (EC; MYB)

Chemical ('000 Mg)		Year				Source
		1997	2002	2007	2012	
Sizing						
Aluminum sulfate	$Al_2(SO_4)_3$	486	332	- ⁱ	- ⁱ	EC
Rosin sizing		151	92	45 ⁱⁱ	58	EC
Starch		1,414	1,158	621 ⁱⁱⁱ	990 ⁱⁱ	EC
Coating & Filler						
Calcium carbonate, precipitated	$CaCO_3$	1,858	2,497	2,350	2,133	EC
Kaolin and Ball clay		2,550	2,118	1,619	956 ^{ii,iii}	EC
Titanium dioxide	TiO_2	3,908	2,990	2,639	1,371	USGS
		212	150	- ⁱ	- ⁱ	EC
		263	165	114	77	USGS
Talc		178	112	143	101	USGS
Other						
Glues and adhesives		46 ^{ii,iii}	2 ^{iii,iv}	78 ⁱⁱ	- ⁱ	EC
Synthetic resins		328 ⁱⁱ	281 ⁱⁱ	- ⁱ	- ⁱ	EC

(i) Data withheld in source.

(ii) Excludes inputs to integrated newsprint mills.

(iii) Excludes inputs to integrated paperboard mills.

(iv) Excludes inputs to integrated paper mills.

4.3.2.2.2 Outputs

4.3.2.2.2.1 Paper & paperboard products

Data on paper production tonnage is collected by the AF&PA; the US FS (Howard & Westby, 2013, pp. 75–76) and the Statistical Abstract of the United States (SAUS) publish this data in slightly different ways. The US FS reports just aggregated paper and paperboard totals, while the SAUS includes detailed breakdowns of product type as well as data on specialty products: wet machine board, hard pressed board, insulation board, and construction (building) paper. These specialty products are manufactured in insignificant quantities. Annual paper and paperboard production is presented in Figure 4-28.

Moisture content of paper and paperboard at the mill is difficult to ascertain. Information is available on the impacts of moisture content on paper performance. As best I can tell, moisture content of just-produced paper ranges from 6.6–10.9%, although TAPPI standards instruct that the measurement of equilibrium moisture content be performed after a drying and re-wetting cycle (Biermann, 1996, p. 163). Moisture content is also influenced significantly by the relative humidity.

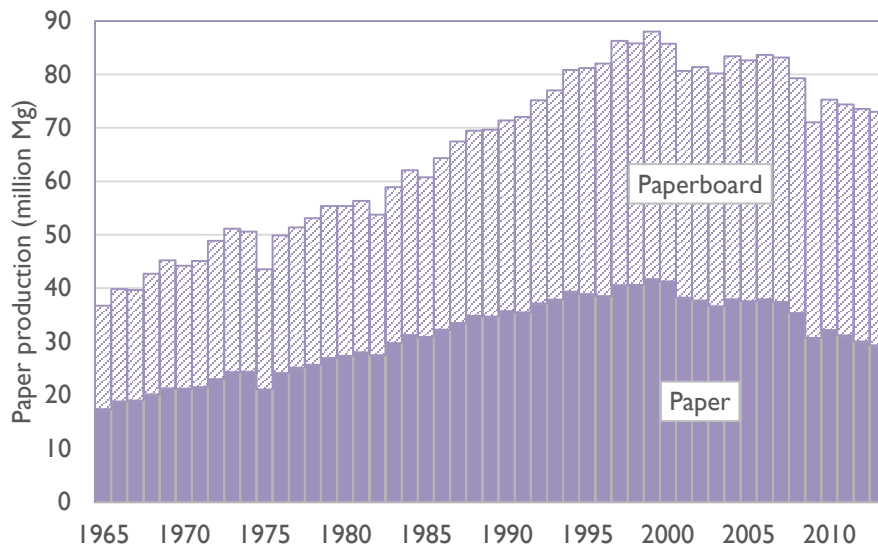


Figure 4-28. Paper and board production, 1965–2013. (Howard & Westby, 2013, pp. 75–76; AYS)

4.3.2.2.2 Papermaking lost mass

Lost mass from papermaking is calculated as the difference between pulp and chemical inputs and paper and paperboard products out. Ayres & Ayres (1998, pp. 58–59) correct the lost mass by claiming an “internal recycle” loop, where a combination of papermaking wastes and unsatisfactory products are lumped in with input repulped wastepaper. The Ayreses do not cite any reference in making this assumption. Three other equally probably explanations are 1) the change in mass is due to a change in moisture content, 2) lost mass is waste from the paper mill, including repulping losses (see next section), or 3) the source data is in error. Total inputs, outputs, and lost mass are presented in Figure 4-29.

4.3.2.3 Waste paper re-pulping

The third activity in the model is the production of secondary pulp from waste paper. Waste paper is recovered from a diverse recycling and secondary materials collection industry in the United States, sourcing from the heterogeneous (and often contaminated) fully commingled municipal recycling stream to pure and high quality sources of recycled office paper from commercial establishments. Data on recovered paper includes categories such as mixed grades, old newspapers, old corrugated cardboard, pulp substitutes, and high grade deinking. Recovered paper ultimately finds its way mainly to either paper mills or export markets, with a small amount used in other manufacturing activities, such as insulation production.

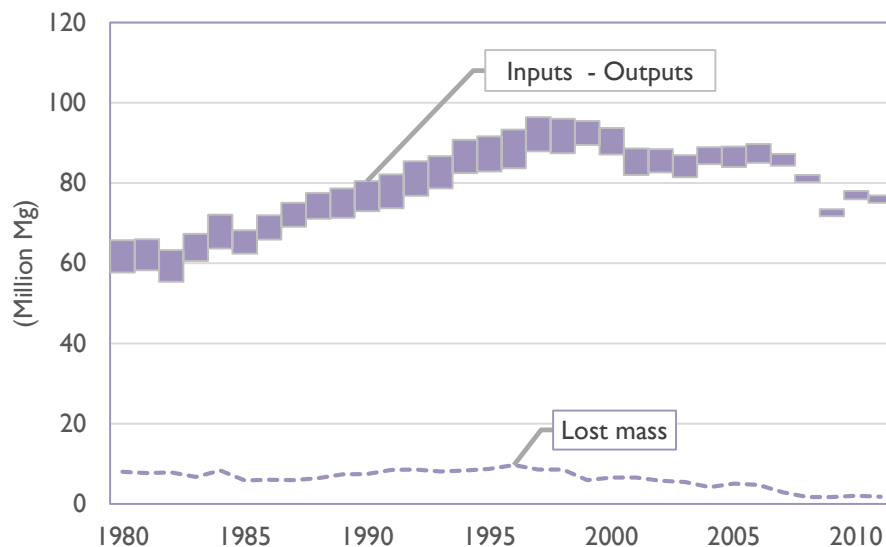


Figure 4-29. Lost mass calculated as the difference of total inputs and outputs, 1980–2011.

Data on waste paper production, recovery, and reuse is plentiful but somewhat untrustworthy. The US FS reports two different sets of data on waste paper consumed at pulp mills, both from the AF&PA: one set is reported in the context of other uses and international trade of recovered wastepaper (Howard & Westby, 2013, p. 78), while the other is the summation of different categories of recovered paper consumed in mills (ibid., p. 79). The latter is routinely 200,000–250,000 Mg (about 1–2%) larger than the former. This is not a substantial difference, but indicates the challenge of using waste data in any materials balance exercise. The US FS report also reports recovery rates, which uses reported quantities of new paper and paperboard supply as proxy for total paper waste generation.

Another source of waste paper recovery data is the annual U.S. EPA report on municipal solid waste in the United States (US EPA, 2013). This estimate (which is the source of the ubiquitous figure of 250 million short tons per year MSW generation), is built on a complex materials flow analysis model by Franklin Associates, the go-to MSW contractor for the EPA for decades. The report states that EPA figures for paper and paperboard are derived from the AF&PA data, presumably the same upon which US FS also relies. At first glance, the two sources (US EPA and US FS) disagree quite dramatically, but on closer inspection, it appears the both generation (“G”) and recovery (“R”) estimates track quite closely for the entire time period (see Figure 4-30), which leads me to guess that the EPA (or Franklin Associates) processed the data before publication. In fact, the EPA report discusses a variety of “deductions” made from the AF&PA data, including converting scrap and waste diversion (US EPA, 2013, pp. 38–39). The US FS data on wastepaper consumption in pulp mills (“C-USFS” in Figure 4-30) helps to clear up remaining confusion, as it *exceeds* the US EPA estimate of recovered waste for most of the time series.

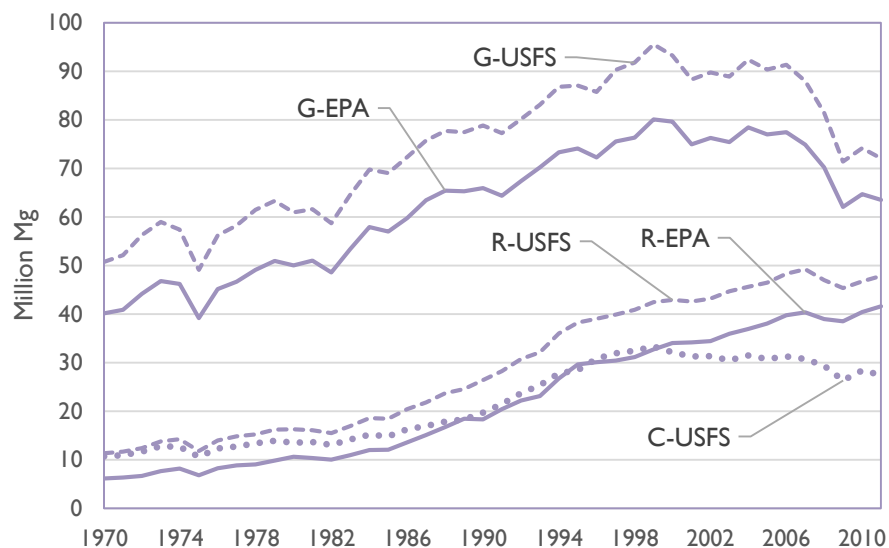


Figure 4-30. Gaps between the US FS and EPA references for waste paper recovery data.

Recovered paper repulping is a wasteful process. Deinking sludges include many of the chemicals added during papermaking (fillers and pigments), printing ink, and fibers. Losses are roughly 10% (Blechsmidt, 2006, p. 21). It is unclear if the data for wastepaper consumption at mills from the US FS (Howard & Westby, 2013, pp. 78–79) is pre- or post-deinking/repulping. If post, it indicates a slightly higher wastepaper recovery rate than has been reported; if pre-, it helps to explain some of the lost mass in the papermaking materials balance, but 10% losses would lead to a higher than is possible waste flow given the other material flows for the years since 2007. The mystery remains.

4.3.2.4 Energy generation

The final activity in the pulp and paper materials balance model is energy generation. The majority of the energy consumed in the pulp and paper industry comes from on-site combustion of bark, wood, paper, and liquor wastes. Only 10% of primary energy is provided by purchased electricity, with the balance provided by on-site combustion of fossil fuels. Although energy itself is excluded from this material balance analysis, the consumption of solid fuels contributes to the solid waste output of the industry. Therefore, those fuel materials are relevant to this analysis. Distribution of primary energy consumption in the pulp and paper industry in 2010 by energy source is presented in Figure 4-31. Total consumption by the industry in that year exceeded 2.2 EJ (US EIA, 2013, Tables 1.1 & 1.2).

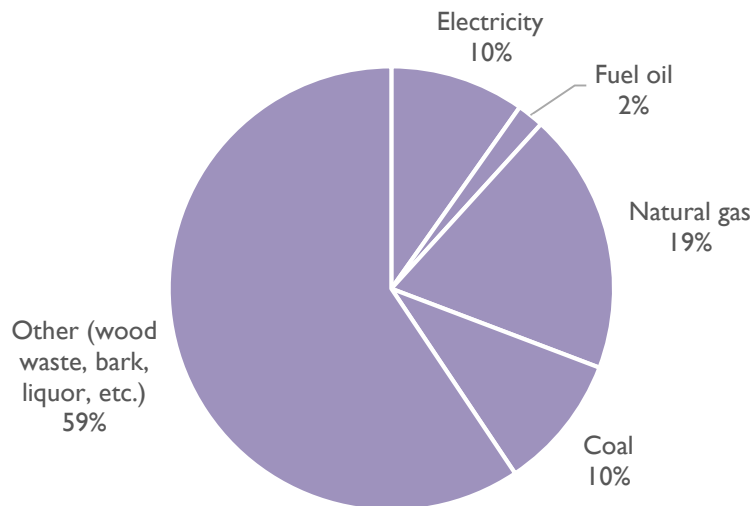


Figure 4-31. Distribution of energy sources, 2010. (US EIA, 2013, Tables 1.1 & 1.2)

4.3.2.4.1 Wood fuel

Howard & Westby (2013, p. 91) publish wood energy use in the United States as reported by the Energy Information Administration. The vast majority of wood energy is consumed in industry, presumably wood-related industries. Ayres & Ayres (1998, pp. 57–61) integrate this activity into their material balance quite elegantly, as their model encompasses the entire forest products industry, and therefore all wood energy would be endogenous. Here, that is less possible, as the only sources of wood energy within the scope of my model are bark from pulpwood chipping and lignin wastes.

The outputs from wood energy recovery are overwhelmingly combustion products: carbon dioxide and water. Non-incinerable content within the wood becomes ash, which must be disposed as solid waste. Ash fraction is defined in the literature as the oven-dry composition of inorganic compounds in the wood. Ash content ranges considerably from species to species, and among different parts of a tree. Bark ash content for softwoods ranges from 0.4% to 4.2% and for hardwoods from 1.7% to 17.8%, although the extremely ashy woods are unusual pulpwoods (IPC, 1978, pp. 96–97). Ash content in dry pulping wastes range between 1–2% (Ayres & Ayres, 1998).

Quantities of pulpwood bark are derived from the input flows of pulpwood (Section 4.3.2.1.1). The bark content of pulpwood is estimated to be 40–56 kg (dry) / m³ (US EPA, 1980, p. 3-27). Here is one place where the volumetric reporting of timber flows is a benefit. Lignin wastes are given in Section 4.3.2.1.3.3. Estimated values of ash from bark and lignin waste combustion are shown in Figure 4-32.

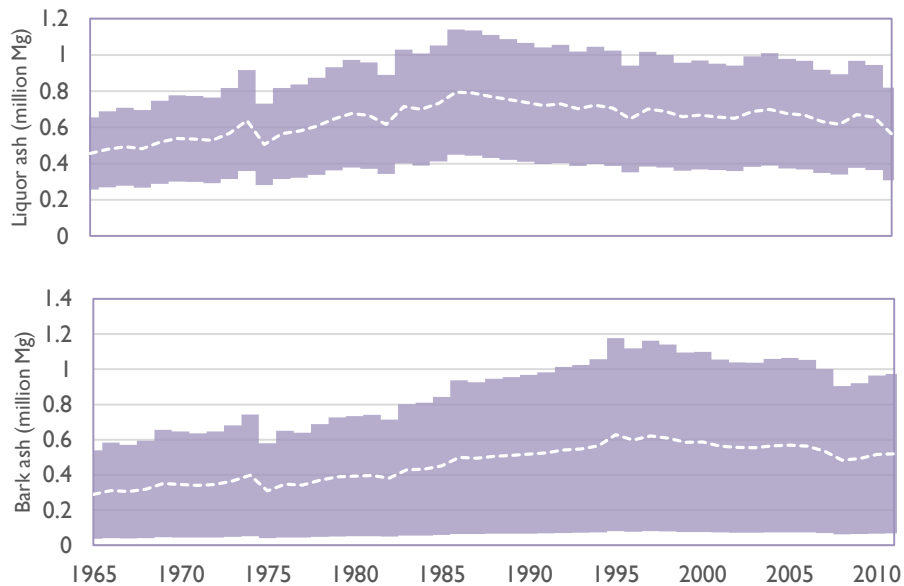


Figure 4-32. Estimated ranges of ash from bark and lignin waste combustion.

4.3.2.4.2 Coal

Of the three fossil fuels consumed on-site, coal is the only one to yield any appreciable quantity of solid waste in the form of coal ash. Within the industry, coal is consumed exclusively by paper and paperboard manufacturers (i.e. not pulp producers). Coal ash is the major solid waste output from coal combustion, and its quantity depends on the ash content of the fuel, which in turn is a function of the fuel type and local geology of the mine. A documented range for coal ash content is 3–15 wt.% (Speight, 2005, p. 42). The consumption of coal by the industry is documented by the U.S. Energy Information Administration’s roughly quadrennial *Manufacturing Energy Consumption Survey*. Results from this survey show a decline in both absolute consumption of coal and the relative share of primary energy from coal over the available time period (Figure 4-33). Coal ash outputs can be estimated by multiplying coal consumption values by the selected ash content percentage. Assuming a reasonable value of 12% (US EPA, 1980, p. 3-32), 1–2 million Mg of coal ash are produced each year.

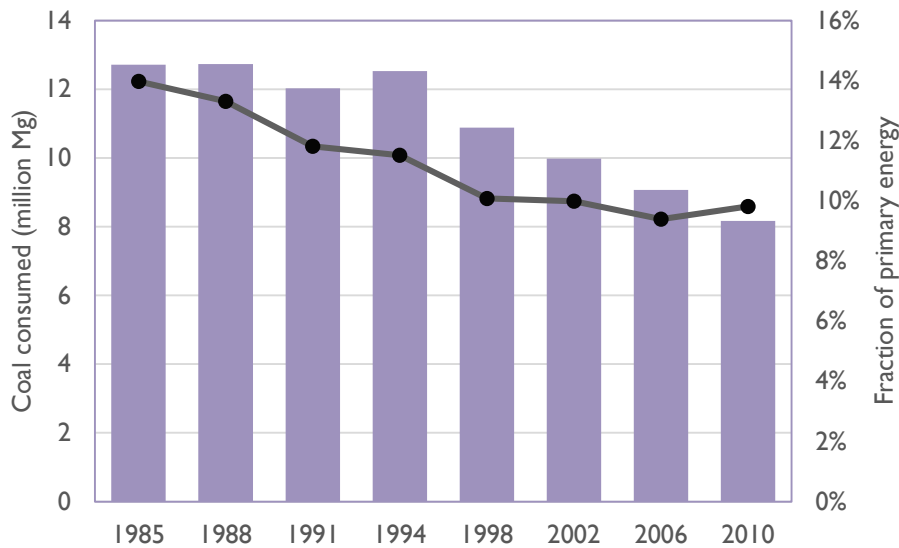


Figure 4-33. Total quantity of coal consumed (bars) and fraction of total primary energy provided by coal (line). (MECS)

4.3.3 Material balance: 2010

The detailed analysis presented above provides sufficient (or in many cases excessive) information for the construction of a materials balance model for the US pulp and paper industry in the year 2010 (Figure 4-34). A summary of non-hazardous wastes is found in Table 4-17.

Table 4-17. Summary of NHIW from the US pulp and paper industry, 2010, as calculated by materials balance.

Waste category	Low	High
	(million Mg)	
Ash		
Coal ash	0.33	1.22
Wood ash	0.43	1.91
Chemical sludge	3.28	4.79
Lost mass	1.61	3.90
De-inking sludge		2.84
Total	8.49	14.66

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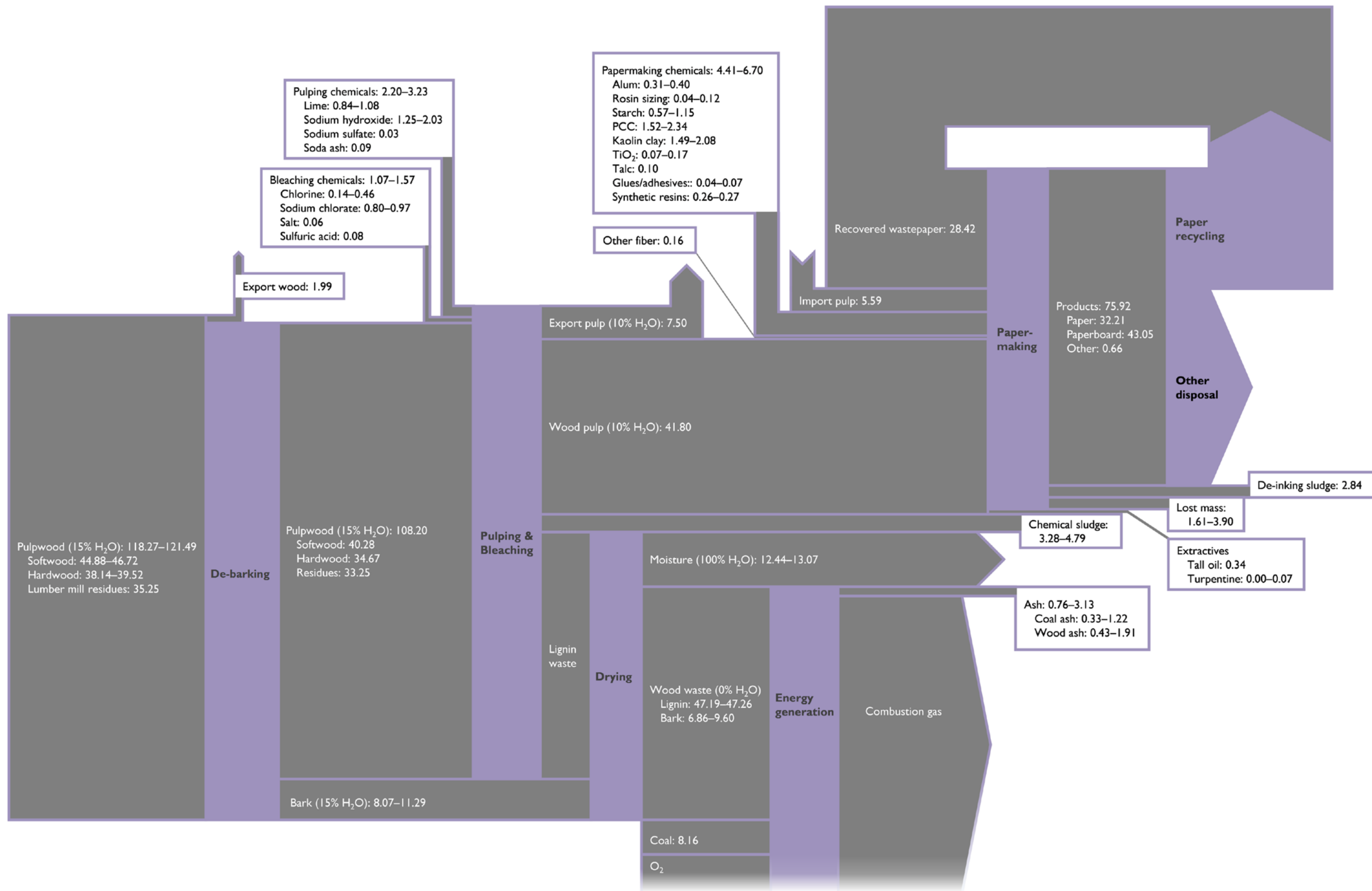


Figure 4-34. Material balance for the US pulp and paper industry, 2010. All units in million Mg.

4.4 Spatial scale-up

The pulp and paper industry in Pennsylvania is a relatively small one in this heavily industrialized state.⁴⁷ In 2012, the 15 facilities (seven each non-newsprint paper and paperboard mills and one undesignated facility, out of 13,988 manufacturing establishments state-wide) employed less than 2% of the workforce and contributed just 3.5% to the total value added of the state's manufacturing industries (EC). The contribution of Pennsylvania mills to the nation-wide pulp and paper industry, on the other hand, ranks it second among all states in terms of total value added (8.2% of national total) and fourth for employees (5.4%) and shipment value (7%) (EC). Both absolute output of the industry and ratio of paper to paperboard production have remained relatively stable since the mid-1990s (Figure 4-35).

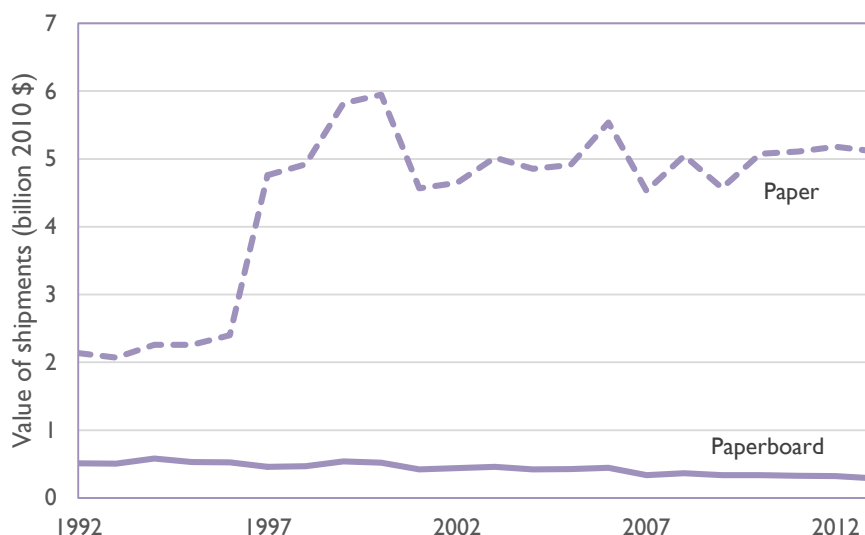


Figure 4-35. Value of shipments from the pulp and paper industry (NAICS 3221) in Pennsylvania, 1992–2013 (billion 2010 \$) (EC; ASM). Five-digit NAICS codes (32212—Paper mills; 32213—Paperboard mills) only reported in semi-decadal EC; fraction of shipments values of 3221—Pulp, paper & paperboard mills reported in ASM interpolated from EC. Nominal dollars deflated to real dollars using industry-specific producer price index, re-indexed to 2010 dollars (PPI).

⁴⁷ Pennsylvania is technically a commonwealth; “state” is used in the generic sense throughout this section for ease of the narrative.

4.4.1 History of papermaking in Pennsylvania

Although a minor industry today, papermaking has a storied history in the state. The first paper mill in North America was built in 1690 by William Rittenhouse in Germantown, now a neighborhood in northwest Philadelphia, on the banks of Paper-Mill Run⁴⁸ (Weeks, 1916, p. 3). The first Rittenhouse Mill, which stood for little more than a decade before being destroyed when the Wissahickon Creek flooded in 1701, manufactured printing and other papers from cotton and linen rags supplied in part by cuttings and wastes from the Philadelphia textile industry, as explained in the following poem published in 1692 (*ibid.*, p. 5):

“The *German-Town*, of which I spoke before,
Which is, at least, in length one Mile and More,
Where *lives High-German* People, and *Low-Dutch*,
Whose Trade in weaving Linnin Cloth is much,
There grows the Flax, as also you may know.
That from the same they do divide the Tow;
Their Trade fits well within their Habitation,
We find Conveniences for their Occupation,
One Trade brings in imployment for another,
So that we may suppose each trade a Brother;
From Linnin Rags good Paper doth derive.
The First Trade keeps the second Trade alive:
Without the first the second cannot be,
Therefore since these two can so well agree.
Convenience doth approve to place them nigh.
One in the *German-Town*, ‘tother hard by.
A Paper Mill near *German-Town* doth stand.
So that the Flax, which first springs from the Land,
First Flax, then Yarn, and then they must begin,
To weave the same, which they took pains to spin.
Also when on our backs it is well worn,
Some of the same remains Ragged and Torn;
Then of those Rags our paper it is made,
Which in process of time doth waste and fade;
So what comes from the Earth, appeareth plain,
The same in Time returns to Earth again.”⁴⁹

⁴⁸ Paper Mill Run is also known as Monoshone Creek, a tributary of the Wissahickon Creek just a few km from the Schuylkill River.

⁴⁹ This poem, by Richard Frame, “A Short Description of Pennsylvania; or, A Relation What things are known, enjoyed, and like to be discovered in this said Province,” was printed and sold by William Bradford, a well-known publisher who was a major investor in the Rittenhouse mill (Scharf, 1884, p. 223). This fact goes a long way to explain how the mill is featured so prominently just two short years after being established.

The rebuilt Rittenhouse mill had a neighbor up Wissahickon Creek when the new world's second paper mill opened there in 1710. With the establishment in 1729 of the Ivy Mills 20 miles away on the west branch of Chester creek in Concord township, the fledgling industry achieved regional status (Weeks, 1916, pp. 10-12).

The eighteenth century saw an expansion of papermaking to other highly populated northern colonies, but by the time of the American Revolution, more than half of colonial printing, including the numerous pamphlets and newspapers advocating for and against independence, were printed on Pennsylvania paper (*ibid.*, p. 49). By the end of the eighteenth century, papermaking had spread to the western part of the state, with the first mill supplying Pittsburgh opening in 1795. As both production capacity and demand for paper continued to grow, the opening of each new mill would be accompanied by entreaties for new supplies of rags printed in local newspapers. Soon the supply of rags throughout the country was running scarce, and the hunt was on for replacement fibers.

Straw pulp, an early contender to replace rags in papermaking, was pioneered by William Magaw and put into production in Chambersburg, Pennsylvania, about halfway between Philadelphia and Pittsburgh, in the late 1820s. Straw pulp would be overtaken by wood pulp following the development of chemical pulping technologies. Soda pulping (a predecessor of the kraft sulfate process), although invented in England in 1851, was commercialized and first put into large scale production in Philadelphia later that decade (Weeks, 1916, pp. 226-228).

The Gilded Age brought with it rapid growth and industrialization at scale in the United States, a trend that was not overlooked by the Pennsylvania paper industry, much of which was now relocating to areas of the state proximate to the essential feedstock: wood. By the turn of the twentieth century, Pennsylvania had the third-largest paper industry in the country, with mills spread across the state (*ibid.*, p. 332). In 1890, a large paper mill was opened in Johnsonburg, on the Clarion River, near what is now the Allegheny National Forest (Williams, 2014). Further to the northwest, the first all-sulfite pulp mill in the country was opened 1899 in Erie, Pennsylvania, a location selected because "it offered ready access to water, trees, railroads, coal, and labor...[and] was ideally situated roughly halfway between Chicago and New York" (Ingold, 2010). The fates of these two mills are illustrative of the experience of the whole Pennsylvania pulp and paper industry through the twentieth century.

The Johnsonburg mill was one of three mills owned by the New York and Pennsylvania Company, and by the end of the nineteenth century was the second largest paper mill in the state, with a capacity of 145 (short) tons per day (tpd) of high quality paper (only the Philadelphia Paper Manufacturing Company mill was larger, producing 280 tpd of paperboard). Johnsonburg had two integrated pulp mills: one producing 90 tpd of soda pulp and the other 75 tpd of bleached sulfite pulp (Weeks, 1916, p. 332). The mill was situated in an industrial cluster in the Clarion Valley that also included numerous tanneries and wood chemical plants, which relied heavily on the hemlock

trees of the northern Allegheny basin (Williams, 2014). The chemical wastes from these three industries quickly led to the river becoming “one of the worst streams in the state,” (Ortmann, 1909, p. 106) with public use of the water ultimately ceasing by 1912. The contributions of the mill to this pollution problem were lessened with improved water quality control, and “by 1996 ... portions of the [river] were included in the Federal Wild and Scenic Rivers System,” indicating a dramatic improvement in river cleanliness and health (WPC, n.d.).

The mill itself underwent considerable changes. Today, the mill has a production capacity of 356,000 (short) tons per year of high quality paper and 230,000 Mg of pulp (Domtar, 2007, p. 47). It also changed hands numerous times since originally opened in 1890. The Curtis Publishing Company (of *Saturday Evening Post* acclaim) purchased the New York and Pennsylvania Company in 1922 and operated the Johnsonburg site until falling into financial hardship in the late 1960s; Curtis shut down the plant in July 1969 (“Johnsonburg,” 1969). Later that year, the mill was purchased and reopened by Penntech Papers (McGeehan, 2009, p. 47). In May 1990, the mill was purchased by Willamette Industries, who immediately invested \$550 million in upgrading the mill, including wastewater treatment improvements and pollution prevention programs (PA DEP, 1998). In 1994, the mill began achieving considerable reductions in solid waste disposal by diverting the wastewater treatment plant solid sludges for use in reclaiming abandoned strip mines and, notably, the mill’s own now-obsolete surface impoundment. The state Department of Environmental Protection acknowledged this program with its 1998 Governor’s Award for Environmental Excellence; the citation for the award explains that “this method of use [of residual waste] is effective because the hardwood pulp fibers hold water in dry weather and compost into the soil, while the calcium carbonate present in the mixture eliminates the need for lime on the acidic mine soil.”

Willamette was purchased by the Weyerhaeuser Company in 2002, which in turn was purchased by Domtar Corporation in 2007, who has operated the Johnsonburg mill since then (Domtar, 2007, pp. 18–19).

The Lake Erie mill of the Hammermill Paper Company began as one of “the foremost establishments in the country in the production of bond, ledger, superfine, and writing” paper (Weeks, 1916, p. 333). Its 100 tpd capacity was enabled by five state-of-the-art Fourdrinier paper machines. Hammermill made numerous innovations in papermaking, watermarks, sales,⁵⁰ and employee relations, many pioneered at the Erie mill (Ingold, 2010). The company expanded numerous times through the mid-20th century, in 1965 purchasing the Lock Haven mill founded by original Johnsonburg mill owners New York and Pennsylvania Company (International Paper, 2014). Hammermill was purchased by International Paper (IP) in 1986. As a result of an industry-

⁵⁰ “The first national advertisement for Hammermill Bond [paper]...ran in the May 11, 1912 issue of the *Saturday Evening Post*” (Ingold, 2010), the publisher of which later owned the Johnsonburg mill.

wide slowdown in the early 2000s, IP closed both the Lock Haven and Erie mills in the spring of 2002 (Panepento, 2002).

Rapid growth, technology and feedstock change, movement westward, environmental harm preceding environmental improvement, consolidation, and demise is a common story arc of the Pennsylvania paper industry over the past two centuries. The final, missing, chapter is the main trend characterizing the national industry in the latter part of the 20th century: paper recycling. Of the top five paper producing states—Alabama, Wisconsin, Georgia, Pennsylvania, and South Carolina—four remain heavily forested, able to provide sufficient pulpwood for a still large, if somewhat mercurial, paper demand. In Pennsylvania, virgin production occurs in historically forested areas (like Johnsonburg), but secondary paper demand reoriented production back to the urban centers that spawned the industry more than three centuries ago.

An industry that was initially based on a waste material (which accumulate in urban areas) has become one again, to some extent. Consider Newman & Co., which produces 100% recycled paperboard at their mill in Philadelphia. Beginning as a scrap paper and rag dealer, David Newman (grandfather and great-grandfather of current company owners) opened his own recycled paperboard mill in 1918. The mill (relocated and expanded in 1952) now produces 220 tpd on a site shared with the Bridge View Paper Company, United States Recycling, Inc., and the Mill Corporation, which are a producer of high quality paper, a recycler of fiber and other waste materials, and a transport broker, respectively, an industrial cluster that seems to be a useful bulwark against the vicissitudes of the global waste commodities market (Schupak, 2013; “Member spotlight,” 2014).

Recycling has also revitalized ailing mills and mill towns. Tyrone, in central Pennsylvania, in 1880 became home to the new Morrison and Case Paper Company mill, purchased soon thereafter by the West Virginia Pulp and Paper Company (Westvaco) (Weeks, 1916, p. 310). One hundred twenty one years later, in the midst of the industry downturn that claimed numerous mills across the state and country, Westvaco shuttered its 90,000 tpy mill, leaving 270 people unemployed (“Mead,” 2001; Ferguson, 2003). In 2003, the mill was purchased and reopened as American Eagle Paper Mills, focusing on envelopes and other specialty grade paper from recycled content with a capacity of 90,000 tpy. As of 2008, the flourishing mill employed 220 people and had doubled down on its commitment to produce secondary paper (and other environmentally-friendly practices), purchasing on average 95,000 tpy of waste paper and supplying the paper-hungry industries and cities of central Pennsylvania (Willis, 2008).

Recycled paper is essential to Pennsylvania’s paper industry. Of the 32 facilities that report under the PA Residual Waste program (see below), 22 were confirmed to be consuming recovered paper as of 1996, with at least one more having publicly announced a commitment to consume more than 200,000 tpy of recovered paper starting in 1997 (AF&PA, 1996).

4.4.2 Data & facilities

The Pennsylvania Residual Waste program has collected and published data on non-hazardous industrial waste generation and disposition from the PA pulp and paper industry since 1992. Over the 11 biennial cycles of the program, 32 facilities designated within NAICS 3221 (and SIC antecedents) have reported information at least once,⁵¹ although only 11 have reported consistently throughout the entire time period (see Figure 4-36). Of the others, some either opened or closed during the time period, and the remainder presumably neglected to report in years they are absent from the database. Although unlikely, it is also possible that in some facilities' waste production vacillate around the reporting threshold, leading to periodic absence from the database.

The data is highly multi-dimensional; in each reporting period, facilities report tonnage and medium of discharge (solid, liquid, or solid-liquid mix) of any of 118 residual waste types, along with disposal facility and type. Figure 4-37 displays total waste generation from every facility in all three industry subsectors in the three reported media. These data corroborate the absence of NAICS 32211 (standalone pulp production) from the Census Bureau accounts of the state industry. The three pulp mills that have reported to the program did so only for a maximum of two cycles each, all between the years 1998 and 2006. Paper making (NAICS 32212) has the most number of facilities that generate the most waste in all three media. Liquid wastes are by far the largest quantity, with multiple facilities reporting outputs of many millions of tons per year for the years 1994–2004. The data is unstable, however, with the second decade appearing very different than the first. This is due in part to a change in the reporting requirements that excluded process wastewaters discharged to a publicly owned treatment plant or under a NPDES permit from the residual waste program. Despite this, one facility did report wastewater output in 2010. Solid and semisolid wastes are, on balance, more consistent across the time series.

⁵¹ The raw data, 1992–2012, contains 40 unique generator IDs claiming SIC codes 262, 263, 2611, 2621, 2631 and NAICS codes 32211, 32212, and 32213. Of these, six proved to be typos when ID-NAICS/SIC code pairs were compared with the entire data set; corrected NAICS codes for these generators were 32221, 32229, 32311, 32711, and 33211. The checking procedure also found one generator that had erroneously reported its 2004 data under NAICS code 32221, while all other years 1992–2002 and 2006–2012 under 32212. These transposition errors are understandable but frustrating. While the false positives (erroneous reports claiming 3221 codes) total just 1509 tons over four years, making them completely insignificant, the false negative was more troubling: that single facility reported tonnage makes up a full 30% of the total waste tonnage reported in 2004 (24% excluding liquid discharges). Further examination revealed two facilities that had each been reassigned ID numbers in 2004 and 2006, respectively. Correcting for the errors and combining the duplicate IDs yields 32 facilities.

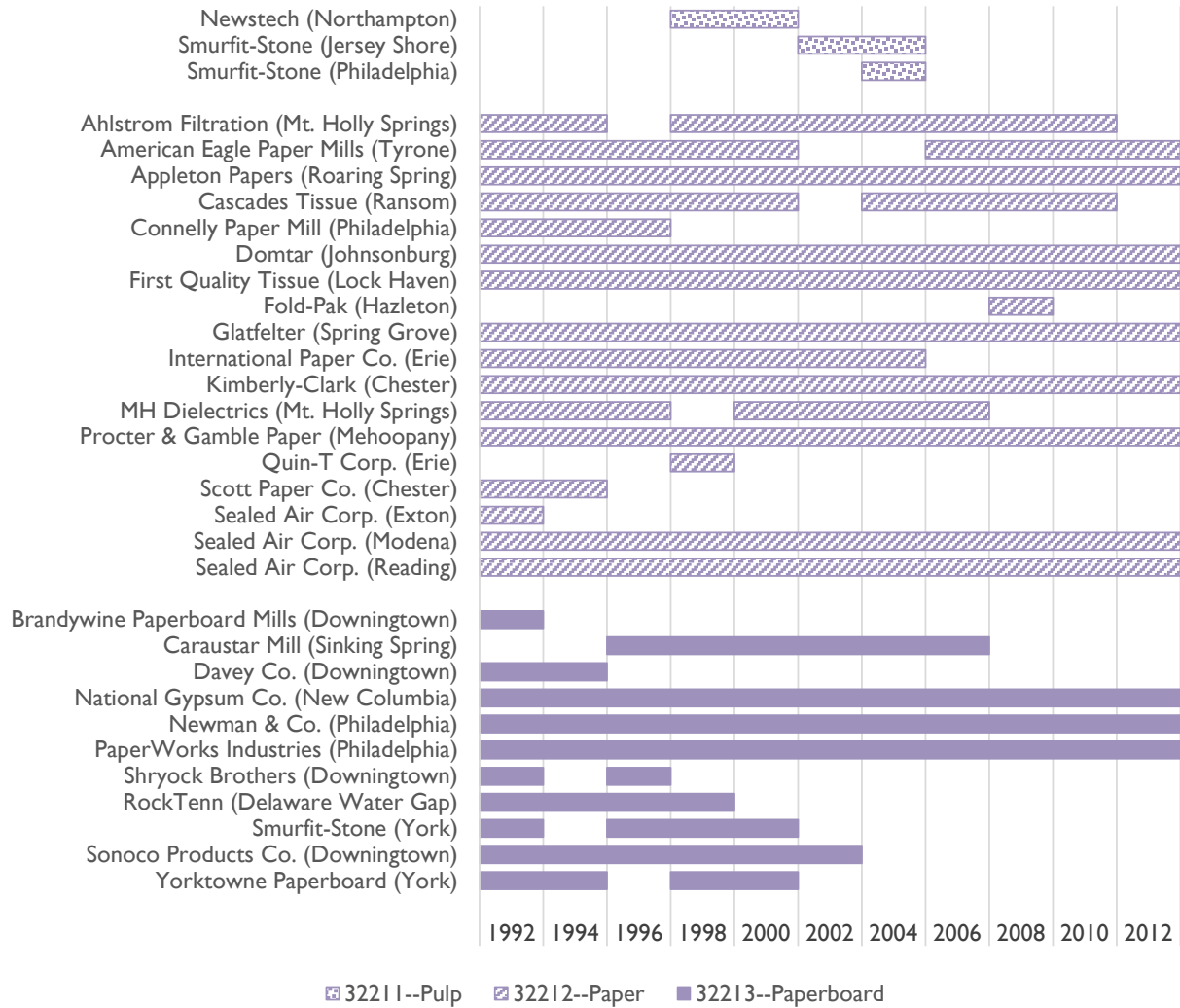


Figure 4-36. Pulp & paper industry facilities that report to the PARW program by subsector, indicating years of reporting. Two facilities—the First Quality Tissue plant in Lock Haven, PA and Sealed Air Corp. in Reading, PA—seem to have been issued new ID numbers by the state DEP before the 2004 and 2006 reporting periods, respectively.

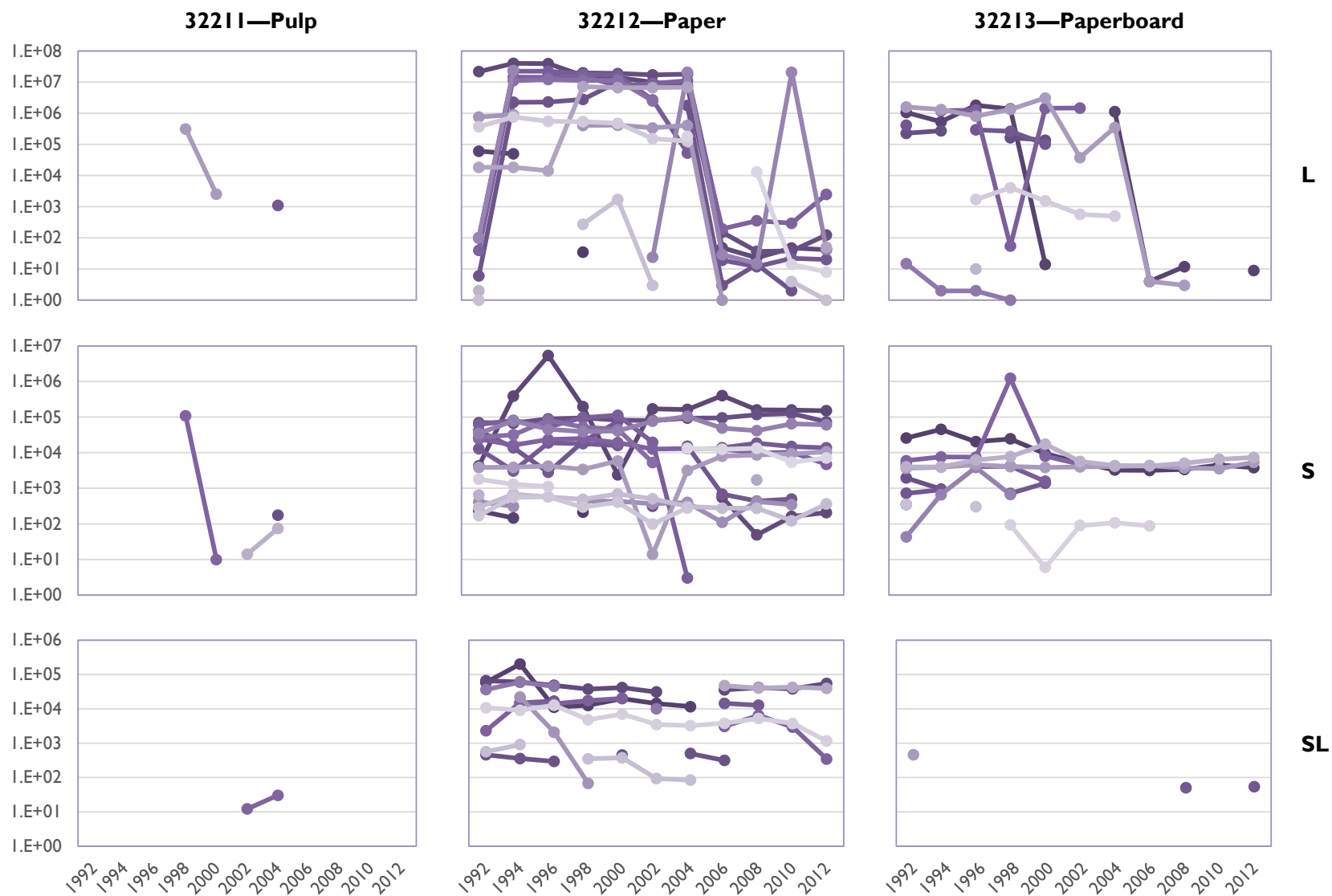


Figure 4-37. Raw residual waste data (in Mg) from the PARW database, disaggregated by industry subsector and medium of discharge. Each shade refers to a unique facility (colors are not consistent between plots). Inconsistencies in reporting such as skipped years and inter-year jumps in excess of an order of magnitude, are rampant.

It is apparent from inspection that the data is extremely messy. Numerous gaps and year-to-year jumps exceeding an order of magnitude engender a low confidence in the self-reported data to this low-priority government program with little-to-no oversight capacity. Nevertheless, this is the only data of its kind, and simple manual data cleaning methods can be employed to improve its quality.

Data cleaning occurred at the facility-waste medium level (i.e. individual discharges from each facility summed by medium in each year—the level of the data displayed in Figure 4-37. For data gaps (when a firm reports reasonable quantities of waste in years t and $t+2$ but not in $t+1$) and when year-to-year changes exceed an order of magnitude, the data for that year is interpolated from reported values on either side. Beginning and ending values of each time series are left untouched, as start-up and shut-down operations can realistically result in order of magnitude changes in waste output, especially if only open for a fraction of the reporting period (i.e. a few months). The results of this data cleaning procedure are presented in Figure 4-38.

As expected, large changes in waste output from year to year are reduced in all three media, the most significant in liquid, where reported wastewater generation in 2010 was used to estimate wastewater generated in 2006 and 2008. Similarly, an unreliably large output of solid waste from a single facility in 1996 was replaced with a value interpolated from 1994 and 1998, resulting in a much smoother graph.

Composition of non-liquid waste output from pulp and paper mills varies considerably facility-by-facility. Of the 118 available waste types (111 before 2010), 71 are generated by the industry as represented by the data set: 28 as liquid, 64 as solid, and 10 as semisolid, with 17 waste codes reported in two and seven in all three media. Solid waste is dominated by coal and wood ashes and sludges of different types, with wood, paper, and plastic wastes and plant trash also produced at some quantity. The distribution of waste types in each year from the industry is presented in Figure 4-39. Sludge and scale reported as semisolid is added to that reported as solid under the assumption that both reports refer to the same material with comparable water content, the differences existing mainly in the minds of the compliance officer who completed the forms each year.

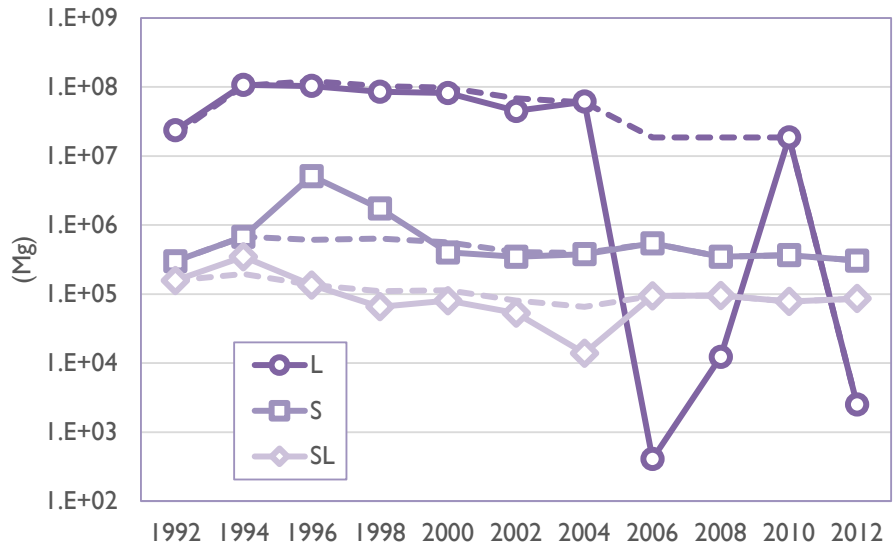


Figure 4-38. Residual waste generation from the Pennsylvania pulp and paper industry, by medium of discharge, 1992–2012. Raw data is displayed in solid lines, while corrected (interpolated) data in dashed lines.

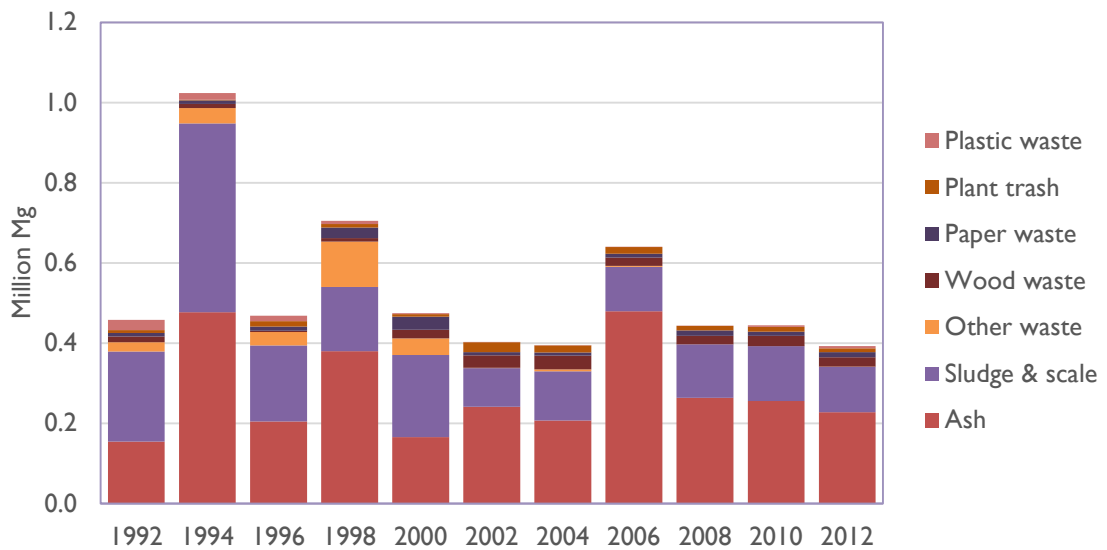


Figure 4-39. Tonnage and composition of residual wastes from the Pennsylvania pulp and paper industry (NAICS 3221), 1992–2012. Sludge & scale is wet tonnage (sum of solid and solid-liquid reported quantities); all other categories are solid waste. Liquid wastes exceed these tonnages by two orders of magnitude, but are nearly entirely composed of non-hazardous process wastewaters.

4.4.3 Scale-up

Three indicators for industry size are available for the pulp and paper industry segments in Pennsylvania and the United States. These indicators are proxies for the physical output of pulp and paper with which NHIW more reliably scales but is not available. Scaling factors for employment, value added, and shipment value, calculated as the value of that indicator in Pennsylvania as a fraction of the value of that indicator in the entire United States, are presented in Figure 4-40. The apparent differences between the scaling factors of the two subsectors, NAICS 32212—Paper and NAICS 32213—Paperboard, justifies the focus at that level of industry categorization rather than the comparatively easier approach of lumping everything together in the 4-digit NAICS code level. For the few points of data in the PARW database from pulp-only mills (NAICS 32211), scaling factors for the whole industry (3221) are used.

Also apparent from the scaling factors is the considerable influence of classification scheme on how reality is understood. The SIC (before 1997) and NAICS (1997 and after) schemes offer dramatically different pictures of the relationship between the Pennsylvania pulp and paper industry and that of the United States. At the very least, these differences are caused by shifting category boundaries, which include and exclude different firms at both state and national levels. The change in the relationship among the three indicators in the two schemes is illustrative as well, suggesting that more than mere system boundary shifting is at play.

Overall, the state paper segment (32212) is considerably more nationally representative than the paperboard segment (32213). As the scaling procedure divides state waste production by the fraction of state industry size to national industry size, the smaller the state industry, the larger the multiplicative scaling factor. So, waste from the relatively small state paperboard industry have an outsized influence on the scale-up results.

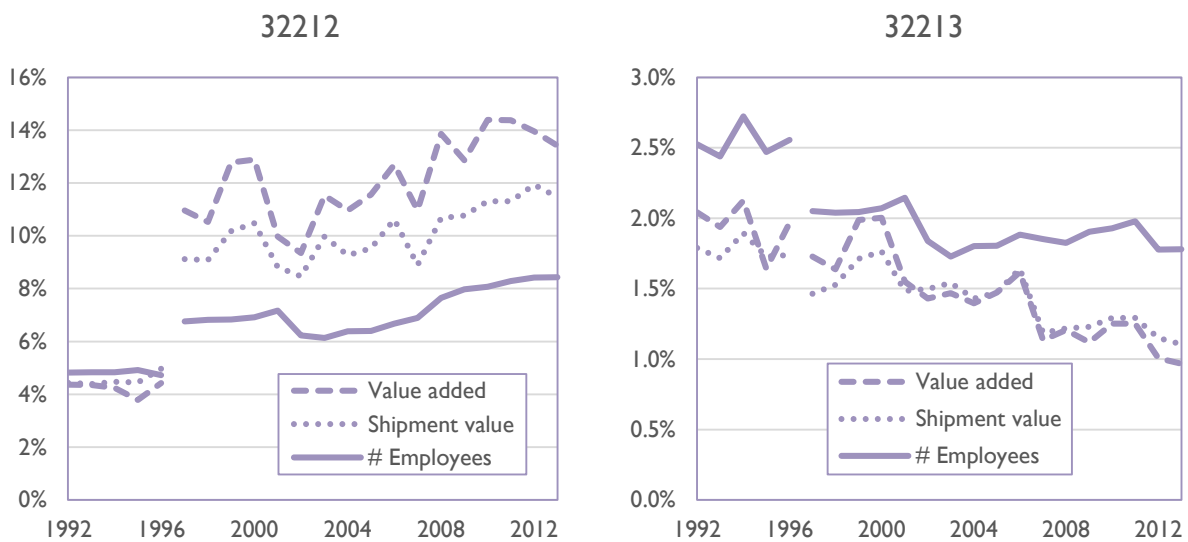


Figure 4-40. Scaling factors from PA to US for paper (32212) and board (32213) (ASM)

The approach used here cannot determine which, if any, of the three scaling factors is the most reliable. Combining the three into a range, data reported at the state level can be scaled to the national level. For the year 2010, the ranges are 8.1–14.4% for 32212–Paper and 1.3–1.9% for 32213–Paperboard. No pulp-only mills reported in 2010.

That the PARW data is reported by medium offers an interesting opportunity to test the conjecture by Allen & Behmanesh (1992) that the 1988 EPA estimate of NHIW, specifically of the pulp and paper industry, was comprised primarily of dilute process water, while the earlier SAIC figure (US EPA, 1985) more accurately represented solid wastes. Figure 4-41 displays the results from scaling up total waste generated in each medium in each reported year by the range of scaling factors and comparing the results to the two EPA estimates, forecast using annual production figures (see Section 4.2). On the log scale, it appears that liquid wastes are, at times, of the order of magnitude of EPA 1988 and solid and solid/liquid wastes are that of SAIC. In 1996, the method comes eerily close to replicating precisely the two EPA figures. Considering that it would have taken a couple of years for the PARW program to find its sea legs after its foundation in 1992 and the raft of exclusions that have come into force in recent years, this result is strong corroboration.

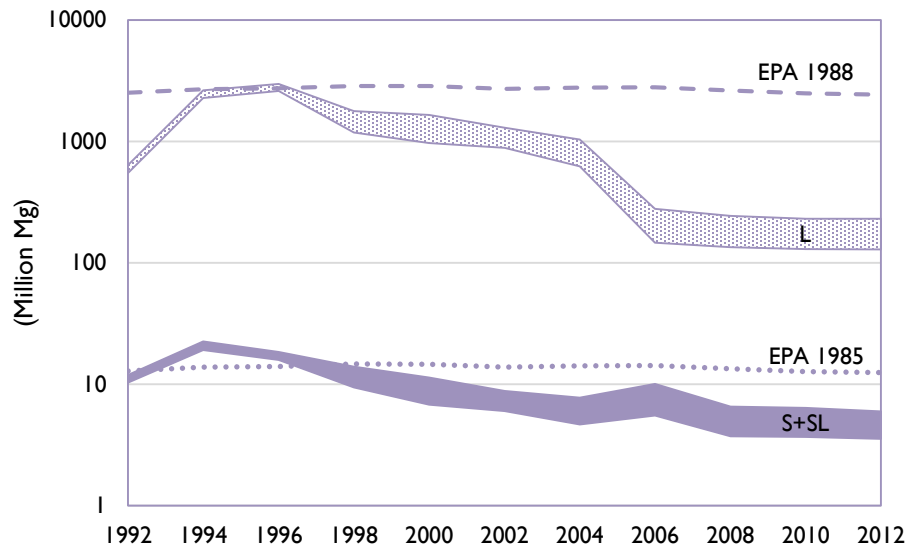


Figure 4-41. Scaled-up waste generation from pulp and paper reported as liquid (L) and solid and solid/liquid (S+SL) overlaid with the waste estimates from US EPA (1985; 1988).

4.4.4 Results

The detailed results of the solid waste scale-up are presented in Table 4-18, with summary by waste category in Figure 4-42. Although a large number of waste categories are represented in the data, the results are primarily sludge and ash, with plant trash and paper, wood, and plastic wastes as less important contributors.

Table 4-18. Results of the upscaling method for pulp and paper, 2010.

PARW waste code and description	PA (Mg)		US ('000 Mg)		Category
	32212	32213	Low	High	
001 Coal-derived bottom ash	8,360	-	58	103	Ash
002 Coal-derived fly ash	193,083	-	1,341	2,384	Ash
007 Other ash	54,207	-	376	669	Ash
109 Sandblast abrasive and residue	10	-	0	0	Other
203 Industrial wastewater treatment sludge	78,189	-	543	965	Sludge
207 Tank bottoms	406	-	3	5	Sludge
210 Air emission control sludge	255	-	2	3	Sludge
211 Other industrial sludge	55,193	-	383	681	Sludge
212 Lime/cement kiln scale, residue	2,482	-	17	31	Sludge
214 Cooling tower sediment/sludge	5	-	0	0	Sludge
305 Spent activated carbon	2	-	0	0	Other
307 Filter media/aids	56	-	0	1	Other
311 Off-spec products, intermediates	78	-	1	1	Other
403 Wood wastes	11,312	-	79	140	Wood
404 Paper, laminated paper, cardboard	4,433	5,928	343	511	Paper
407 Polyethylene, polystyrene, polyurethane, other non-halogenated plastics	425	3,208	172	252	Plastic
409 PVC, teflon, CPE, other halogenated plastics	7	-	0	0	Plastic
410 Electronic component wastes	5	-	0	0	Other
418 Sawdust, wood shavings/turnings	14,185	-	99	175	Wood
419 Empty containers	99	-	1	1	Other
424 Treated wood, railroad ties	100	-	1	1	Wood
480 Refractory (furnace, boiler)	151	-	1	2	Other
499 Other generic waste	23	-	0	0	Other
501 Asbestos containing waste	6	-	0	0	Other
503 Oil containing waste	21	-	0	0	Other
506 Contaminated soil/debris/spill residue	81	-	1	1	Other
509 Waste oil that is not hazardous waste oil	12	-	0	0	Other
703 Batteries (non-haz)	1	-	0	0	Other
710 Plant trash	7,804	4,095	270	411	Plant trash
Total	430,989	13,231	3,689	6,339	

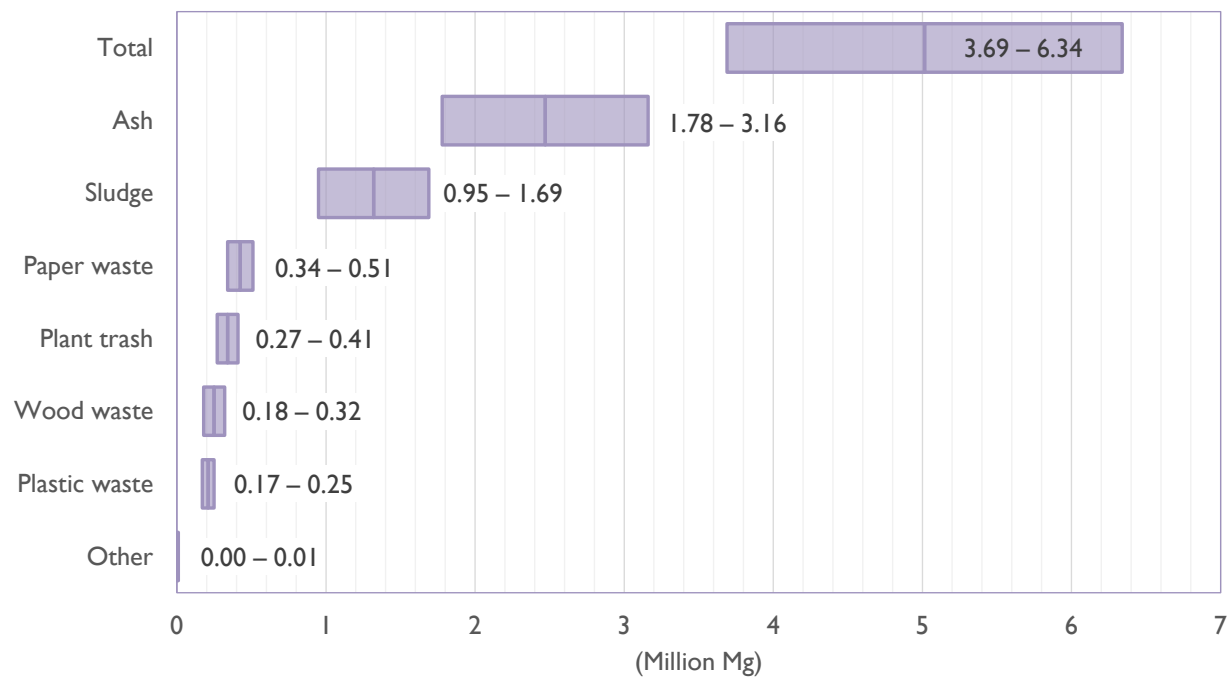


Figure 4-42. Scale-up summary of NHIW from the US pulp and paper industry, 2010

4.5 Triangulation summary

Taken together, the results from the three estimation methods can be used to triangulate a contemporary estimate of NHIW from the US pulp and paper industry in 2010. Each method relies on a unique set of data and theory of socio-economic metabolism, and although it remains possible that all three estimates have missed the mark, cross-corroboration made possible by triangulation reduces this likelihood. Results from the three methods are shown in Table 4-19.

Table 4-19. Results from the three estimation methods for the US pulp and paper industry, 2010

Waste Category	Forecast		Mat-Bal (million Mg)		Scale-up	
	(1978)	(1995)	Low	High	Low	High
Ash	1.63	2.34	0.76	3.13	1.78	3.16
Sludge	4.04	6.37	6.12	7.63	0.95	1.69
Wood waste	2.86	0.74	-	-	0.18	0.32
Other	3.80	2.65	1.61	3.90	0.78	1.18
Total	12.33	12.10	8.49	14.66	3.69	6.34

Extracting the correct range of waste from this list is in many ways a fool’s errand; there is enough internal logic and dependency in each method that I cannot pick and choose the most reasonable—or mid-range—estimate for each waste category. For example, there is an inverse relationship between wood waste and ash, so they must be considered together. Similarly, what in reality may be the same waste materials might show up as “sludge” in one method and “other wastes” in another. But by looking in detail at the results and considering carefully what we have learned about each of the methods and underlying data, a single estimate is within reach.

Looking just at totals, it appears as if the forecast and materials balance largely agree, while the scale-up results are biased low. However, much of the gap is due to a very low estimate of sludge generation from the PARW data. Recall that this estimate is based just on solid and semi-solid wastes reported as sludge at the mill; any suspended or dissolved solids in wastewater that is sent off-site to a treatment plant is not counted. This is most likely a persistent problem throughout the PARW database. Sludge results from the 1995-basis forecast agree very well with those from the materials balance.

The tradeoffs between ash and wood waste are also apparent from the results. On balance, the methods that report higher ash generation also report lower wood waste and vice versa. The trend towards increased on-site energy generation from both coal and wood waste incineration has

been ongoing, and the most recent data, from the PARW, appears to follow a rough trend with the two forecasted data sets.

Impossible to decipher is the “other waste” category. This includes rejects, plant trash, and a wide range of other wastes. Here, the prudent tack is to select a wide range that covers most of the results. Following this brief meta-analysis, the triangulated result stands as follows (million Mg):

- Sludge: 6.1–7.6
- Ash: 1.8–3.1
- Wood waste: 0.2–0.3
- Other: 1.6–3.9
- TOTAL: 9.7–14.9

The extreme range (summing all lows and all highs) is from 9.7 million Mg to 14.9 million Mg. This is an unlikely scenario because of the tradeoffs among different waste categories mentioned earlier. The inconsistency of categorization among the three underlying data sets suggests the “true” value to be close to the average: 12.3 million Mg, which happens to be very close to both the forecasted estimate and the average of the material balance estimate.

Despite the variability of the triangulation result, one conclusion is indisputable, that the infamous figure from the 1988 EPA Report to Congress, two billion Mg, needs to be flushed.

5 Iron & Steel Manufacturing

Iron and steel manufacturing has been claimed as the second largest contributor of NHIW in the US, in large part due to its generation of slag in blast furnaces and steel furnaces. Wastes from this industry have been recovered, recycled, and beneficially used for many years, following the lead of widespread use of iron and steel slag in construction applications. The results from the three estimation methods demonstrate both the success of industry beneficial use strategies and the importance of consistent accounting standards. While the forecast and materials balance methods yield estimates between 24.7–26.3 million Mg of NHIW for the year 2010, the scale-up method suggests just 2.0–4.3 million Mg. The PA residual waste data used in the scale-up excludes wastes sold or otherwise used as byproducts. The result of the triangulation yields a final estimate of 21.2–24.7 million Mg.

5.1 Introduction

This section introduces the US iron and steel industry and details important for completion of the triangulation methods and interpretation of results.

5.1.1 Motivations

Steel is the second most prevalent human-made material on Earth, behind only cement in annual global production tonnage (Allwood & Cullen, 2012). Primarily used in construction applications, steel is essential to the manufacture of vehicles, industrial equipment, home appliances, and other products. Iron and steel have been central materials technologies for more than three thousand years of human history, enabling new and stronger tools and weapons, an increased ability to transform and dominate the natural world, and new modes of societal organization (Sass, 1998; Smil, 2013).

Iron is abundant, comprising roughly 5% of the Earth's crust. Even when found at relatively high concentrations, however, mining and refining the ore into raw metal generates a large amount of waste material. According to the EPA's official account, the iron and steel industry is the second largest source of NHIW in the US, responsible for 1,180 million Mg in 1985, 17% of the total. SAIC also ranked the iron and steel industry second in its estimate at 60.7 million Mg, 15% of the total. This represents an unusual convergence of the two otherwise highly uncorrelated data sets.

Also somewhat unique to this industry is the extent to which solid wastes have been recovered, recycled, and beneficially used. Due to a broad set of economic and environmental

pressures facing all primary materials industries the late 20th century, the steel industry responded by developing new methods for metals recovery, reprocessing, and recycling waste, building on the long history of marketing iron and steel slag to a variety of construction applications.

The American Iron and Steel Institute (AISI) is the main trade association of iron and steelmakers in the US. AISI collects and publishes a range of industry data, including some environmental statistics. However, it appears as if waste has not been a policy priority of AISI or of any of the partner trade organizations, like the Steel Manufacturers Association (SMA) or the Association for Iron & Steel Technology (AIST). While there has been some discussion in the latter organization in particular of waste minimization as a mill-level goal, there have been no industry-wide studies or publications akin to those put out by the paper industry on NHIW generation. Even the trade association dedicated to beneficial use of NHIW from the industry, the National Slag Association, only publishes data on sold—not generated—material. For these reasons, the iron and steel industry is an important candidate for this dissertation, and offers opportunities for testing the triangulation method in a distinct manner.

5.1.2 Iron & steel sector in the US

The iron and steel sector is classified as part of NAICS 331—Primary metal manufacturing, even though the industry includes both primary and secondary metals production. NAICS distinguishes between the manufacture of iron, steel, and ferroalloy products in integrated mills that also smelt raw iron and steel (NAICS 3311) and the manufacturing of steel products in dedicated, non-integrated rolling, drawing, and finishing facilities (NAICS 3312). The industry is classified into four six-digit codes: 331110, 331210, 331221, and 331222, which largely correspond to the superseded SIC codes 3312–3317, as indicated in Table 5-1. Iron, steel, and ferroalloys are manufactured only in mills classified under 331110, but rolled or finished steel products are made both in the integrated 331110 mills and the equivalent non-integrated 3312 mills (Table 5-2).

The subsequent series of SIC codes (3321–3325) are those associated with iron and steel foundries (equivalent to NAICS 33151). Both the SAIC (US EPA, 1985) and *Industrial Facilities Survey* (US EPA, 1988) results include at least iron foundries (SIC 3321) in their system boundaries for the iron and steel industry. Here, I exclude foundry activities from the industry scope because the activities involved and wastes generated have more in common with non-ferrous foundries than primary and secondary metal production. Even so, due to the nature of the industry, there are likely foundry processes occurring in large, integrated iron and steel mills and some steel production occurring in facilities that are primarily foundries.

Table 5-1. Crosswalk between NAICS and SIC for the US iron and steel industry (US CB, 2014)

<u>NAICS</u>	<u>SIC</u>
331110: Iron and steel mills and ferroalloy mfg	3312: Blast furnaces and steel mills
331210: Iron and steel pipe and tube mfg from purchased steel	3313: Electrometallurgical products
331221: Rolled steel shape mfg	3315: Steel wire and related products
331222: Steel wire drawing	3316: Cold finishing of steel shapes
	3317: Steel pipe and tubes

5.1.2.1 Physical production

The total production tonnage of iron and steel in the US has varied during the second half of the 20th century (Figure 5-1). Following a local peak during World War II around 80 million Mg/year, production climbed to nearly 140 million Mg in 1973. After a crash in the early 1980s, production has been relatively stable between 90–100 million Mg, although the Great Recession sent 2009 production to levels lower than they had been since before WWII. For much of this recent history, pig iron production was approximately 65–70% the volume of raw steel and mirrored its annual volatility. But after the 1980s, the ratio of iron/steel production decreased steadily, reaching 36% around the 2009 crash. The proximate reason for this change is illustrated in Figure 5-2, which shows the share of ferrous metal inputs to steelmaking commanded by pig iron, steel scrap, and direct reduced iron (DRI). Having hovered around 50/50 iron/scrap during the mid-20th century, scrap overtook pig iron in subsequent years, with nominal quantities of DRI also substituting for blast furnace iron in the last 20 years.

The move away from production and use of pig iron in steel furnaces can be explained by the shifts in steelmaking technology throughout the last century (Figure 5-3). Following an extremely rapid transition away from the rudimentary open hearth (OH) process to the basic oxygen furnace (BOF), that technology in turn gave way gradually to the electric arc furnace (EAF). The two techniques reached parity around the year 2002, with all subsequent growth in the industry occurring in EAF capacity. This shift explains the trends in raw materials production and consumption described above because whereas BOF consumes mainly pig iron to produce steel, EAF consumes steel scrap and DRI.

Although the iron- and steelmaking processes are optimized for those primary products, slag—the main waste product from blast and steel furnace—has come to be considered a by-product. Seemingly as long as there has been recordkeeping, slag has found beneficial use as aggregate in Portland cement concrete, asphalt concrete, road base construction, and railway ballast. It has also been used in the manufacture of mineral wool insulation and, most recently, as a source of cementitious material itself (Figure 5-4).

Table 5-2. 2012 NAICS Index entries for NAICS 3311 & 3312 (US CB, 2013)

331110: Iron and Steel Mills and Ferroalloy Manufacturing

Armor plate	Frogs	Spiegeleisen ferroalloys
Axles, rolled or forged	Galvanized metals	Spike rods
Bars	Hoops	Sponge iron
Billets	Ingot	Stainless steel
Blackplate	Iron ore recovered from slag	Steel balls
Blooms	Iron sinter	Strip
Coke oven products	Manganese metal ferroalloys	Structural shapes
Concrete reinforcing bar (rebar)	Molybdenum silicon ferroalloys	Superalloys
Direct reduced iron	Nut rods	Template
Electrometallurgical ferroalloy	Paste	Terneplate
Electrometallurgical steel	Pig iron	Ternes, long or short
Fence posts	Pipe	Tie plates
Ferroalloys	Plate	Tin-free steel
Ferrochromium	Powder	Tinplate
Ferromanganese	Rail joints and fastenings	Tool steel
Ferromolybdenum	Railroad crossings	Tube
Ferrophosphorus	Rails	Tube rounds
Ferrosilicon	Rods	Tubing, seamless steel
Ferrotitanium	Sheet pilings	Well casings
Ferrotungsten	Sheets	Wheels, car and locomotive
Ferrovandium	Shell slugs	Wire mesh
Flakes	Silicomanganese ferroalloys	Wire products
Flats	Skelp	Wrought pipe and tubing
Forgings	Slab	

331210: Iron and Steel Pipe and Tube Manufacturing from Purchased Steel

Boiler tubes, wrought	Tube (e.g., heavy riveted, lock joint, seamless, welded)
Conduit, welded and lock joint	Tubing, mechanical and hypodermic sizes
Pipe (e.g., heavy riveted, lock joint, seamless, welded)	Well casings

331221: Rolled Steel Shape Manufacturing

Bars	Flakes	Paste
Cold rolled steel shapes (e.g., bar, plate, rod, sheet, strip)	Flat bright steel strip	Powder
Concrete reinforcing bar (rebar)	Metal powder and flake	Razor blade strip steel
	Nut rods	Wire, flat, rolled strip

331222: Steel Wire Drawing

Barbed and twisted wire	Mesh, wire	Welded iron or steel wire fabric
Baskets	Nails	Wire cages
Brads, wire or cut	Paper clips	Wire carts (e.g., grocery, household, industrial)
Cable, insulated or armored	Spikes	Wire cloth
Chain link fencing	Staples	Wire garment hangers
Fence gates, posts, and fittings	Tacks	Wire products
Form ties	Tie wires	Wire (e.g., armored, bare, insulated)
Horseshoe nails		

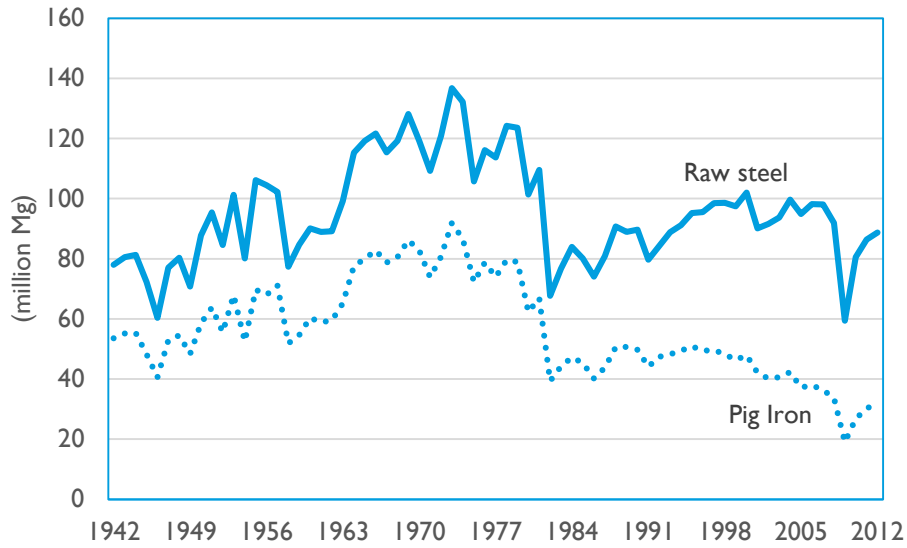


Figure 5-1. Production of pig iron and raw steel in the US, 1942–2012 (MYB Iron & Steel)

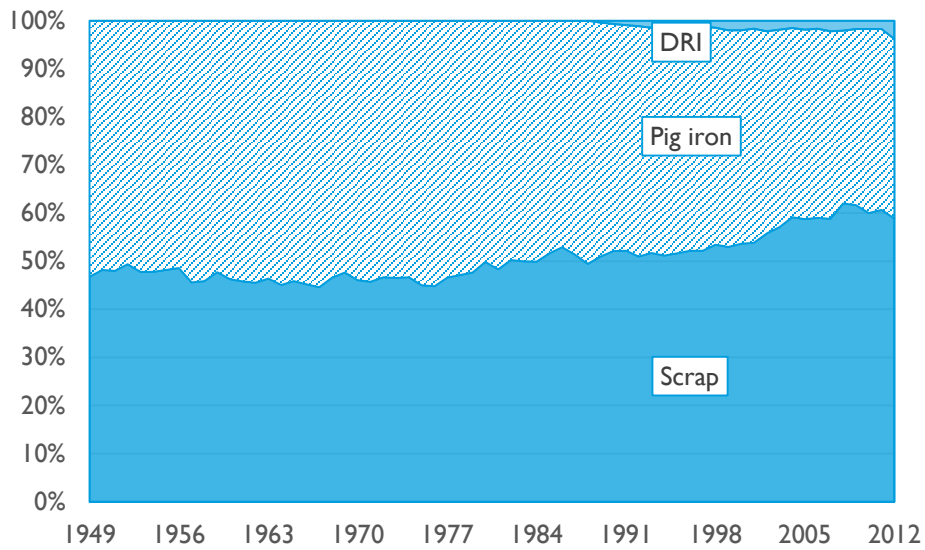


Figure 5-2. Pig iron, scrap, and DRI inputs to steelmaking in the US, % of total, 1949–2012 (MYB Iron & Steel Scrap)

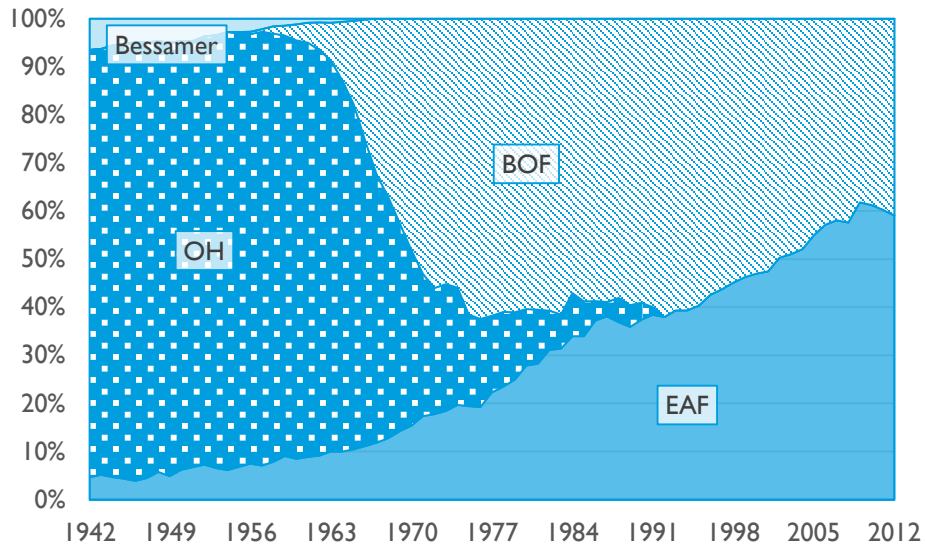


Figure 5-3. Evolution of steel furnace technologies in the US, 1942–2012 (MYB Iron & Steel)

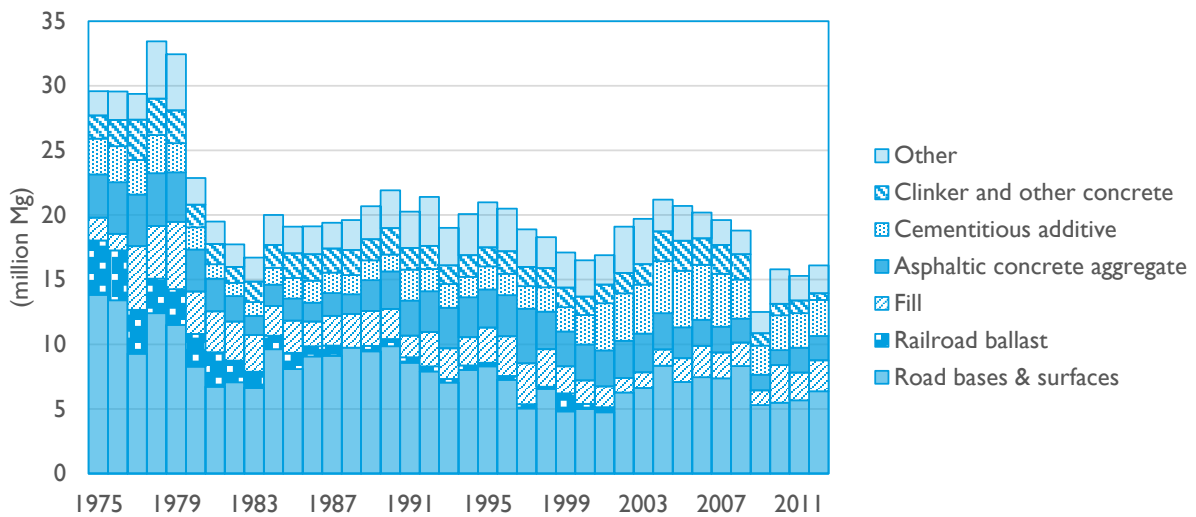


Figure 5-4. Quantities and uses of sold iron & steel slag in the US, 1975–2012 (MYB Iron & Steel Slag)

5.1.2.2 *Economic indicators*

Of the four iron and steel industry subsectors classified by NAICS, the vast majority of economic—and presumably physical—output comes from 331110—Iron and steel mills and ferroalloy manufacturing.⁵² In all three economic indicators examined, total employment, total value of shipments, and value added, NAICS 331110 facilities were responsible for 70–80% of the total (Figure 5-5). The non-integrated steel finishing mills classified under NAICS 3312 contributed the remaining quantities.

Over the course of the 22-year time period for which economic data was collected, the two dollar-value indicators, value of shipments and value added, track closely with the physical production of raw steel. On the other hand, there has been a secular decrease in employment in all industry segments. The increased labor productivity reflected by these two trends reflects the same famously occurring throughout the US economy. What is less clear is the effect it may have had on NHIW generation or the utility of one of these measures or another as an indicator thereof. Decreased employment reflects efforts made by the industry to minimize costs through automation and other labor productivity interventions. Perhaps similar cost-cutting strategies were employed around mill-level waste generation. One would think that circumspect steelmakers would see underutilized waste streams as a possible revenue source, although anecdotal evidence suggests that identifying pollution prevention or beneficial use avenues often requires a different mental model than is often employed by conventional factory managers.

Steel mills themselves have also evolved over the time period examined (Figure 5-6). Although the number of individual establishments (1100) is roughly the same in 2012 as it was in 1987, slight growth in the number of NAICS 331110 mills has come at the expense of the nonintegrated mills. Looking closer at the distribution of sizes of facilities within each industry segment, it is clear that the largest integrated mills have given way to smaller EAF mills, while the distribution of the non-integrated side has remained roughly constant.

5.1.2.3 *Geographic distribution*

Iron and steel production capacity is concentrated, as the name would suggest, in the so-called “rust belt” of Indiana, Pennsylvania, and Ohio, with other Midwestern states (Alabama, Kentucky, Illinois, and Michigan) rounding out the list of largest producers (Figure 5-7). Non-integrated producers are found slightly further afield, with capacity spreading out over the past decade to be closer to population centers in Texas and California. Many of the rust belt states’ steel industries still contribute a sizeable fraction to total manufacturing output in the state (Figure 5-8).

⁵² This subsector is somewhat unusual in that the same four-digit, five-digit, and six-digit codes refer to the same set of economic activities, with no subdivision.

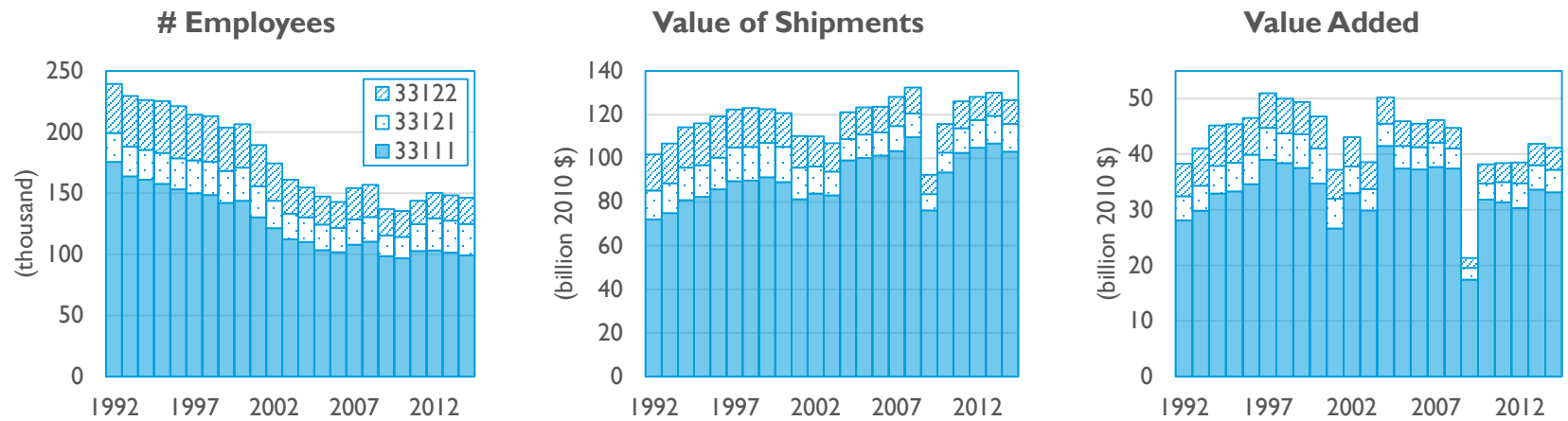


Figure 5-5. Economic indicators for the iron and steel industry in the US, 1992–2014 (EC, ASM, PPI)

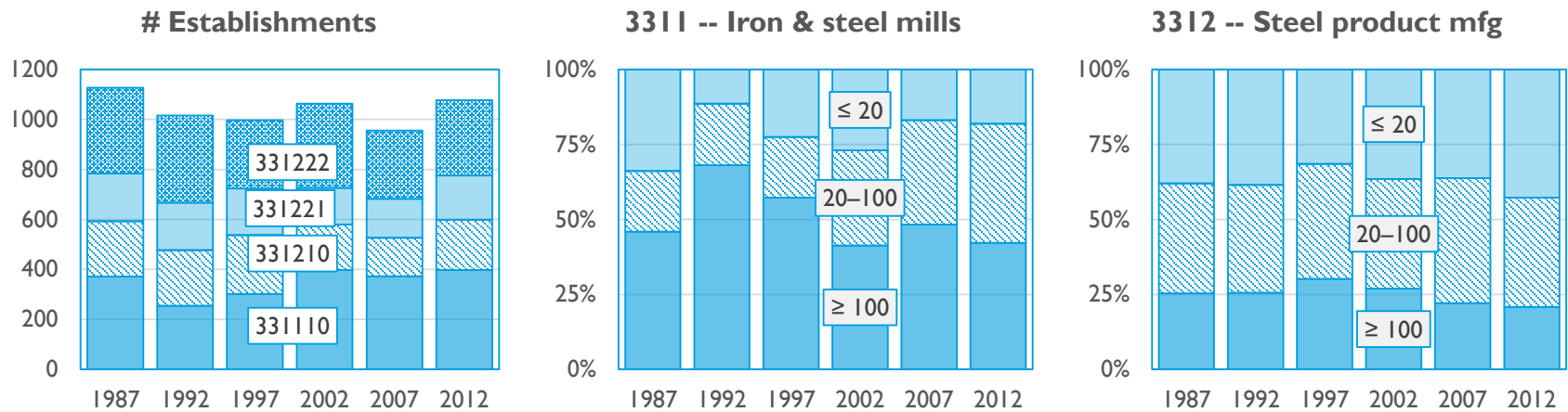


Figure 5-6. Iron & steel industry establishments: quantity by subsector and size distribution by employment for NAICS 3311–3312 (EC, ASM)

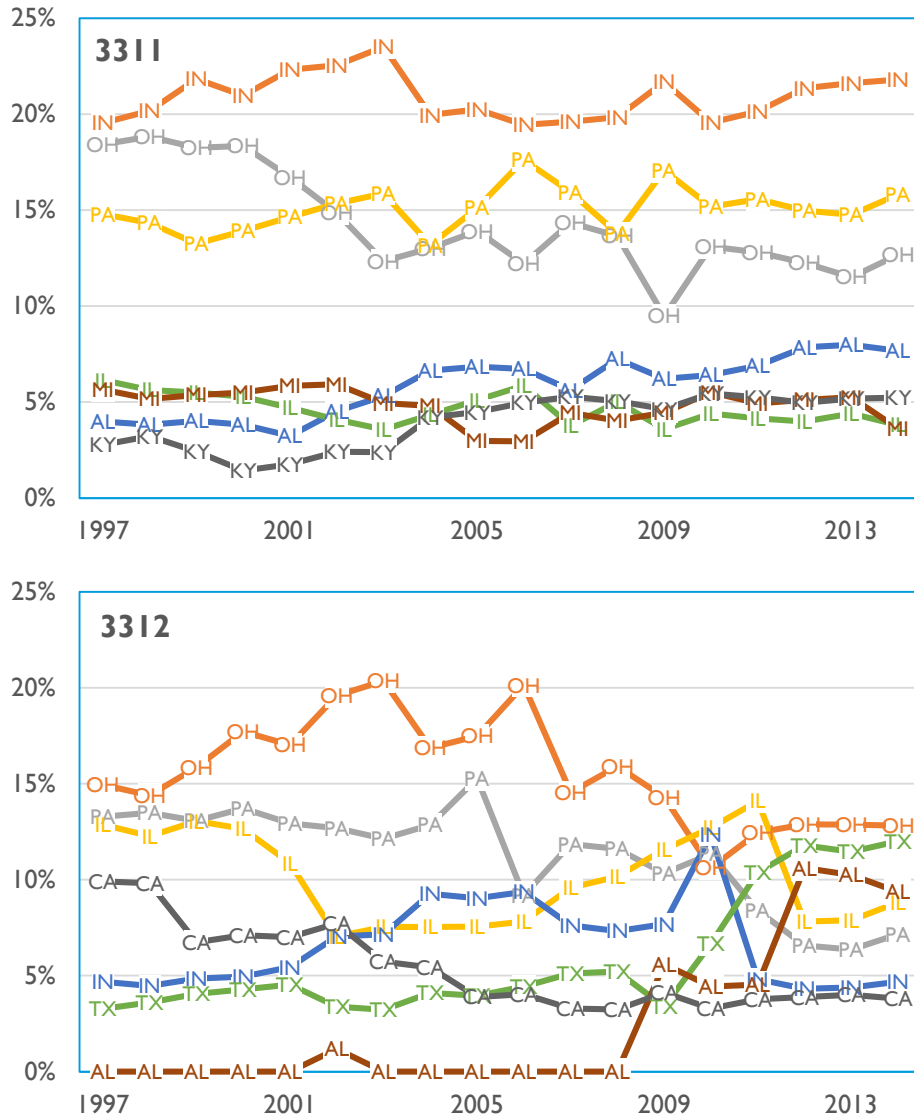


Figure 5-7. State iron & steel sectors as a fraction of the national industry, 1997–2014, by total value of shipments (EC, MYB)

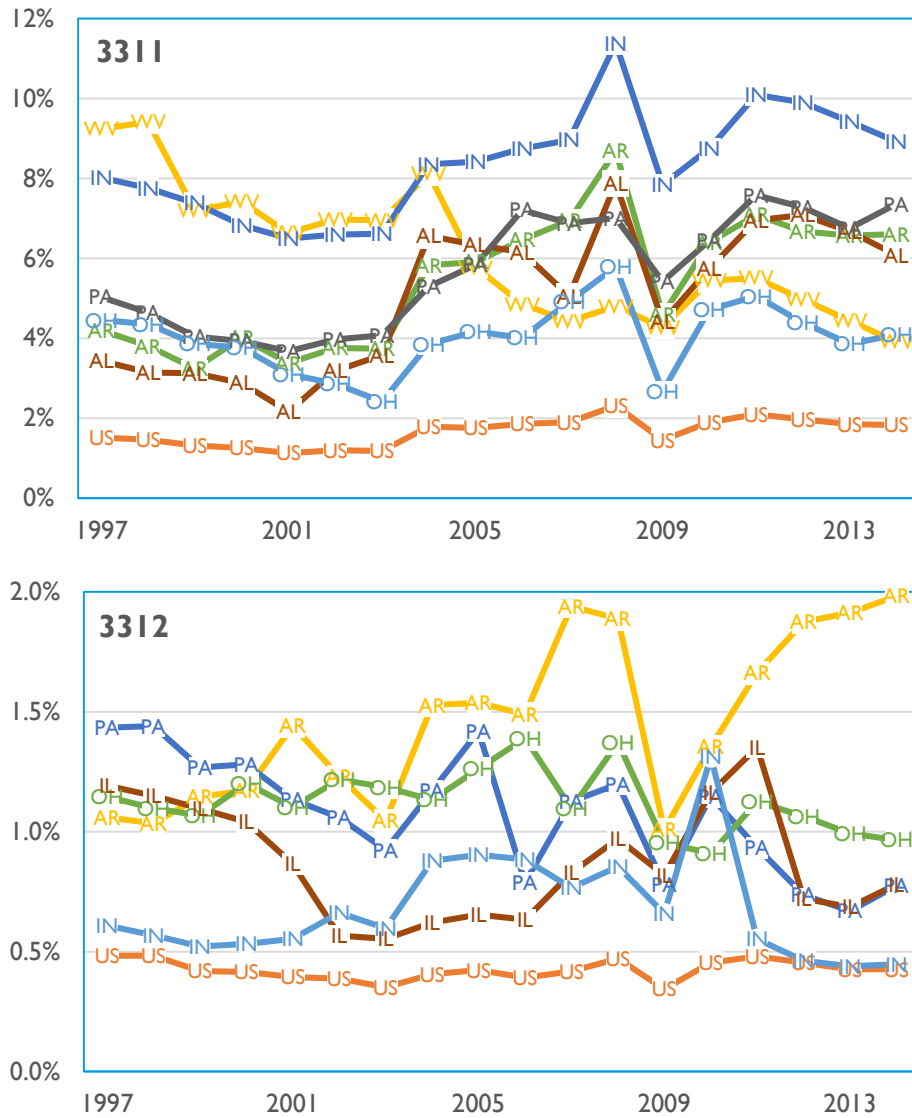


Figure 5-8. State iron and steel sectors as a fraction of total state industry, 1997–2014, by total value of shipments (EC, MYB)

5.1.3 Iron & steel manufacturing and NHIW production

According to UN estimates, the manufacturing of one Mg of crude steel yields 550–600 kg of wastes and potential byproducts, arising from nearly every step in the iron and steel manufacturing process (UN ECE, 1990).⁵³ Table 5-3 summarizes the waste materials from eight separate processes involved in the industry, including the preparation of precursors, ironmaking, steel and ferroalloys manufacturing, and finishing products. For the iron and steel industry, most of the major waste streams have been to varying degrees exploited as byproducts.

5.1.3.1 Precursors

The raw material inputs to blast furnaces are primarily coke, iron ore, and lime, the preparation of all of which produces solid waste. Coke is a solid, high-carbon material manufactured via the pyrolysis of coal. The volatile organic chemicals that are liberated during coking were once lost as air pollution, but today are recovered and utilized on site or sold as byproducts (US DOE, 2000). The fine particulates of coke that are produced from material handling and forming into the geometries best suited for the blast furnace are called “coke breeze.” If recovered, breeze can be used as a fuel for other processes in an integrated mill or sold. Other wastes are generated from the coking chemical recovery process and environmental control.

Early iron smelting was performed using ore with any geometry. Modern blast furnaces have been designed to operate the best using ore prepared into uniformly sized, porous pellets via sintering and pelletizing. Both processes begin with crushing the ore, which generates dust that is collected in baghouses and other environmental control processes. The crushed ore fines are then either combined with water and fuel and fired (sintering) or combined with a binder and baked in a kiln (pelletizing).

Lime (CaO) is produced from the combustion of limestone (CaCO₃). This process does not yield any unique wastes, but any air pollution stemming from impurities in the limestone may end up as environmental control sludge.

5.1.3.2 Iron

The predominant method of manufacturing iron is in blast furnaces, in which pelletized iron ore is combined with coke and lime and fired to produce ingots (“pigs”) of iron with more than 2% carbon content. Iron ore is an agglomeration of iron oxide and many other inorganic mineral oxides of crustal elements like silicon, aluminum, magnesium, and sulfur. At temperatures

⁵³ The Association for Iron and Steel Technology developed a comprehensive online module explaining the iron and steel manufacturing process. It can be accessed at <http://apps.aist.org/SteelWheel/index.html>.

exceeding 1000°C, the coke reduces the iron oxide to elemental form (generating large quantities of CO₂ in the process) and the lime preferentially bonds with the non-ferrous elements in the ore to produce slag. Blast furnace slag is therefore primarily composed of the same crustal element oxides as were contained in the ore, along with the calcium from the lime flux. The gas evolved from the blast furnace contain large quantities of dust and chemicals which are captured and disposed as sludge.

According to a UN report on iron and steel industry by-products, “most ironmakers reject the notion that their slag is a waste material, preferring to view it as a saleable product exhibiting an exciting range of properties and uses” (UN ECE, 1990, p. 32). Early uses for the material were primarily in construction applications, and “even where external markets are not available ironmaking slag has been used extensively for foundations and land reclamation on steelworks development projects.” The similarity of the composition of slag that of Portland cement also leads to its use as a substitute input for cement clinker.

As a result of coke scarcity, other methods have been developed for directly reducing iron ore in a reducing environment, a process that yields a product called “sponge iron.” Direct reduced iron production also generates slag and environmental control sludge.

5.1.3.3 *Steel & ferroalloys*

Steelmaking is the process of converting pig iron and scrap into steel, an alloy of iron, carbon, and any number of other elements. Steel generally has less than 2% carbon content, which gives the material great tensile strength. Modern steelmaking is done in two main types of furnaces, the basic oxygen furnace (BOF, also called the Linz and Donawitz or LD process), and electric arc furnace (EAF). The dominant technology in the early part of the 20th century, the open hearth process (OH), is not in use in the US anymore.

BOF steelmaking is an evolution of the early Bessemer/Thomas process that first enabled the industrial production of steel in the mid-19th century. BOF is the main process by which the high-carbon pig iron is converted into lower-carbon steel. In the furnace, molten iron (and smaller quantities of other ferrous sources like scrap and some high quality iron ore) is combined with alloying metals and lime. Oxygen is blown through the molten metal, combusting the carbon in the pig iron, increasing the temperature in the furnace and evolving CO and CO₂. As in the blast furnace, lime and other flux materials bond with impurities in the charge, producing slag. BOF steelmaking is a very capital and energy-intensive process, and as a result is done almost exclusively in large, integrated mills that often include all the steps necessary to convert iron ore and coal into finished steel processes.

EAF steelmaking, on the other hand, converts mainly iron and steel scrap along with some DRI and pig iron to produce raw steel with desired properties. The ferrous materials are melted

using an electrical arc, after which impurities are removed using fluxes and, in some cases, injected gases (US DOE, 2000). EAF starts with cold metal, so can be non-integrated with the rest of the iron and steelmaking process. The development of stand-alone “mini-mills” in the latter part of the 20th century has transformed the US steel industry.

In order to create steel with desired physical properties, a large number of alloying metals are used, including chromium (for stainless steel), nickel, vanadium, and many others. BOF and EAF processes consume these alloys in the form of ferroalloy, which are also often manufactured on site at the steel mills in which they are to be consumed.

BOF and EAF steel and ferroalloy manufacturing all produce process slag and environmental control sludges, while steelmaking also generates dust in some quantity. There is high iron content in many steelmaking slags, which is often recovered. The remainder of the slag can be further processed and used in beneficial applications, although “the oxides present in BOF slag can result in volume expansion of up to 10% when hydrated... [so] its use is more limited than blast furnace slag” (US DOE, 2000, p. 58). EAF dust and sludge are listed hazardous wastes (K061).

5.1.3.4 Finished products

Molten raw steel is cast into a set of standard semi-finished shapes, including ingots and rounds (circular cross section), slabs (thick rectangular cross section), strip (thin rectangular cross section), billets (thin bars), and blooms (thick bars). These semi-finished products are then surface treated, cleaned, rolled, and formed, all of which generate waste. Mill scale is the thin veneer that flakes off of steel during rolling and surface treatment. It has a high iron content, much of which can be recovered. Pickling is the process of using a strong acid to remove surface impurities; spent pickle liquor is a listed waste (K062). Scarfing is the process of removing surface defects. Soaking pits are used to equalize the temperature of semi-finished steel, in preparation for rolling. The dust, slag, and sludge from all of these processes make up a substantial quantity of waste from the iron and steel industry.

Table 5-3. Solid wastes and by-products from the iron and steel industry (UN ECE, 1990, pp. 3–4)

1. Coke production <ul style="list-style-type: none">• Coke breeze• Boiler and cooler cleaning residues• Lime sludge from ammonia production• Sludge from mechanical clarification of coking plant effluents• Sludge from activating units for the treatment of coking plant effluents• Dusts	5. Production of ferroalloys <ul style="list-style-type: none">• Slag• Sludge
2. Sintering plants and pellet production <ul style="list-style-type: none">• Small fraction oxide-bearing ore• Sludge• Dusts	6. Steel production (OH/BOF/EAF) <ul style="list-style-type: none">• Steelmaking slag• Dust from secondary emission control• Dust from dry fume collection• Sludge from the process
3. Pig-iron production <ul style="list-style-type: none">• Blast-furnace slag and products of its granulation• Dust from cast house fume collection• Dust and slurries from top gas cleaning• Sludge from top gas scrubbing water cleaning	7. Production of rolled products <ul style="list-style-type: none">• Scale• Rolling mill sludge• Scarfing slag• Soaking pit slag• Grinding and cutting waste• Sludge from roll grinding shop• Spent oil and grease
4. Direct-reduction processes <ul style="list-style-type: none">• Slag• Sludge	8. Further treatment of steel products <ul style="list-style-type: none">• Scale from mechanical surface treatment• Scale from process water treatment• Dusts• Neutralization sludge• Spent heat treatment salts• Residues from metal degreasing and cleaning

5.2 Historical forecasting

Residuals from iron- and steel-making have been environmentally problematic for much of the industry's history. As early as 1939, "the rapid growth of the iron, steel, and associated by-product coking industries has brought problems in the utilization and disposal of waste materials; among the more important are slags, flue dust, mill scale, scrap iron, spent pickle liquor, coke breeze, ammonia liquors, coal tar, and phenolic liquors" (Hodge, 1939, p. 1364). Interest in ameliorating these problems can be traced back to the late 19th century, motivated both by acute environmental hazards (e.g. waste pickle liquor) and opportunities for by-product reuse (e.g. slag) (Hoak, 1947). The waste outputs of this industry have been affected considerably by changes in production and pollution control technologies, market size and structure, and evolving regulatory requirements (US EPA, 1995a; US DOE, 2000). This section presents the application of the historical forecasting estimation method to the iron and steel manufacturing sector in the US.

5.2.1 Data

Since the US EPA's last direct survey of NHIW in the mid-1980s, much of the available data has come courtesy of research by individual industry trade organizations, such as NCASI for the pulp and paper industry and API for petroleum. The equivalent organization for the steel industry, AISI, seems to not have focused on solid waste as a policy priority, and so has not conducted, or at least published, any similar studies. Nevertheless, empirical data from the 1970s and 1980s and other estimates from the 1990s are available for examination.

The earliest EPA-era data on solid waste from the modern iron and steel industry come via a 1976 EPA report on solid waste generated by pollution control processes. This subject was of interest at the time due to the air and water pollution control regulations that had recently come into force which resulted in increases in the tonnage and, in some cases, toxicity of solid wastes. In contract with the EPA, researchers from the Dravo Corporation visited 11 integrated steel mills in the United States, selected to ensure statistical representativeness (US EPA, 1976b). Data was also provided by two additional mills. In total, the 13 mills surveyed produced 28% of the total 132 million Mg of raw steel manufactured in the US in 1974. Based on 200 total samples of waste materials generated by the various activities at the mills, the authors estimated that the entire US iron and steel industry generated just over 15 million Mg of pollution control residues in 1974, 55% of which were recycled and 45% were discarded (Table 5-4). They also concluded based on a compositional analysis that with technology improvements, much of the 6.8 million Mg of NHIW that were dumped could potentially be recycled as well. This figure notably excludes the large quantities of slag produced in iron and steel smelting, although it does include the dust and sludge generated in those same activities (blast furnace, BOF, and EAF).

The next empirical data on waste generation from iron and steelmaking was published in 1977 in service of the new hazardous waste regulatory program authorized by RCRA (US EPA, 1977). Following the passage of that law, the EPA commissioned industry-by-industry studies by different engineering consulting firms to “provide the USEPA with as detailed and pertinent information on the generation, management, treatment, disposal, and costs related to wastes considered to be ‘potentially hazardous’” (p. 3). The EPA would use this information to develop their regulatory agenda. Contractors were given wide berth in developing the methodology for characterizing waste outputs and hazard criteria. Calspan Corporation received the contract to study the metals smelting and refining industries, including both ferrous and non-ferrous metals, and chose to characterize all solid waste outputs from their subject industries, and then determine the fraction that posed a risk to human and environmental health.

Calspan conducted “intensive sampling and chemical analyses of steel plant residuals” of 10 integrated steel mills “located in the North Central and Great Lakes region of the United States” (p. 20). Based on this data, the authors calculated waste generation factors for 26 waste types grouped into five categories—slag, sludge, dust, scale, and pickle liquor—and used those factors to estimate national waste production in 1974, 1977, and 1983 (Table 5-5). The 1974 estimate was based on reported steel production figures and those for 1977 and 1983 were achieved using forecasted annual growth rates of 2.1%–2.5%. The results of this analysis show waste generation rates for 1974 at nearly 74 million Mg, increasing to 80 million Mg in 1977 and 91 million Mg in 1983. The vast majority (>80%) of this waste is in the form of slag from both iron- and steelmaking. Excluding this material, as was done in the 1976 study, yields generation rates of 13.3–16.3, roughly the same as Dravo’s conclusions (US EPA, 1976b). Calspan’s estimates are in dry mass, even if some of the waste is generated in aqueous form. The authors acknowledge this by suggesting a 5:1 wet/dry ratio for pickle liquor (US EPA, 1977, p. 39).

In 1979, the EPA commissioned a study with the explicit goal of determining “the nature and quantities of waste residues in the iron and steel industry” (US EPA, 1979a, p. xvi). The two previous studies discussed above may have resulted in useful accounts, but the study goals were often oblique to the construction of a comprehensive account: Dravo examined only pollution control residues and Calspan was looking for hazardous or potentially-hazardous residuals. This new study, conducted by the Research Triangle Institute (RTI), was motivated by resource recovery considerations, and as such was “primarily concerned with the waste materials produced by the iron and steel industry which are not likely to be hazardous subject to regulation under Subtitle C of RCRA” (p. 33). For the most part, the study was a synthesis of available literature, including the two studies introduced above. Detailed process models and supplementary information enabled the researchers to calculate waste generation factors based on the specific waste-producing activity, e.g. coking, EAF steel, cold-rolled steel. Wastes are categorized by “coke plant,” “slag,” “iron oxide,” and “scrap” (Table 5-6).

Table 5-4. “Estimates of iron and steel mill pollution control residues in the United States in 1974” (million Mg/year) from Dravo (US EPA, 1976b, p. 23)

Waste stream	Residue	Recycled	Dumped
		<i>Million Mg</i>	
Coking	0.9	0.9	< 0.05
Sintering	0.8	0.8	< 0.05
BF (iron)	3.0	2.1	0.9
BF (Fe-Mn)	< 0.05	-	-
MOF	1.5	0.4	1.2
OH	0.5	0.1	0.4
EAF	0.4	0.0	0.4
Vacuum degassing	< 0.05	-	-
Continuous casting	0.2	0.1	0.1
Rolling	6.7	3.8	2.9
Pickling	0.4	-	0.4
Coating	< 0.05	-	-
Waste water plant	0.6	-	0.6
TOTAL	15.1	8.3	6.8

Table 5-5. Estimated national solid waste from iron and steel industry, 1974, 1977 & 1983, from Calspan (US EPA, 1977, pp. 27–41)

Waste stream	1974	1977	1983
	<i>Million Mg (dry)</i>		
Total slag	60.5	64.2	74.5
Total sludge	4.1	4.4	5.1
Total dust	2.7	2.8	3.3
Total scale	6.3	8.9	7.7
Pickle liquor	0.2	0.2	0.2
TOTAL	73.8	80.4	90.8

Table 5-6. “Summary of waste generation [and disposition] for 125,000,000 tonnes of steel per year” from RTI (US EPA, 1979a, pp. 56–58). L = Landfilled, S = Stored, R = Recycled or reused

Waste Stream	Generated (Million Mg)	L	S	R
		(%)		
COKE PLANT				
Coke breeze	1.8	-	-	100
Sludge	0.1	100	-	-
<i>Total from coke plant</i>	<i>1.9</i>	<i>7</i>	<i>-</i>	<i>93</i>
SLAG				
Ironmaking	28.3	10	-	90
Steelmaking	19.4	55	-	45
<i>Total slag</i>	<i>47.7</i>	<i>28</i>	<i>-</i>	<i>72</i>
IRON OXIDE				
Dust:				
Sinter	0.7	5	-	95
Ironmaking	1.3	13	9	78
Steelmaking	1.1	66	18	16
<i>Total dust</i>	<i>3.1</i>	<i>29</i>	<i>10</i>	<i>61</i>
Sludge:				
Ironmaking	2.0	13	9	77
Steelmaking	1.2	53	24	23
Mill	0.8	96	-	4
<i>Total sludge</i>	<i>4.0</i>	<i>41</i>	<i>12</i>	<i>47</i>
Scale:				
Soaking pit	1.3	100	-	-
Mill	5.6	-	30	70
<i>Total scale</i>	<i>6.9</i>	<i>19</i>	<i>24</i>	<i>57</i>
<i>Total iron oxide</i>	<i>14.0</i>	<i>27</i>	<i>18</i>	<i>55</i>
SCRAP				
Metallic scrap	42.3	-	-	100
Rubble, brick	12.5	100	-	-
<i>Total scrap</i>	<i>54.8</i>	<i>23</i>	<i>-</i>	<i>77</i>
Fly and bottom ash	0.4	100	-	-
GRAND TOTAL	118.3	25	2	73

The authors estimate the generation of waste from the production of 125 million Mg of raw steel, roughly the production in the year 1977. Thirty-two types of wastes are studied, with estimates of total generation as well as disposition (landfilled, stockpiled, or recycled/reused). Somewhat confusingly, two adjacent tables in the report have slightly different totals. The first (p. 56) sums to roughly 140 million Mg of waste, while the second (pp. 57–58) reports 118 million Mg.

The difference is explained by the inclusion in the first table of 18.5 million Mg of sinter fines, which are directly reused in the mill, and 0.4 million Mg of fly and bottom ash, the quantity of which, unlike most of the other waste streams, was not sourced from an empirical study, but an RTI estimate based on coal usage. RTI's account also included large quantities of metallic scrap and rubble, the former which can be wholly recycled and the latter better classified as construction and demolition waste than NHIW.

The SAIC report (US EPA, 1985) draws its data from the Dravo, Calspan, and RTI reports, as well as one by Franklin Associates, the firm best known for generating the EPA's annual MSW estimate. Franklin, like RTI before it, was tasked with detailing the "state-of-the-art of resource recovery practices in the Metals Smelting and Refining Industry (SIC 33)" (US EPA, 1982). It is unclear to me why the EPA would need two reports (RTI and Franklin) on such similar subjects within three years of each other. Perhaps it was because the RTI report was limited to the iron and steel industry; Franklin's efforts characterizing all of SIC 33 waste was one of 11 industry reports prepared for the EPA on the subject of resource recovery. Nevertheless, Franklin's work was, also like RTI's, a literature review, adding no new empirical information about residuals generation. In fact, large sections of the Franklin report were taken verbatim from Calspan's.

SAIC combined a synthesis of the four studies presented above with data from the ferrous foundries industry (SIC 3321 / NAICS 33151) to reach its estimate of 60.7 million Mg (Table 5-7). Excluding the 14.4 million Mg of waste sand from ferrous foundries, the remaining 46.3 million Mg was taken mainly from the RTI study, which in turn had relied heavily on both the previous Calspan and Dravo reports. SAIC added data on open hearth steelmaking from the Franklin report and, somewhat inexplicably, did not include BOF slag in their final account, despite referencing the BOF slag waste generation factor from Calspan elsewhere in the report.

The final source of data that I identified came from a pair of two reports prepared by Energetics, Inc. for the US Department of Energy's Office of Industrial Technologies to support efforts to accelerate energy efficiency and environmental performance improvements in the iron and steel industry (Margolis & Sousa, 1997; US DOE, 2000). The two reports included estimates of major solid waste flows from the industry for the years 1994 and 1997 (Table 5-8). The authors include a long list of references for their estimates, but do not go into any specific detail, limiting my ability to critique and validate their estimates like I did with SAIC's. The largest contributor to the change from 1994 to 1997 is the increase in spent pickle liquor from 0.82 to 5.44 million Mg. This magnitude of change seems unlikely to occur in just three years, especially with no other similarly large changes in any of the other waste streams. It is possible that the authors located a more reliable source of data between publishing the earlier and later reports. The two estimates differ by a factor of six; Calspan suggested that pickle liquor has a liquid to solid ratio of five, which suggests another possible explanation.

Table 5-7. SAIC estimate of NHIW from primary iron and steel and ferrous foundries (US EPA, 1985)

Waste Stream	Quantity (‘000 Mg)
Coke breeze*	1,752
Blast furnace slag	23,132
Blast furnace dust	1,467
Blast furnace sludge	1,536
EAF slag	3,764
EAF dust and sludge*	408
Open hearth slag	2,026
Continuous casting scale	319
Continuous casting sludge	4
Soaking pit scale	837
Primary mill scale	2,505
Primary mill sludge	104
Rolling scale (hot and cold)	973
Rolling sludge (hot and cold)	5
Galvanizing sludge	40
Tin plating sludge	16
Bricks and rubble	7,374
Foundry sand and other wastes	14,417
TOTAL	60,679

*Includes potentially hazardous fraction

Table 5-8. Energetics estimates of iron and steel industry major solid wastes and byproducts (Margolis & Sousa, 1997, p. 111; US DOE, 2000, p. 25)

Waste Stream	Quantity (‘000 Mg)	
	<i>1994</i>	<i>1997</i>
Blast furnace slag	11,250	11,880
Blast furnace dust	370	370
Blast furnace sludge	630	630
BOF slag	5,440	7,040
BOF dust	240	1,000
BOF Sludge	1,160	–
EAF slag	4,170	4,170
EAF dust	590	540
Mill scale	3,330	3,330
Rolling sludge	910	910
Spent pickle liquor	820	5,440
Other	~ 910	–
TOTAL	~ 29,030	35,320

5.2.2 Baseline

Despite there being numerous reports on NHIW from the iron and steel industry, a close look at those reports finds few actually generate new empirical data for waste generation in the industry useful for forecasting to the present. I identified two sources, specifically, the 1977 Calspan data and the mid-1990s Energetics data. Calspan was the reference for three subsequent additions and revisions, the most substantial of which was by RTI in 1979. RTI adapted the Calspan data into generation factors for residual waste based on specific reference products. These factors can be used in lieu of a specific baseline account to forecast residual waste from the iron and steel industry. The high resolution of this model internalizes various types of technology and market changes that influence NHIW generation (although not regulatory changes that would have the effect of modifying waste generation factors).

SAIC's additions to RTI's waste factors serve as the first baseline for the forecast (Table 5-9). The Energetics estimates, being the most recent national-scale NHIW data that I was able to locate, are also useful as a second baseline.

5.2.3 Forecast

Use of the SAIC/RTI/Calspan waste generation factors allows for, and in fact requires a more sophisticated forecasting model than is employed in the pulp and paper case study. Instead of using just a single reference product (e.g. total raw steel), the activity-by-activity basis of the waste account relies on 13 separate reference products, throughout the iron and steelmaking process. Production data for coke, sinter, iron, raw steel (EAF, BOH, and OH), and steel products were drawn from three sources: the World Steel Association (WSA, formerly IISI), AISI, and USGS Iron & Steel Minerals Yearbook (MYB) (Table 5-10). The most complete set of available production data begins in the year 1985, which, coincidentally, is also the year of the EPA's prevailing NHIW account.

Generation factors for the 13 reference products, normalized to their 1985 values, are displayed in Figure 5-9. From this perspective, it is clear that although total raw steel production has increased slightly from its 1985 value, the sub-product story is more complicated. Three products—continuous casting steel, galvanized steel, and EAF steel—all show large growth over the time period, while most of the rest of the products show decreases. Because different wastes are generated by these different activities, this multi-variable forecasting model presents a more nuanced result than would have been achievable with just the single reference product.

Based on the RTI model, the waste types accounted for by Energetics can also be forecasted using specific reference products, specifically, blast furnace iron, BOF steel, EAF steel, hot rolling mill, and total raw steel.

Table 5-9. Waste generation factors for the US iron and steel industry (US EPA, 1985).

Waste Type	Generation Factor (Mg/Mg)	Reference Product
Coke breeze	3.60×10^{-2}	Coke
Still lime sludge	6.04×10^{-4}	Coke
Tar sludge	6.00×10^{-4}	Coke
Coke treatment plant sludge	1.70×10^{-3}	Coke
Blast furnace slag	3.48×10^{-1}	Iron
Blast furnace dust	1.59×10^{-2}	Iron
Blast furnace sludge	2.50×10^{-2}	Iron
EAF slag	1.20×10^{-1}	EAF steel
EAF dust	1.30×10^{-2}	EAF steel
BOF slag	1.45×10^{-1}	BOF steel
BOF dust, sludge	2.05×10^{-2}	BOF steel
Sinter fines	5.27×10^{-1}	Sinter
Sinter dust	2.10×10^{-2}	Sinter
Open hearth slag	2.43×10^{-1}	OH steel
Open hearth dust	1.37×10^{-2}	OH steel
Continuous casting scale	8.70×10^{-3}	Continuous casting steel
Continuous casting sludge	1.04×10^{-4}	Continuous casting steel
Soaking pit scale	1.50×10^{-2}	Soaking pit steel
Primary mill scale	4.49×10^{-2}	Primary mill steel
Primary mill sludge	1.87×10^{-3}	Primary mill steel
Hot rolling scale	1.83×10^{-2}	Hot rolling mill steel
Hot rolling sludge	1.74×10^{-3}	Hot rolling mill steel
Cold rolling scale	5.20×10^{-5}	Cold rolling mill steel
Cold rolling sludge	1.60×10^{-4}	Cold rolling mill steel
Galvanizing sludge	1.08×10^{-2}	Galvanized steel
Tin plating sludge	5.32×10^{-3}	Plated steel

Table 5-10. Sources for iron and steel forecasting reference products (Figure 5-9)

Ref. Product	Year range	Source
Coke	1977-1986	WSA
	1987-2014	AISI
Sinter	1977-1983	WSA
	1984-2012	AISI
Iron	1977-2014	WSA
EAF Steel	1977-2014	WSA
BOF Steel	1977-2014	WSA
OH Steel	1977-2014	WSA
CC Steel	1977-2014	WSA
SP Steel	1977-1983	WSA (Total steel - Continuous Casting)
	1984-2014	WSA (Ingots)
PM Steel	1977-1983	WSA (Total steel - Continuous Casting)
	1984-2014	WSA (Ingots)
HRM Steel	1977-1989	WSA (Total Finished Product Deliveries)
	1990-2014	WSA (Production of Hot Rolled Products)
CRM Steel	1985-2013	MYB (Cold rolled sheet & strip, tinmill, galvanized)
Galvanized Steel	1985-2013	MYB (galvanized)
Plated Steel	1985-2013	MYB (tinmill, other)
Total Steel	1977-2014	WSA

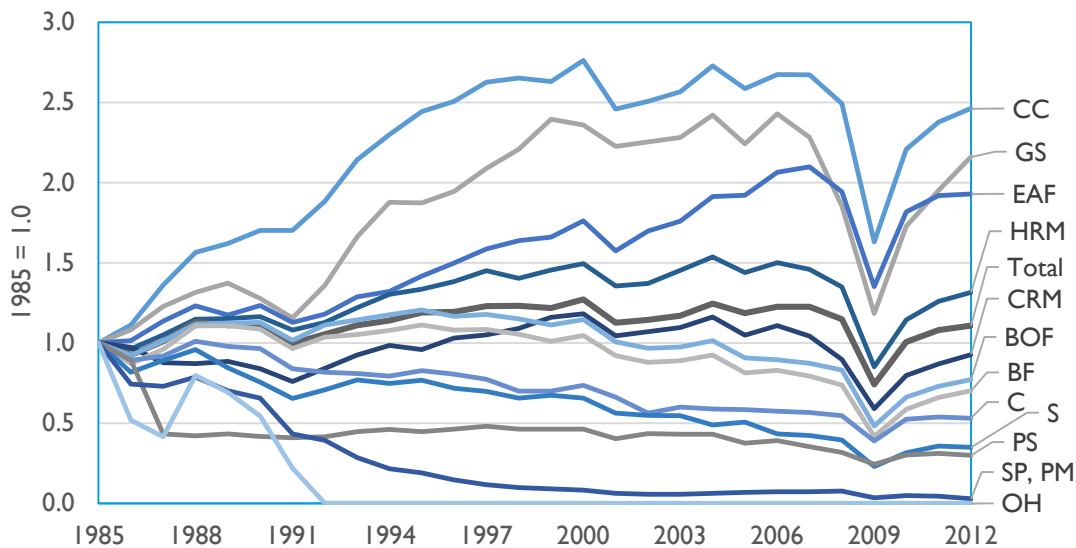


Figure 5-9. Normalized production factors for US iron and steel NHIW, 1985–2012 (WSA, AISI, MYB Iron & Steel). CC—continuous casting steel; GS = galvanized steel; EAF = electric arc furnace steel; HRM = hot rolling mill steel; Total = total raw steel; CRM = cold rolling mill steel; BOF = basic oxygen furnace steel; BF = blast furnace iron; C = coking; S = sinter; PS = plated steel; SP = soaking pit steel; PM = primary mill steel; OH = open hearth steel.

5.2.4 Results & discussion

Figure 5-10 shows the results of the forecasting estimation method. Five baseline NHIW estimates are presented: the original 1977 RTI estimate, the 1983 SAIC adaptation, the application of the SAIC/RTI waste generation factors to 1985, and the 1994 and 1997 Energetics estimates. The lines (dotted and dashed lines are there to improve visibility) indicate the forecast to the present. I attempted to rationalize the baseline estimates to just process wastes, excluding scrap, rubble & bricks, and sinter fines, which either do not leave the factory gates or are classified as something other than NHIW (e.g. C&D waste or recycled material). The results show two clusters of estimates in 2010: the 1977 and 1983 baselines yield a cluster between 41–45 million Mg, and the 1985, 1994, and 1997 baselines yield a cluster between 22–25 million Mg. This seems to hold despite differences or similarities in the baselines themselves, which suggests it is due more to the technological and market dynamics of the industry itself, i.e., the forecasting method. Based on the elegant bifurcation of the results, and some anecdotal evidence that “solid waste production (excluding slag) at a typical mill has been reduced by more than 80%” over the period 1975–2000 (US DOE, 2000, p. 14), the lower cluster of estimates can be assumed as the result of the forecast.

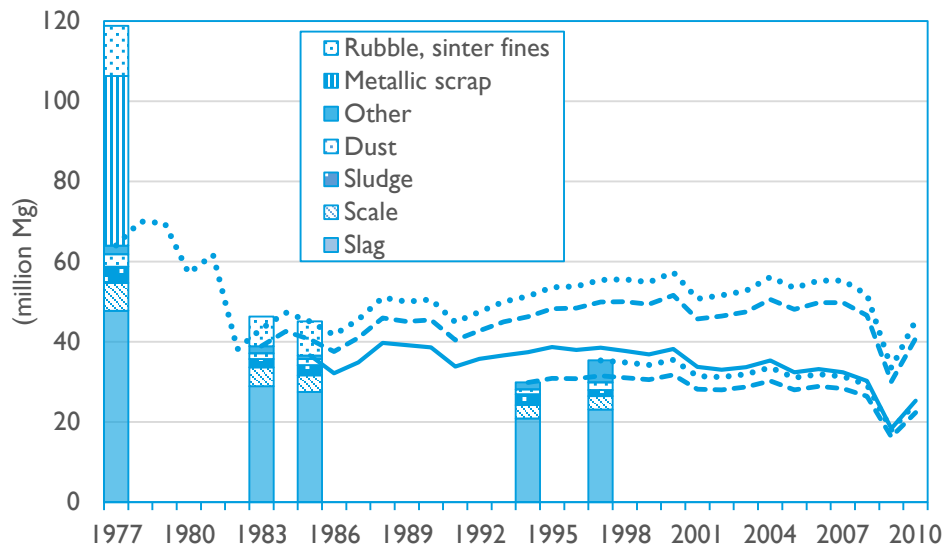


Figure 5-10. NHIW from iron and steel manufacturing forecasted to 2010.

Table 5-11 presents a compositional summary of the three forecasted estimates, the 1985 SAIC/RTI baseline and the two Energetics baselines. The clustering is probably even tighter than these results suggests, since the earlier Energetics estimate (1994) seems to have been preliminary work, and may very possibly have underestimated the quantities of NHIW in that year. The forecasts each tell a different story of NHIW composition, with the earlier estimates claiming more slag production and the later estimates more pickle liquor, but, as discussed above, that may be a function of wet- vs. dry-mass basis.

Table 5-11. NHIW from the iron and steel industry, per the forecasting method, 2010.

Waste type	Base year		
	1985	1994	1997
	<i>(million Mg)</i>		
Slag			
BF	9.3	6.1	6.4
EAF	5.9	5.7	4.8
BOF	4.5	3.1	4.0
<i>Total slag</i>	<i>19.8</i>	<i>14.9</i>	<i>15.2</i>
Sludge	1.6	1.8	1.1
Dust	1.2	1.1	1.4
Scale	2.2	2.9	2.6
Spent pickle liquor	–	0.7	4.4
Other	0.5	0.8	–
TOTAL	25.3	22.3	24.7

5.3 Materials balance

This section presents the application of the materials balance method to the US iron & steel industry for the estimation of lost mass / residual waste flows in the year 2010.

5.3.1 Background

Materials balance has been used in the past for estimating NHIW generation from the iron & steel industry. The SAIC estimate itself relies in part on the result of a previous materials balance estimate. The RTI report on solid waste from iron and steel making (US EPA, 1979a) combined the empirical Dravo and Calspan data with material balance models of industrial activities to create their account, which was the basis of SAIC's report to the EPA in 1985. RTI used the technique to rationalize empirical data, which is often messy, with the physical constraints of the steelmaking process(es). The mill-level analysis that RTI and others conducted runs the risk of missing wastes that may be generated by activities not accounted for, however. This was the case for RTI, and SAIC amended the RTI account with other data on slag from open hearth steelmaking.

Resources for the Future (RFF) dealt explicitly with residuals from the iron and steel industry using a materials balance-constrained model in the fourth report of their industrial residuals research program (Russell & Vaughan, 1976). Like the others, the steel model employed linear programming to explore the effects of various technological, regulatory, and economic factors on the generation of residuals to air, water, and land. The modeled mill produced 2,000 short tons per day of semi-finished steel shapes, the specific steelmaking process (BOF, EAF, OH) being a model parameter. Assuming high iron, low sulfur ore fines, the model estimates the generation of slag and other solids at rates presented in Table 5-12. Other relevant assumptions include a BOF charge of 70% primary iron, 30% scrap steel, an OH charge of 50/50, and an EAF charge of 100% steel scrap. It should be noted that these waste generation rate, ranging from a low of 24.5 kg/Mg of EAF steel to a high of 345.8 kg/Mg of OH steel, include just steel mill residues, excluding any sintering, coking, or blast furnace wastes (Bower, 1975, p. 296).

Ayres presents an industry-wide materials balance model based on a general set of "metals processing relationships" between mining, beneficiation, smelting, and refining activities, illustrated in Figure 5-11 (Ayres & Ayres, 1998, p. 89). These relationships serve as the starting point for the authors' analyses of ferrous and non-ferrous metals alike. Using data from the U.S. Bureau of Mines, the EPA, and other sources, Ayres & Ayres estimate lost mass from iron and steel production to be nearly 20 million Mg for the years 1988 and 1993 (Table 5-13). The limitations of their model are such that they only calculate three waste streams from the iron and steel industry itself: iron slag, steel slag, and waste pickle liquor in the form of waste ferrous sulfate (FeSO_4). Pig iron production declined a modest amount from 1988 to 1993, but the Ayreses' model show waste output staying essentially constant.

Table 5-12. Residuals generation rates for three types of semi-finished steel shapes by steel furnace type (Bower, 1975, p. 296). Solids include unrecycled mill scale, bottom ash, and unburned forerunnings.

	Slag	Solids
	<i>(kg/Mg steel)</i>	
Drawing quality steel		
OH	228.6	0.4
BOF	341.6	0.6
EAF	118.0	9.9
Commercial quality steel		
OH	230.2	0.4
BOF	343.2	0.6
EAF	26.6	26.7
Alloy steel		
OH	345.8	0.6
BOF	224.2	0.4
EAF	24.5	26.7

Table 5-13. Lost mass from the iron and steel industry estimated by Ayres & Ayres (1998; 1999)

	1988	1993
	<i>(million Mg)</i>	
Blast furnace iron output	50.9	48.2
Iron ore mining overburden	103.0	129.0
Concentration wastes	140.0	148.2
Iron slag	14.2	12.3
Steel slag	5.2	6.7
Waste pickle liquor (FeSO ₄)	0.3	0.6
Total iron & steel wastes	19.7	19.6

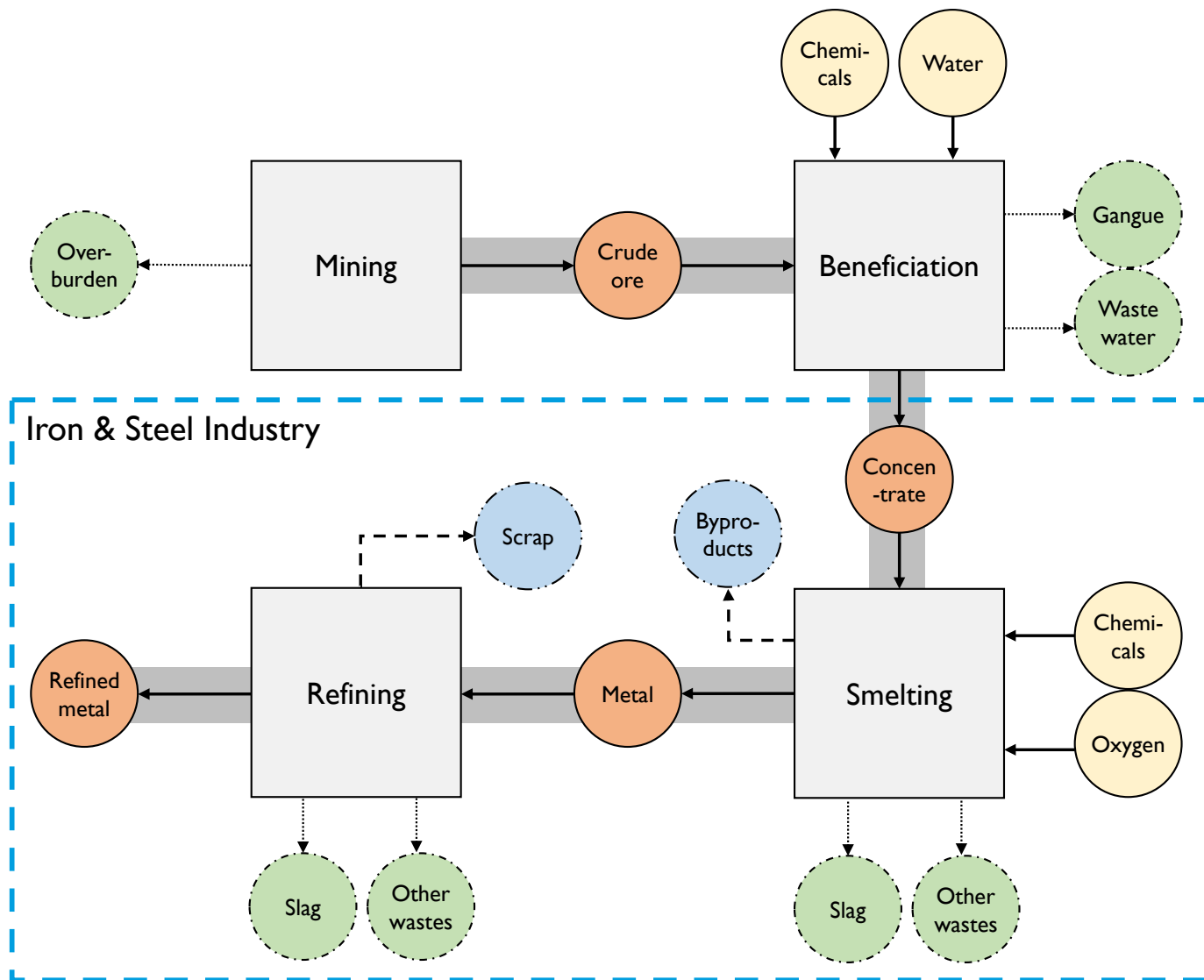


Figure 5-11. Generic “metals processing relationships” adapted from Ayres & Ayres (1998, p. 89). Primary production path links the four activities. Key inputs and other outputs are also shown. Smelting and refining activities comprise the primary metal industry, while the other activities are usually attributed to the mining sector.

5.3.2 Model

The materials balance model of the iron and steel industry that I develop here uses Ayres's model as a starting point. I consider five activities: ore beneficiation, coking, blast furnace iron production, steelmaking, and steel mill finishing (Figure 5-12). Ore beneficiation is, strictly speaking, a mining sector activity, but I include it to improve comparability of my results with the Ayreses'. Coking, while a process that does not involve any iron products, is counted as part of the iron and steel industry because its product is used almost universally for charging the blast furnace. Iron and steelmaking in blast furnaces and basic oxygen or electric arc furnaces, respectively, are the core of the industry and the core of the model, producing the largest waste stream: slag. The final activity, steel finishing, is not included in Ayres's model. I include it to improve comparability with the other estimation methods employed in this dissertation.

5.3.3 Data & material flows

Data was collected from a variety of sources, including the American Iron and Steel Institute *Annual Statistical Yearbook*, the EIA *Quarterly Coal Report*, the USGS *Minerals Yearbooks* for Iron Ore, Iron and Steel, Iron and Steel Scrap, and Iron and Steel Slag (among others), the World Steel Association *Steel Statistical Yearbooks*, and the *Economic Census*. Data and materials balance for each of the five modeled activities are presented below. In the course of this research, I had access to AISI data from the mid-1990's to 2010. This range serves as a constraint for the time series analysis.

5.3.3.1 Iron ore

Although iron ore mining and beneficiation are not counted as part of the iron and steel industry, and wastes from those activities are credited to the mining industry, it behooves this analysis to start here, because it is the origin of the ferrous material that the industry is built around. In 2010, 165 million Mg of crude iron ore was mined in the US, primarily from mines in the Mesabi and Marquette ranges in Minnesota and Michigan, respectively (MYB Iron Ore). This total is down slightly from the 1990s, production peaking at 213 million Mg in 1998 (Figure 5-13). Thirty percent of the crude ore is the iron ore mineral itself (50 million Mg in 2010) with the remaining 70% classified as "gangue" (115 million Mg in 2010). Iron ore comes in many forms, depending on the geologic deposit. The taconite deposits in the Great Lakes region are comprised of two oxides: hematite (Fe_2O_3) and magnetite (Fe_3O_4). The mass of contained oxygen means that the purest iron ore has a maximum elemental iron concentration of 72.4%. The average iron content of usable ore mined in the US was pretty around 63.2% from 1989–2008, when it began to drop to 61.8% in 2012 (Figure 5-14). This may be due to some mines starting to reprocess lower quality ore tailings.

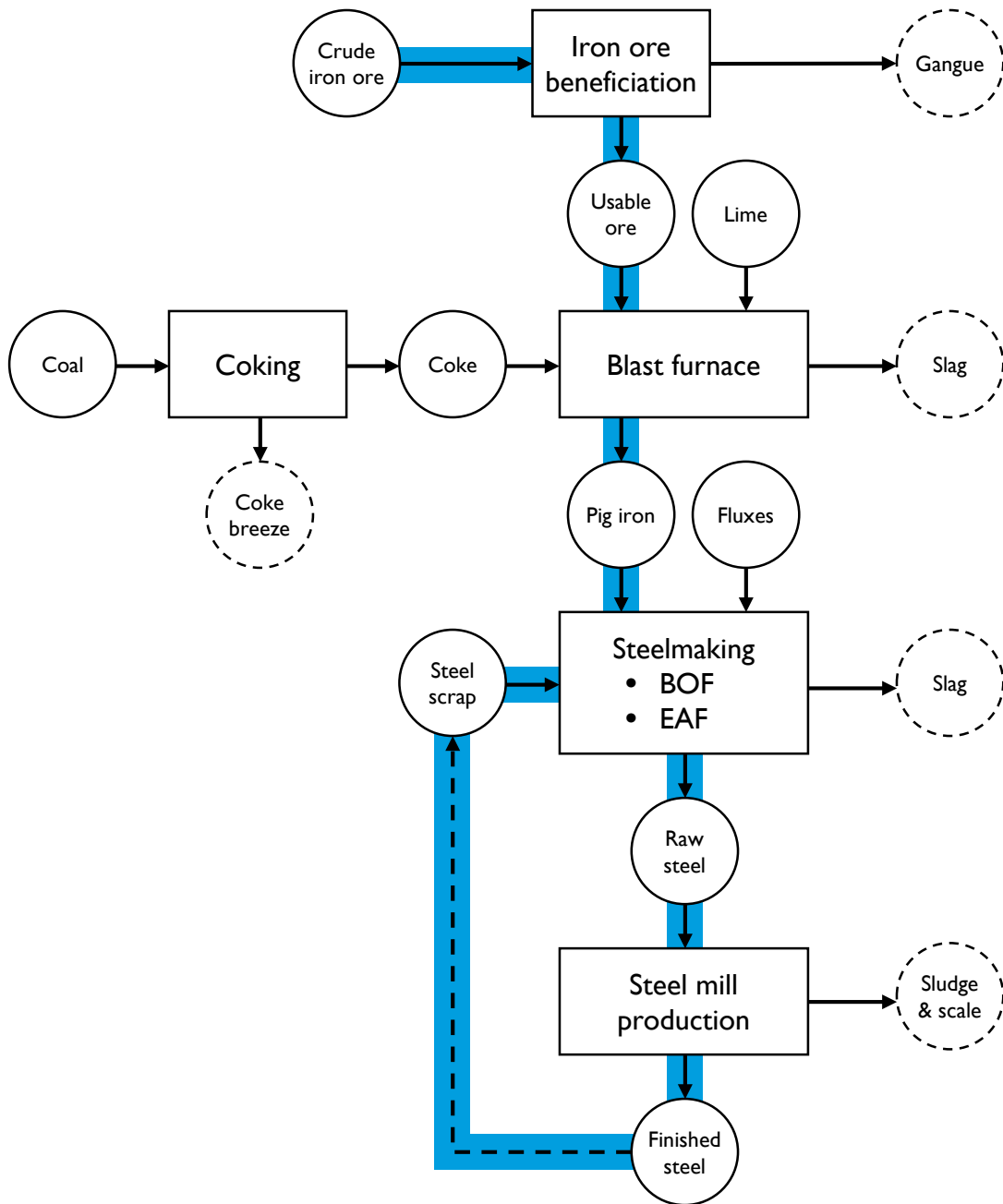


Figure 5-12. High level architecture for the iron & steel industry materials balance model used here. The primary iron pathway from iron ore to finished steel (and recovered steel scrap) is shown, along with major non-iron inputs and outputs.

The number of active mines has also been constant for about 20 years, although the closure of half the active mines in the early 1990's did not noticeably affect either the quantity or quality (Fe content) of ore shipments. Iron mines consume roughly 0.6 million Mg of bentonite clay annually for use as a binding agent in pelletizing iron ore (MYB Clay and Shale).

The trade balance of iron ore has changed considerably from the 1990s to the present. In 1990, the US was a net importer of 15 million Mg of iron ore; in 2010 the country was a net exporter of 3.5 million Mg (Figure 5-15). Apparent consumption (production + imports - exports) in 2010 was therefore $49.9 + 6.4 - 10.0 = 46.3$ million Mg. Reported consumption of iron ore was 42.3 million Mg; the difference in these two figures can be assumed to be addition to stock.

The majority of usable iron ore is delivered to blast furnaces for conversion into pig iron, either in pellet (36 million Mg) or sinter (5.1 million Mg) form (Figure 5-16). Direct-ship ore is no longer a practice in US blast furnaces. A small fraction of produced ore is sent directly to steelmaking (Figure 5-17). Non-steel end uses for iron ore include the production of cement, cattle feed, ferrites, heavy media, lead smelting, manufacturing, paint, refractory and weighing materials (0.6 million Mg in 2010).

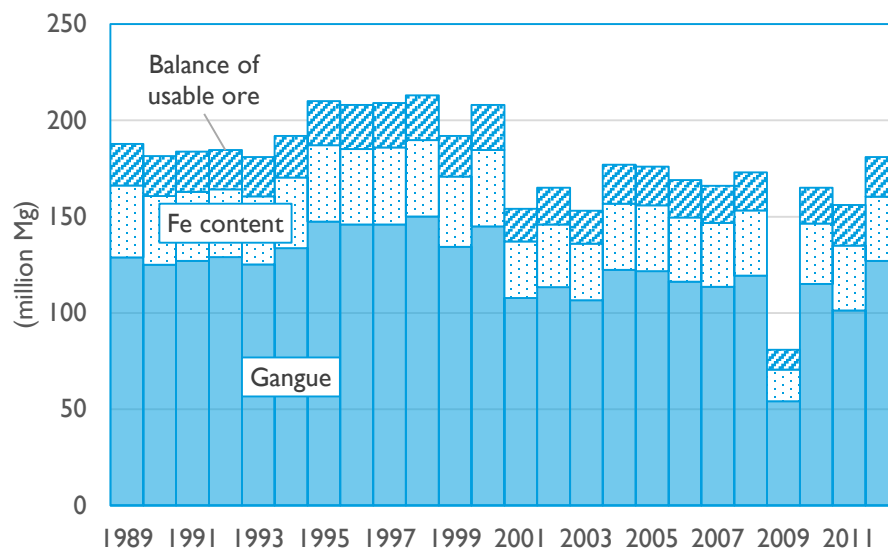


Figure 5-13. Quantity and composition of crude iron ore produced at US iron mines, 1989–2012 (MYB Iron Ore)

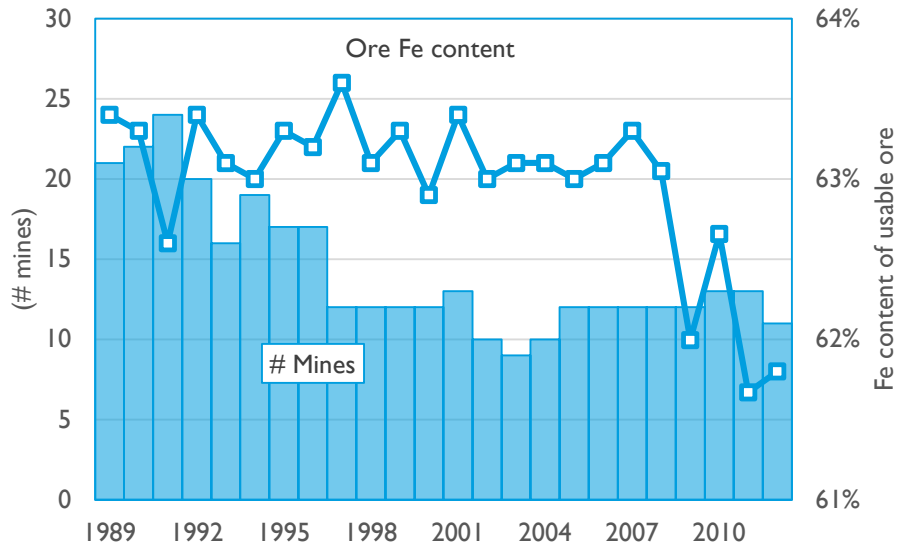


Figure 5-14. Number of active iron mines and average iron content of usable ore in the US, 1989–2012 (MYB Iron Ore)

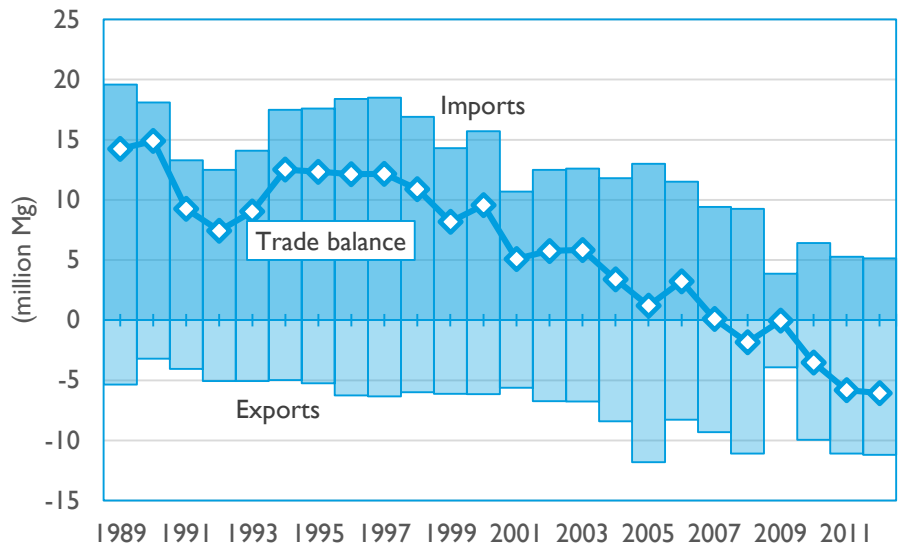


Figure 5-15. Imports, exports, and trade balance of iron ore in the US, 1989–2012 (MYB Iron Ore)

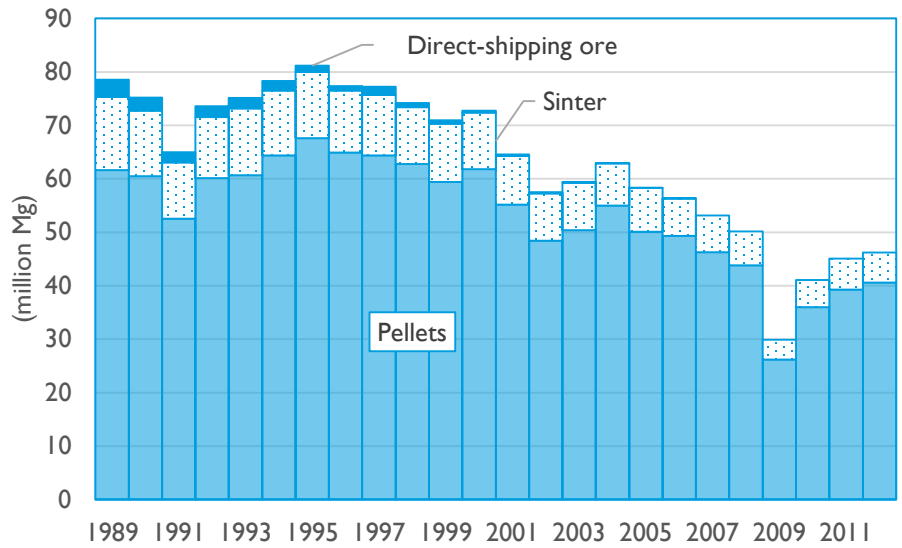


Figure 5-16. Quantity and type of iron ore consumed at blast furnaces in the US, 1989–2012 (MYB Iron Ore)

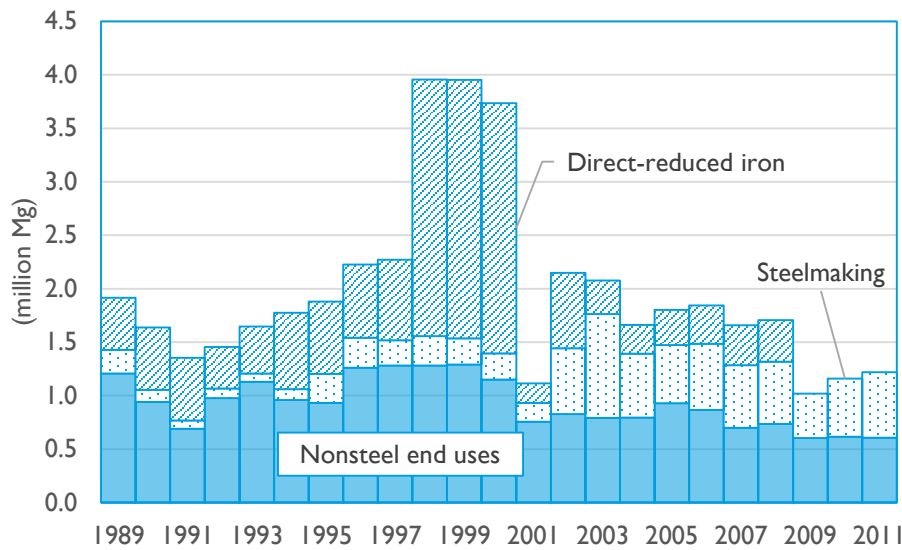


Figure 5-17. Minor uses of iron ore in the US, 1989–2012 (MYB Iron Ore)

5.3.3.2 Coking

Coking is the process by which coal is pyrolyzed to produce a solid fuel with very high carbon content (coke) and coke oven gas. Coke oven gas is a mixture of H₂ (50-55%), CH₄ (25-30%), N₂ (7-10%), CO (6-7%), CO₂ (3%), and various hydrocarbons (2-3%) and is largely recovered and used to heat the coking process (Lacey, 2011). The main waste product from coking is “coke breeze,” the coke dust generated when the material is pulverized. A nominal amount of coal chemicals is also produced, including coal tar, ammonium sulfate, ammonia liquor, and light oil.

The EIA *Quarterly Coal Report* and USGS MYB Iron & Steel include data on coal consumption, coke production, and breeze generation at coke plants (Figure 5-18). Based on six years of data (1991–1996), it appears that approximately 85% of coke production occurs in plants integrated with blast furnaces or steel mills, and the other 15% in merchant plants (EIA Coal). Coke manufacturing accounts for 71–72% of the total mass of coal consumed at coke plants (13.6 million Mg coke and 19.4 million Mg coal in 2010), and coke breeze (1.1 million Mg in 2010) makes up an additional 5% (MYB Iron & Steel). The remaining 23–24% of input mass is made of the chemicals listed above. Lacking empirical data on the generation or recovery of these chemicals, we can turn to the literature for a guide. Typical yields from the coking process are presented in Table 5-14. (Sundholm, 1999, p. 383). The literature values for coke and breeze are borne out by the data, close to the mean of the literature range for coke and the low end of the range for breeze. To meet the material balance constraint, the low ends of ranges for the remaining chemicals are used. Figure 5-19 shows that even using the low end of the ranges, the tabulated yield factors often exceed the materials balance constraint provided by the “lost mass” time series.

If the vast majority of coking occurs in an integrated steel mill, one would expect a close match between annual production and consumption. For most of the time series examined, that expectation is confirmed (Figure 5-20). But starting in 2008, production remains at a high level, greatly exceeding reported consumption. No explanation, beyond blaming the Great Recession, is immediately forthcoming. From 1997–2009, the consumption values reported by AISI agree with those by USGS. But in 2010, AISI’s figure ticks up to 10.88 million Mg, while USGS reports just 8.43 million Mg, the same value that AISI reports for coke production in integrated steel works. Perhaps the USGS analyst made a mistake, but with only one data point, this remains mere conjecture.

Finally, the input coal to the coking process is reported to have contamination content of 1.11 wt% sulfur and 7.93 wt% ash, or 0.2 and 1.5 million Mg in 2010, respectively (EIA Coal). Neither of these non-carbon elements is driven off during the coking process, and so they remain in the resulting coke.

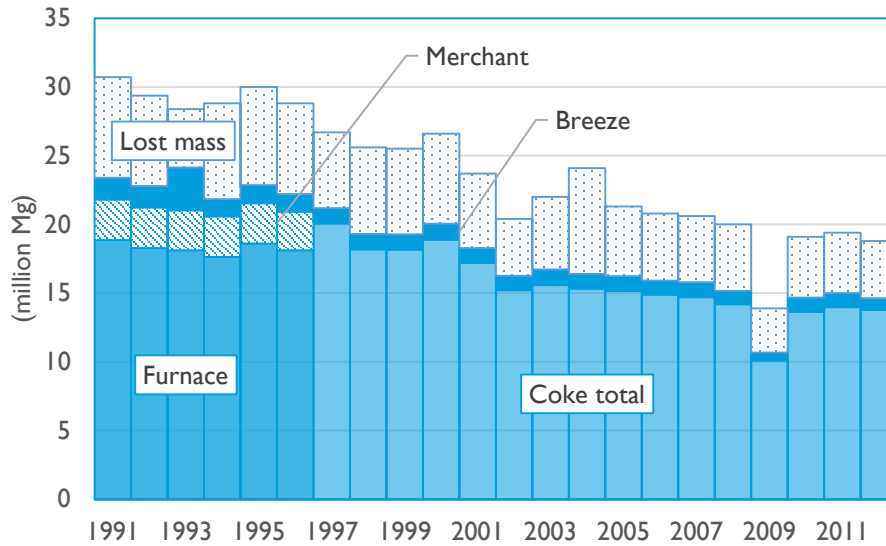


Figure 5-18. Reported coke and breeze production and lost mass calculated from the difference of coal consumption and coke and breeze production, 1991-2012 (MYB Iron & Steel)

Table 5-14. Typical yields of coke, breeze, and coking chemicals (Sundholm et al., 1999, p. 383)

Product	(Unit/Mg coal)			Conversion				(kg/Mg coal)	
	Low	High	Unit	Low	High	Unit	Reference	Low	High
Blast furnace coke	600	800	kg					600	800
Coke breeze	50	100	kg					50	100
Coke oven gas	296	358	m ³	0.55	0.55	kg/m ³	(Sarna, 2013)	161	195
Coal tar	30.3	45.4	L	1.18	1.23	kg/L	(ASTDR, 2003, p. 223)	36	56
Ammonium sulfate	10	13.8	kg					10	14
Ammonia	56.8	132.5	L	0.88	0.88	kg/L		50	117
Light Oil	9.5	15.1	L	0.86	0.99	kg/L	(Fisher, 1938, p. 8)	8	15

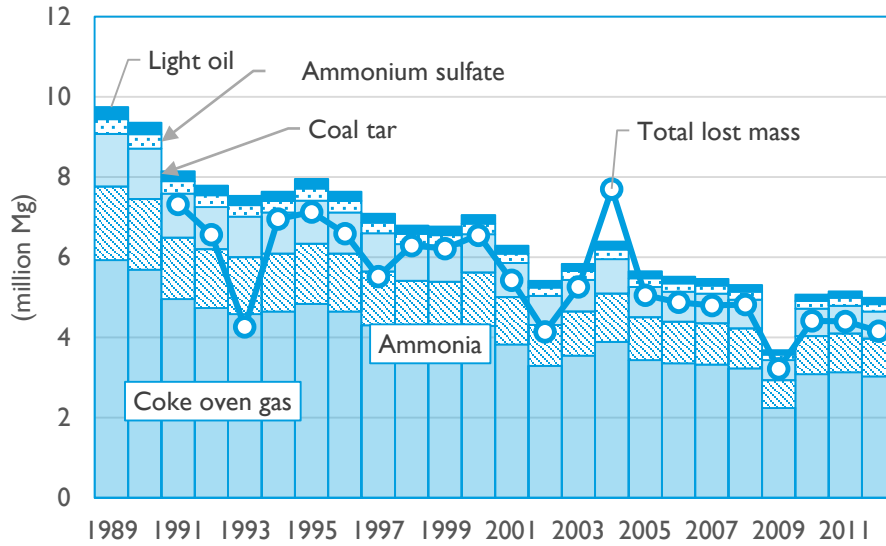


Figure 5-19. Inferred production of coking chemicals and comparison with total lost mass

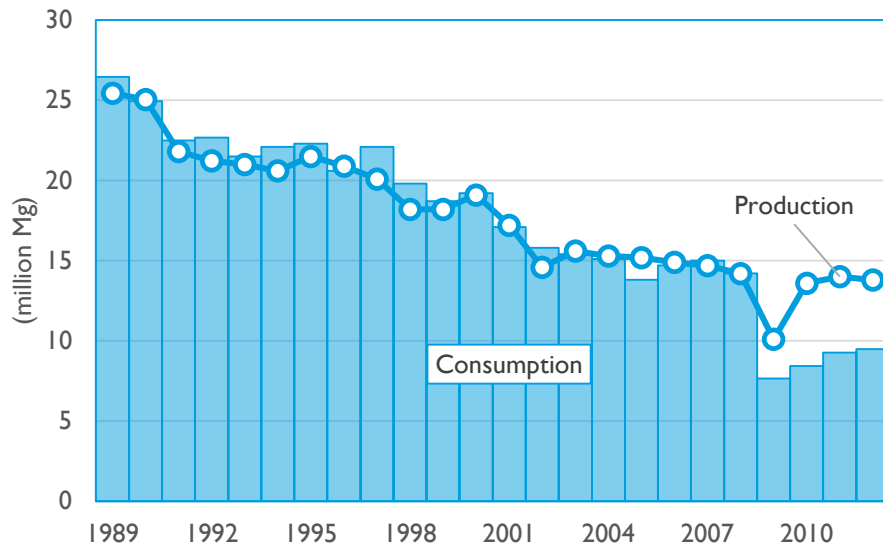


Figure 5-20. Reported production and consumption of coke for blast furnaces in the US, 1989–2012 (MYB Iron & Steel).

5.3.3.3 Ironmaking

The physical transformation activity of the blast furnace is the conversion of iron ore and ferrous scrap, coke, and fluxes into pig iron, slag, and blast furnace gas (BFG). This activity is almost a textbook example of the usefulness of the materials balance method. The available references publish data on five of the seven material flows, which can be used the missing input (flux) and output (blast furnace gas) and check the validity of another output (slag).

The inputs to a blast furnace are iron ore, ferrous scrap, coke, and mineral fluxes (Figure 5-21). The coke serves as a reducing agent separating the oxygen from the iron in the ore, and the fluxes facilitate slag formation by preferentially bonding with other non-ferrous materials in the ore and scrap. Data exists for ore, scrap, and coke consumption in blast furnaces but, somewhat perplexingly, not for the limestone or dolomite that is used as flux material. On the output side, the USGS publishes data on pig iron production and blast furnace slag sales. Completing the material balance uses some basic chemistry knowledge and tricks from Substance Flow Analysis, or tracking compositional elements that stay constant even as the products that contain them change form.

First, it is important to have an estimate of the general composition of each of the known material flows. Iron ore used as blast furnace charge has an iron content of approximately 63%, although this has changed a bit over time (see Figure 5-14). According to Ayres & Ayres (1998, p. 104), ore also contains 5% silica (SiO_2), 2% moisture (H_2O), and 0.35% other minerals (phosphorus, manganese, alumina). Based on data reported by USGS, pelletized ore also contains roughly 0.6 million Mg of bentonite clay, which in 2010 amounted to approximately 1.4% of the mass of the ore charge. This leaves 28.25% of the ore as contained oxygen, which is consistent with the stoichiometric ratios of a mix of different iron ores. The composition of coke is given by the EIA Coal data, which reports the sulfur and ash content of the coal consumed in coke ovens (see above). By calculating the coke yield from coal, these mass fractions can be converted into similar fractions for the coke that is used to charge blast furnaces: 1.52% S and 11.1% ash. The remaining 87.3% of the mass of coke is assumed to be carbon. Pig iron contains 3.5%–4.5% C, 0.5%–1.2% Si, and 0.4%–1.2% other impurities (Mn, P, S).⁵⁴ The remaining 93.1%–95.6% is Fe.

Second, I use these compositional data to estimate the production of blast furnace gas (or at least the mass of BFG that evolves from charge materials, excluding any added O_2 or other gases from the atmosphere). I assume that the O_2 (from iron oxide and silica) and H_2O from the ore and C from the coke are evolved completely as BFG. The results of this estimate show approximately 40% of the ore, coke, and scrap charge becoming BFG (Figure 5-22).

⁵⁴ <https://www.vizagsteel.com/code/products/pigiron.asp>

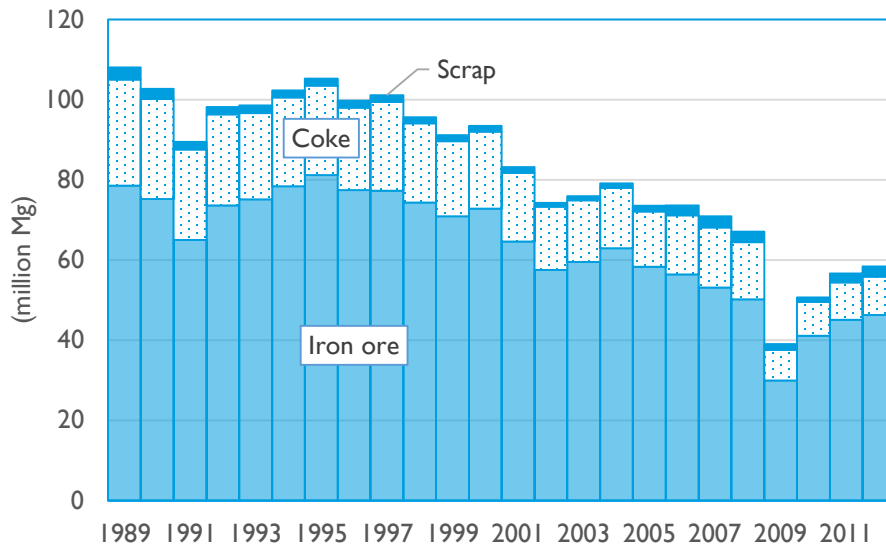


Figure 5-21. Published data on blast furnace inputs, 1989–2012 (MYB Iron & Steel)

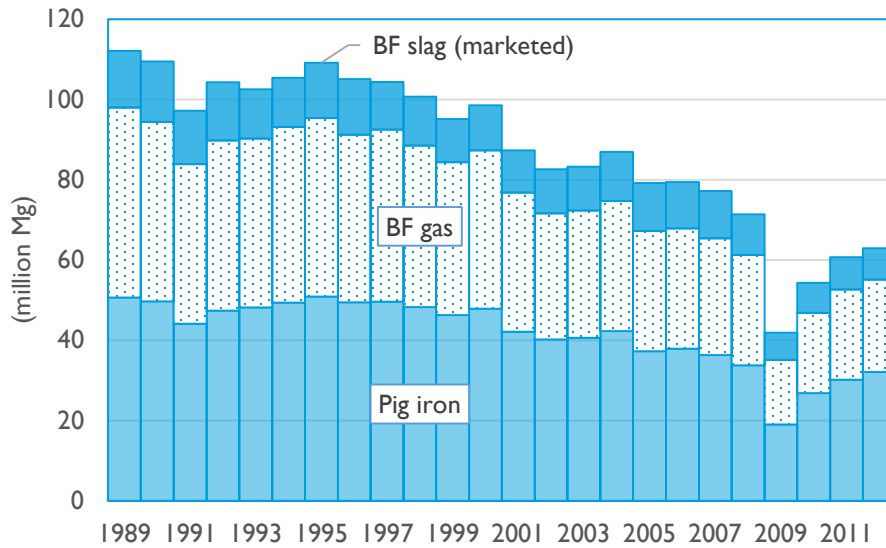


Figure 5-22. Published and calculated data on blast furnace outputs, 1989–2012 (MYB Iron & Steel; Slag—Iron & Steel)

Blast furnace slag is the largest waste product from the iron and steel industry. It has been marketed as a byproduct for many years, to the point that some no longer consider it a waste material at all. The USGS has dedicated a Minerals Yearbook on the subject since 1947, and discussed it as part of the Sand and Gravel Yearbook in earlier years. The reported data is explicitly NOT the quantity of slag produced. According to the MYB Slag–Iron and Steel (2011):

“Data in this report are based on an annual U.S. Geological Survey (USGS) canvass of slag processors and importers and pertain to sales of processed slag, not the amount of slag produced or even processed during the year. Processed slag is sold from stockpiles and although most of the material is a byproduct of current or recent iron and steel output or is of imported material, some slag sales are of material mined from old slag piles (slag banks) produced by iron and steel plants now closed.”

The USGS uses a range of 0.25–0.30 Mg of slag per Mg of produced pig iron to estimate total blast furnace slag production. Comparing this range with the marketed slag data, there is variability from year to year, but the amount of marketed material is usually within the production estimate range (Figure 5-23).

Returning to the total outputs (Figure 5-22), we can see that they are consistently larger than the inputs (Figure 5-21), suggesting the missing flux material. Ayres & Ayres (1998, p. 105) use an argument based on the composition of slag to claim a minimum necessary quantity of limestone, but I am not convinced by their logic, because it relies on MYB data for lime consumption in steel furnaces rather than blast furnaces. My strict mass balance model (calculated and reported outputs – reported inputs) yields an estimate of consumed fluxes of 3.7 million Mg in 2010 (Figure 5-24). This estimate is certainly not beyond reproach, as it does not deal with the oxygen balance, but provides a reasonable conclusion to the blast furnace materials module.

5.3.3.4 *Steelmaking*

Reliable accounting of material flows in steelmaking is a bit elusive, particularly regarding flows of steel scrap that have come to predominate US steel manufacturing raw materials. This is not because of a lack of information, rather it is because there seem to be numerous conflicting estimates. I have done my best to rationalize the various data from USGS and AISI to best represent material flows in the industry, but as a result have reduced the breadth of the time series to just 15 years, 1998–2012, to minimize effects of changing accounting standards among other distractions that complicate the analysis. For my model, steel furnaces consume pig iron (both domestically produced and imported), scrap (purchased and generated on site, or “home scrap”), lime and other flux materials, and other ferrous materials including ferroalloys, direct-reduced or “sponge” iron, and a small amount of iron ore. Production is raw steel, steel slag, and CO₂ evolved from the carbon in pig iron.

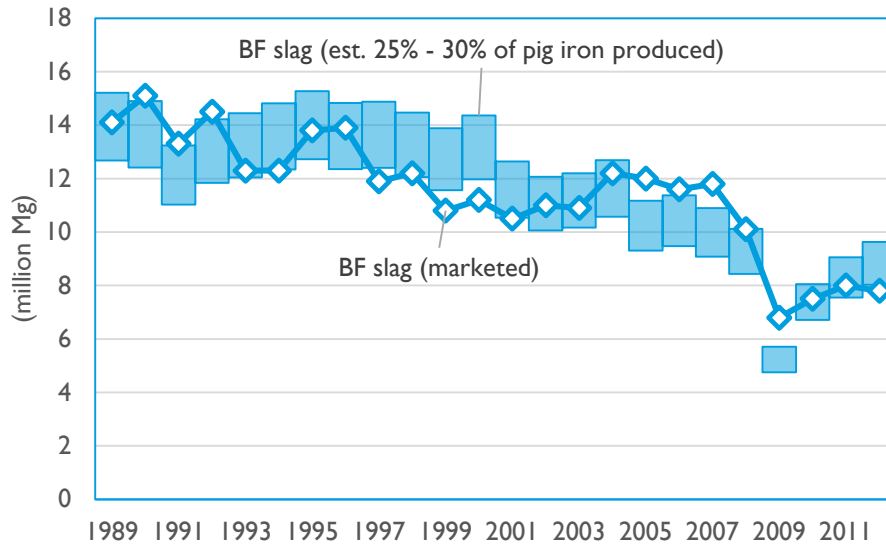


Figure 5-23. Comparison of published data on sold blast furnace slag and estimated range of BF slag generation, 1989–2012 (MYB Slag—Iron & Steel)

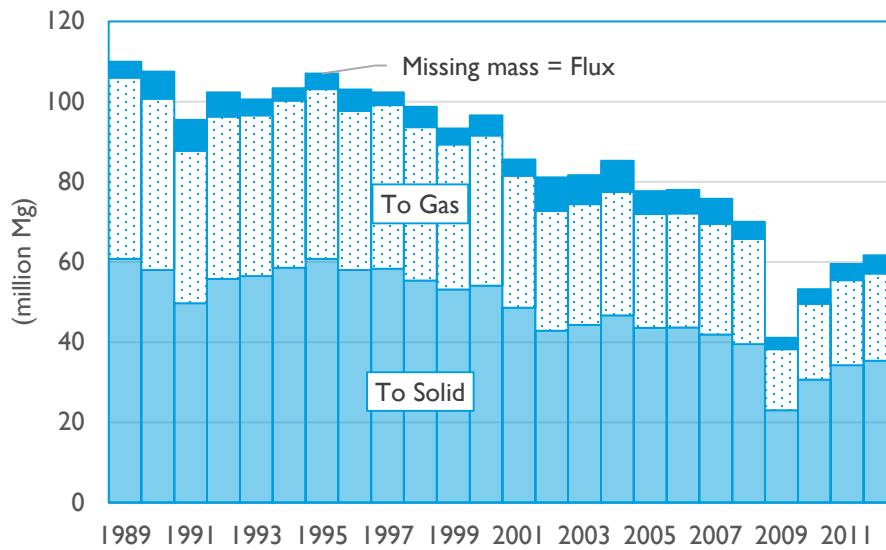


Figure 5-24. Mass balance of blast furnace production, 1989–2012. “To Gas” and “To Solid” are the totals of reported inputs. “Missing mass” is the difference between total outputs and reported inputs, and is equivalent with the input of mineral fluxes.

Historically, pig iron was the primary feedstock to the steel industry, and remains so for BOF steelmaking, even as that process has seen capacity go offline steadily over the past decades. Domestic pig iron production still satisfies most BOF demand, although there is an import flow of 10%–15% the size of domestic production (Figure 5-25) (MYB Iron & Steel; MYB Iron & Steel Scrap). For most of the evaluated period, domestic production and imports were sufficient to satisfy steel mill demand, but, as has been the case with many of the iron and steel industry material flows, the Great Recession turned that on its head. In 2010, reported pig iron demand exceeded the total quantity of reported production and imports, which, if accurate, would have required the steel mills turn to some stockpiles somewhere.

On the other hand, consumption of the ferrous scrap that is the primary feedstock for EAF steelmaking remained robust throughout the time period (Figure 5-26) (MYB Iron & Steel Scrap). Even as quantities of home scrap steadily declined, mills turned to the secondary steel markets to source scrap material. From this perspective, EAF mills seem to have weathered the 2009 recession better than their BOF counterparts. Mills also consume small amounts of other ferrous materials, including direct-reduced iron, iron ore, and various ferroalloys (Figure 5-27). The most significant alloying metals are chromium, magnesium, and silicon (Figure 5-28). Nickel, molybdenum, titanium, niobium, tantalum, vanadium, and tungsten are also used in some small quantities.

The final input to the steel industry is the quantity of flux materials that facilitate slag formation. AISI reports consumed quantities of lime, limestone, fluorspar, and other flux minerals (Figure 5-29). USGS also reports a quantity of lime consumed by steel mills as a fluxing agent that exceeds the total flux quantity reported by AISI for most of the studied period. Not surprisingly, 2009 and 2010 are outliers in this respect. It is most likely that the AISI figures, like other data in their Annual Statistical Report, refer to a class of integrated steel mills, while the USGS figure is more representative of the industry as a whole.

On the output side, the production of raw steel is by far the largest material flow, at times in the last 20 years exceeding 100 million Mg per year (Figure 5-30) (MYB Iron & Steel). Most of this product is in the form of carbon steel, with a small amount of stainless and other alloy steels as well, likely responsible for much of the ferroalloy consumption discussed above.

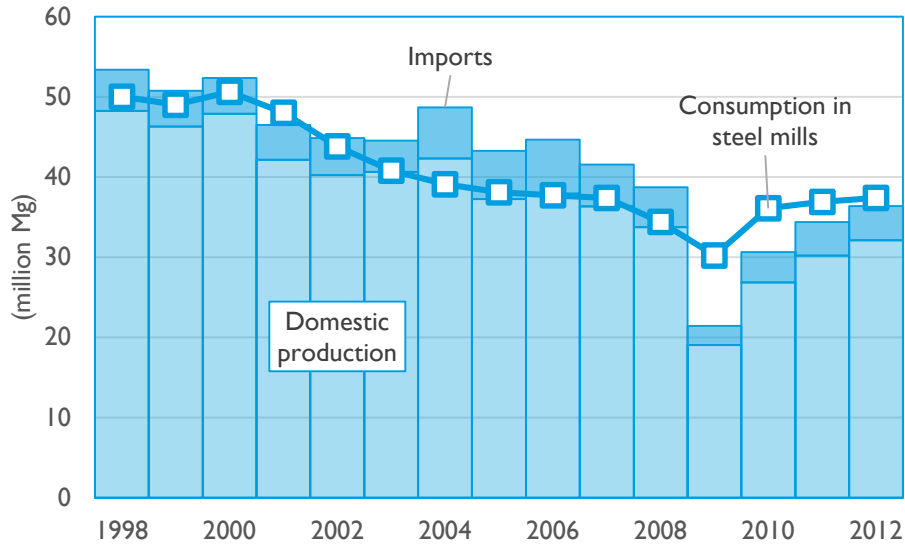


Figure 5-25. Pig iron production, import, and consumption in steel mills, 1998–2012 (MYB Iron & Steel; MYB Iron & Steel Scrap)

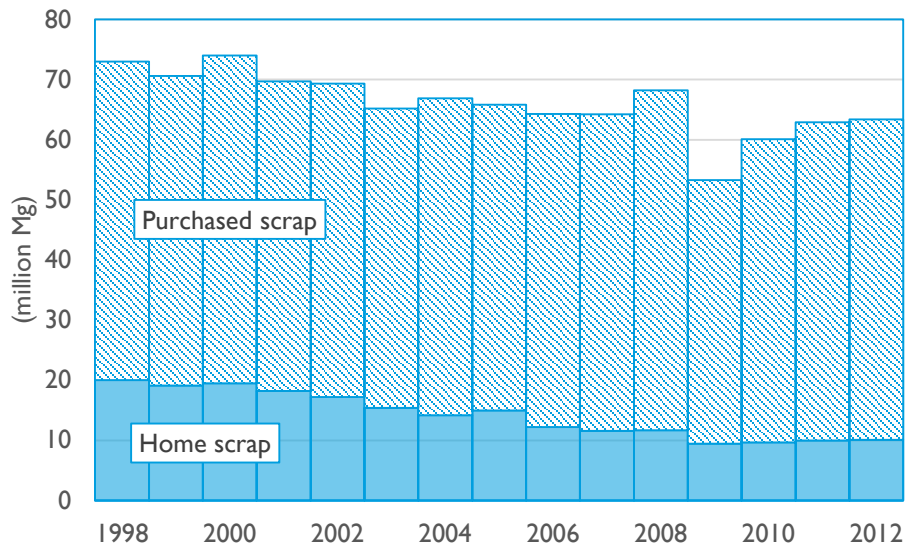


Figure 5-26. Ferrous scrap consumption in steel mills, 1998–2012. Home scrap is scrap from the mill’s own activities (MYB Iron & Steel Scrap)

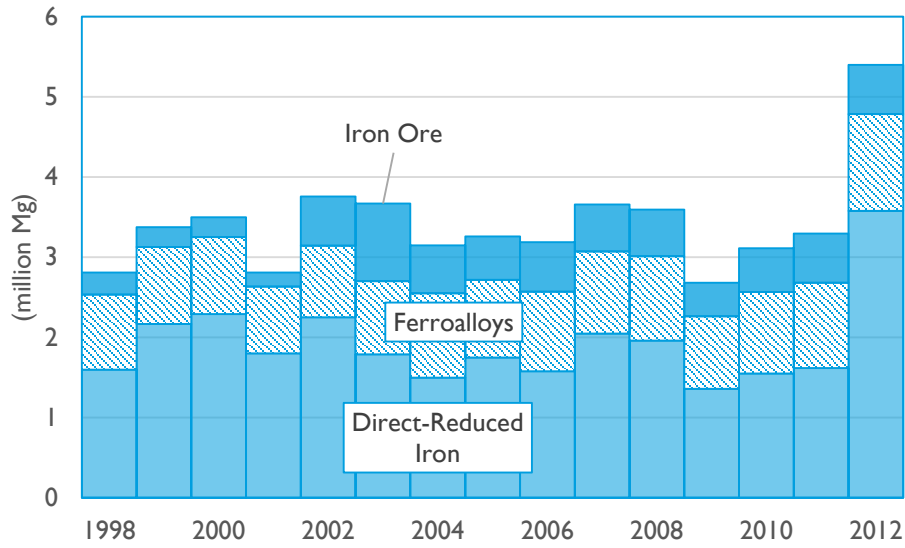


Figure 5-27. Other ferrous inputs to the US steel industry, 1998–2012 (MYB)

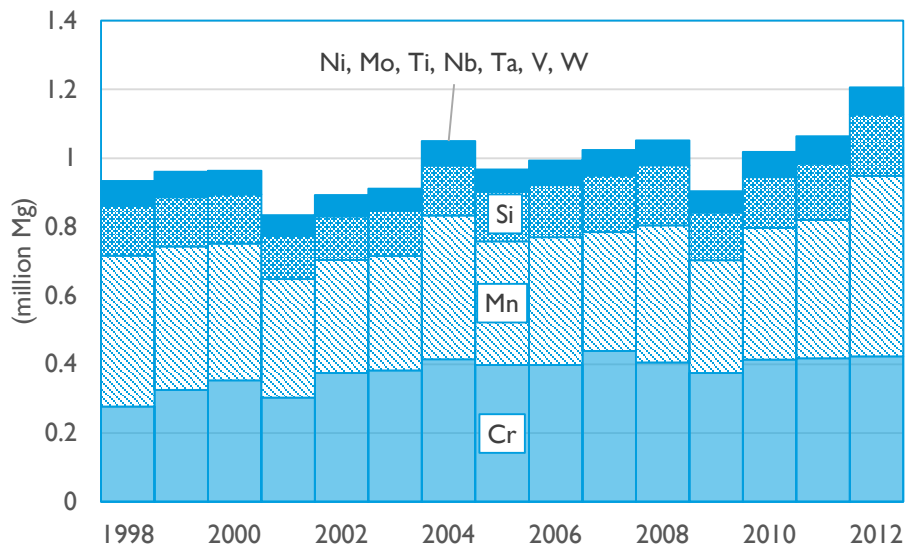


Figure 5-28. Distribution of different ferroalloys consumed by the steel industry, 1998–2012 (MYB)

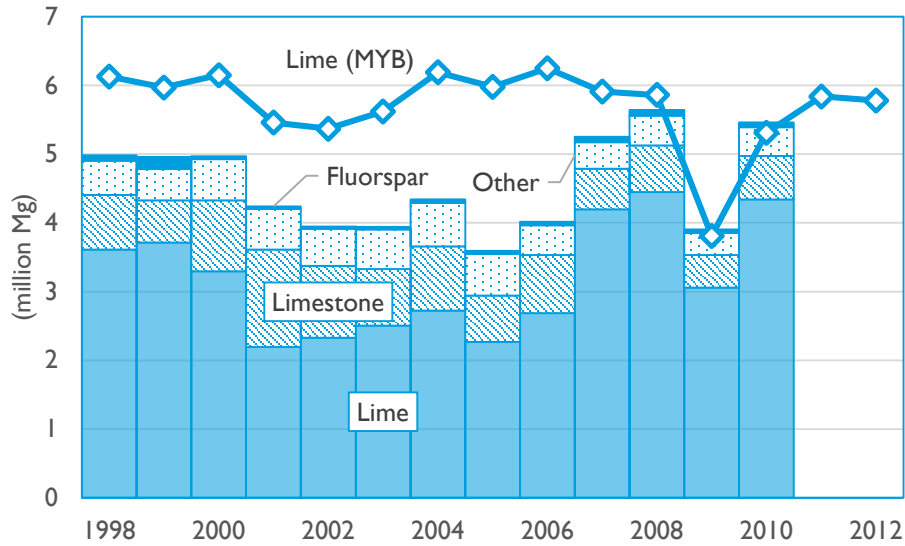


Figure 5-29. Two different accounts of flux consumption by the steel industry, 1998–2010 / 2012. The line is reported by the USGS (MYB Lime) and the bars are reported by AISI.

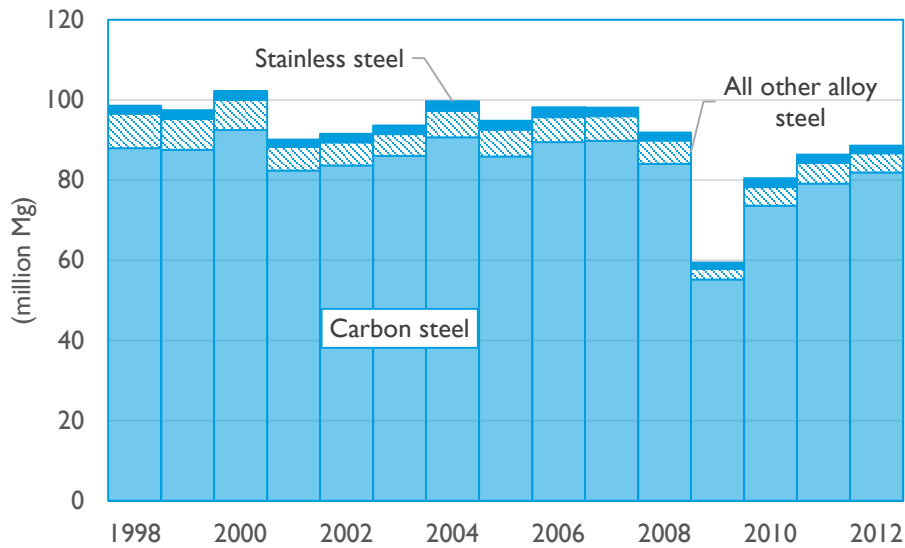


Figure 5-30. Raw steel production by the US steel industry, 1998–2012. The primary product is carbon steel, with smaller quantities of stainless and other alloy steel (MYB Iron & Steel)

As with blast furnace slag, the data for steel furnace slag is that of sales, not generation (MYB Slag–Iron & Steel). The USGS claims that on average, steel slag is equivalent to 20% by mass of raw steel produced, but up to 50% of that is recoverable iron. They claim therefore that marketable slag production is equivalent to 10%–15% of raw steel production. Figure 5-31 compares the reported tonnage of sold slag with this calculated range. This comparison suggests that there might be much more slag being generated than is documented by the USGS. On the other hand, the 20% figure can be found in Mineral Yearbooks going back decades, suggesting it refers more to BOF steel than EAF steel. Since the former generates more slag than the latter, the missing mass may be less than shown in Figure 5-31. The carbon contained within the pig iron inputs to steel furnaces is mostly driven off as CO₂ (max 0.4 wt.% of input pig iron).

Ayres & Ayres (1998) also include one additional material flow in steelmaking: sulfuric acid (H₂SO₄) used in steel pickling, the result of which is pickle liquor, represented by Ayres & Ayres as ferrous sulfate (FeSO₄). I exclude this material flow from my account because waste pickle liquor is listed as a hazardous waste by the EPA with the code K062. The other iron and steel industry source-specific listed waste is K061, EAF dust/sludge. My material balance model lacks the resolution to identify this waste stream in the first place.

Missing mass can be identified by comparing total mass of inputs and outputs in steelmaking (Figure 5-32). The results are mixed. For two periods, 1998–2002 and 2009–2012, inputs exceed outputs by an average of 5.0 million Mg per year (excluding the 2009 outlier), suggesting there is either missing mass (most likely in the form of unsold slag) or errors in the data and/or model. In the period 2003–2008, outputs exceed inputs by an average 6.5 million Mg per year. This is, of course, impossible, making the second explanation (data and model error) the likely one. If I had looked just at a single year of data rather than the whole time series, it would have been possible to draw conclusions about either the presence of lost mass or data or modeling error that may have been erroneous. I feel confident about the model architecture, that I am not missing any major inputs or outputs. It is very possible that the AISI and USGS data are incorrect for the middle time period, which would leave the other two time periods intact. It is also possible that the system boundaries of the various large ferrous material flows are not fully overlapping from one to another.

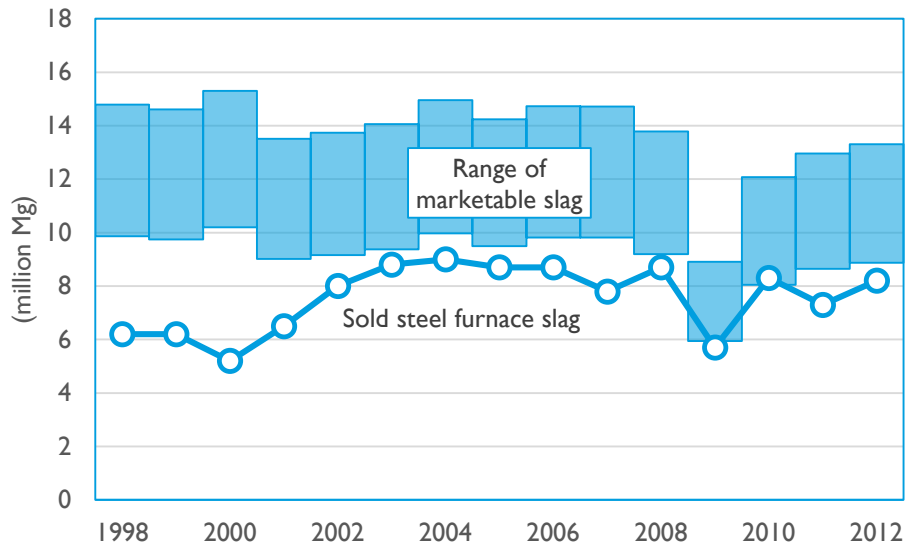


Figure 5-31. Comparison between sold steel slag and estimated ranges of marketable slag production, 1998–2012 (Slag—MYB Iron & Steel)

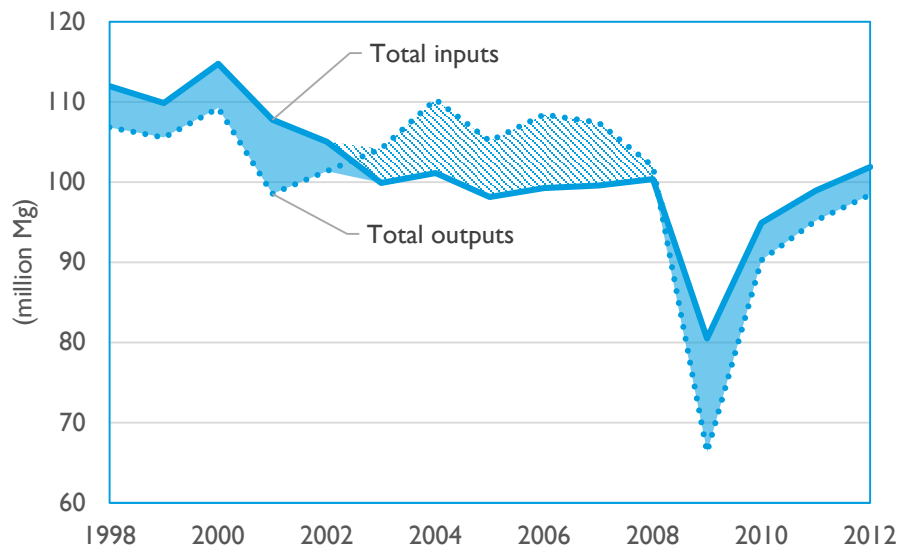


Figure 5-32. Comparison of total inputs and total outputs in the steelmaking module, 1998–2012.

5.3.3.5 Finishing

The Ayres model ends with the production of raw steel (although the inclusion of pickling chemicals does confuse the matter). There is a great deal of data available about the production and shipment of semi-finished and finished steel products from raw steel, which may be able to be used to estimate finishing wastes like rolling mill sludges and scales. AISI reports shipments of semi-finished and finished steel products in both gross and net terms—gross including all shipments from reporting companies, including steel that is “consumed by the companies in their own construction, maintenance, repair and operations, as well as in their own manufacture of fabricated products” (AISI). Net tons eliminates this duplication. The actual, non-duplicative figure for production would actually be somewhere between the gross and net figures because steel that is manufactured for end use by a reporting company, for example in construction, is excluded in the net tonnage along with steel shipped for further processing.

There are not equivalent data regarding the inputs to steel finishing operations. It can be assumed to be the tonnage of raw steel reported above, but upon examination, the difference between raw steel production and finished steel net shipments is volatile and even goes negative over a similar range of years as the steelmaking mass balance inversion (Figure 5-33). This inversion could be addressed by including the net imports of semi-finished steel shapes, but that would essentially just translate the oscillation upwards, suggesting lost mass in 2010 approximately 7 million Mg, which is an unlikely scenario.

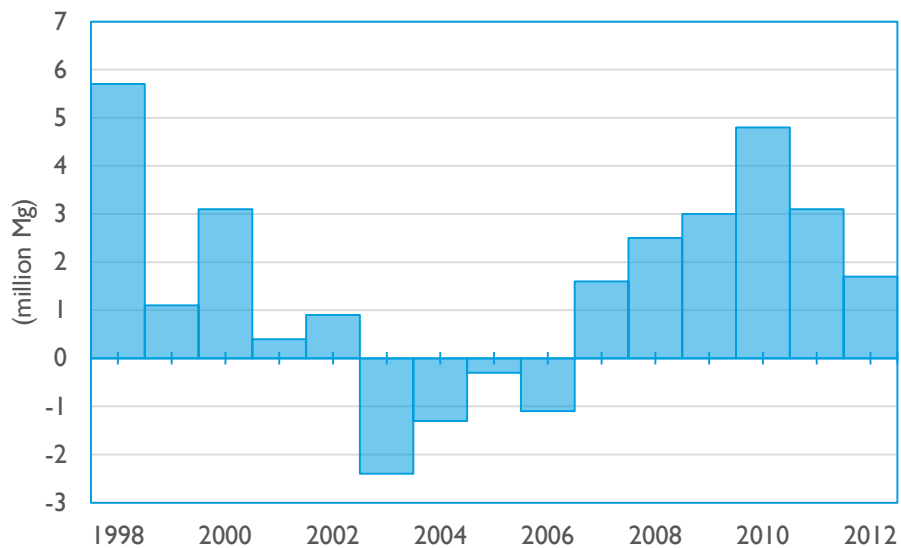


Figure 5-33. Difference between reported raw steel production and finished steel net shipments, 1998–2012 (AISI, MYB Iron & Steel)

5.3.4 Material balance, 2010

Based on the data and analysis presented in the preceding sections, I construct a materials balance model of the US iron and steel industry for the year 2010, with the goal of identifying NHIW quantities (Figure 5-34). For the sake of visual clarity, the crude ore beneficiation step is excluded from the diagram; the quantity of gangue estimated to have been removed from crude iron ore in the US in 2010 was 115.1 million Mg, more than the materials throughput of the entire iron and steel industry.

The estimated (or in the cases of iron and steel slag, reported) NHIW flows from the diagram are summarized in Table 5-15. As discussed above, quantities of lost mass are on par with the reported quantities of sold steel slag. It is likely that some of the lost mass is unsold steel slag and some is the other waste from steelmaking operations, such as dust, sludge, and scale. Lost mass from finishing operations is of more dubious provenance. Although rolling mills do generate waste, it is unlikely to be of the quantities determined by the model, especially considering the poor relationship between reported raw steel production and finished steel net shipments.

5.3.5 Discussion

The results of this analysis expose some of the drawbacks of the materials balance methodology. As illustrated by the two balancing checks performed above (Figure 5-32 and Figure 5-33), the model appears valid for only the first and last thirds of the analytical time series. Although the use of the time series helps to validate materials balance models in some cases, it did not work as intended here. Put simply, the reported data and the requirements of the mass balance are in conflict. It is possible that either could be in error. The reported data largely originates with the AISI and other trade organizations. While I trust the statisticians employed by those organizations report truthfully, it is possible that different data sets reflect different system boundaries within the industry. Longitudinal study of each data set would remain valid, as the system boundary for each indicator would remain the same over time, but cross sectional analysis, such as the material balance, would be compromised. For example, one data set may include all EAFs, include those operated by ferrous foundries, while another may exclude foundry operations altogether.

The materials balance method as I use it here is MFA-lite in that not all product and substance flows are balanced. One reason I avoided constructing a complete MFA is that to do so I would have had to presume the relationship between the known inputs and outputs and the waste output, whereas my goal was to find that value through an emergent process. As it turns out, a prudent approach would have been to incorporate literature-derived waste intensity values into the model as a validation step. However, the strange time-series behavior that is observed would be unlikely to be fixed with a linear waste factor; it would have to instead have some parabolic factor, where the beginning and end behave different from the middle.

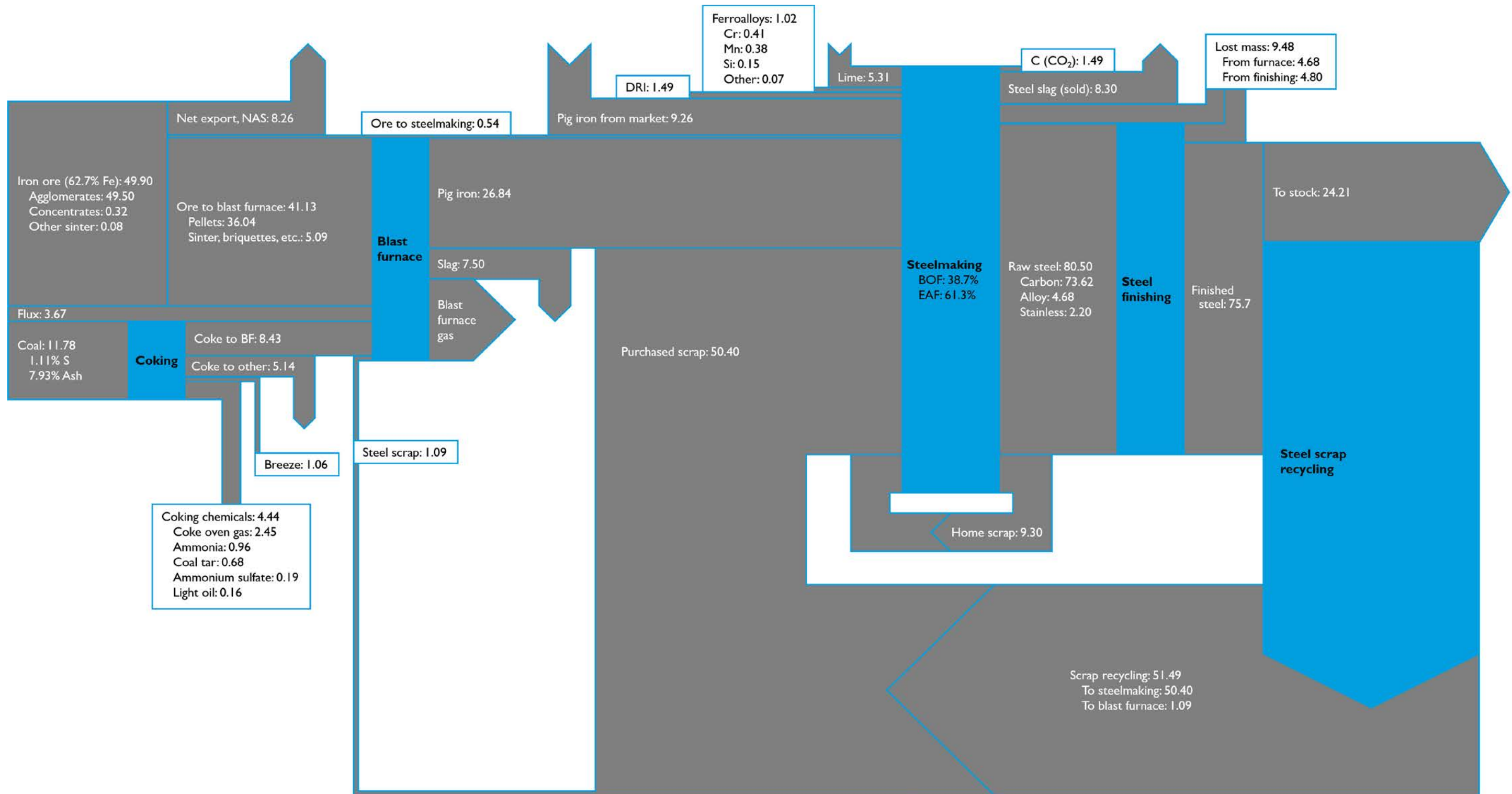


Figure 5-34. Materials balance for the US iron and steel industry, 2010. All numbers in million Mg.

Table 5-15. Summary of NHIW from US iron and steel industry, 2012, estimated by materials balance.

Waste type	(million Mg)
Coke breeze	1.06
BF slag, sold	7.50
Steel slag, sold	8.30
Lost mass, steel	4.68
Lost mass, finishing	4.80
Total	26.34

In any event, the uncertainty suffusing this discussion is exactly the reason for the triangulation meta-method. The materials balance approach is limited in its ability to estimate all waste flows accurately, just like any other estimation technique. Despite the reasons to be skeptical of the results, I am confident in the model construction, and therefore the results should be compared to the results from the other two estimation methods used here before any judgment is passed.

5.4 Spatial scale-up

One need to look no further than the nicknames of cities and sports teams throughout Pennsylvania to get a sense of the significance of steelmaking to the state's industrial heritage. While perhaps not as substantial a contributor to either the national steel industry or Pennsylvania's economy as it once was, in 2010 the state produced just under 6 million Mg of raw steel, 7.1% of the national total (Figure 5-35). Both the total production national fraction had been on the decline since the late 1990's, but the recession of 2008 interrupted that trend.

This section presents the application of the spatial up-scaling method to the iron and steel industry using data from the Pennsylvania Residual Waste database.

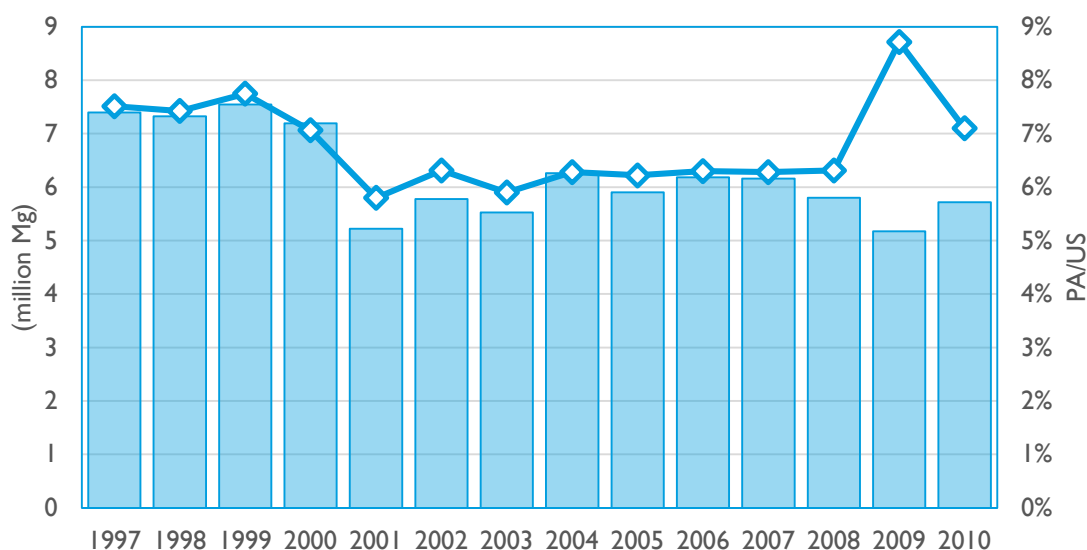


Figure 5-35. Annual Pennsylvania raw steel production (bars) and its fraction of national production (line), 1997–2010 (AISI).

5.4.1 Data & facilities

Of the three industry subsectors examined in this thesis, the iron and steel industry is by far the best represented in Pennsylvania, at least in terms of number of reporting facilities. A full 114 unique reporter codes are present in the database under one of the three relevant 5-digit NAICS codes: 33111, 33121, and 33122 (Figure 5-36). One quarter of those reporting did so for all 11 cycles; 60% reported more than half of the time.

Examining the raw data at a facility level (Figure 5-37) shows NHIW generation in all three media at a higher rate in the iron and steel mills (33111) than in the steel manufacturing facilities

(3312). The data is rather volatile, with mill-level reporting sometimes jumping multiple orders of magnitude in adjacent reporting cycles. There can also be observed some macro-level trends, specifically for liquid wastes, which tailed off dramatically between 2004 and 2006.

NHIW aggregated by discharge medium is presented in Figure 5-38. It appears that much of the volatility observed in the wastes from individual mills is smoothed out due to the large number of reporters. The largest waste stream by nearly two orders of magnitude is that of process wastewaters, which I separated from other liquid wastes to control for the change in reporting requirements in 2006. Solid wastes are the next largest, followed by sludges, and finally the other liquid wastes. The large jumps in the non-wastewater liquid NHIW stream in 1994 and 1996 is caused by waste categorized as “spent pickle liquor,” although it is more likely that this is a mis-categorization of process wastewater, given its quantity and its sudden disappearance from the waste account in 1998.

Zooming in on specific waste categories reported as solid or sludge (excluding all liquid wastes which, after wastewater is excluded, is the smallest minor category anyway), we can see some of the apparent reasons of the observed decrease in reported solid NHIW after 2004. Figure 5-39 shows a precipitous drop in slag reporting in 2006; like process wastewaters, that year saw a change in the reporting requirements for wastes sold as byproducts, like much iron and steel slag.

5.4.2 Scale-up

Scaling the reported NHIW from Pennsylvania to the US can be done multiple ways. AISI reports raw steel production at the state level (Figure 5-9). But not all wastes necessarily scale with raw steel production. Three economic indicators are available at the state and national levels for the relevant industry codes: employment, value added, and receipts (value of shipments). Scaling factors are calculated by dividing the state-level indicator by its national counterpart (Figure 5-40). These scaling factors are somewhat volatile, especially that of value added. For all three industrial subsectors, except perhaps for pipe and tube manufacturing (NAICS 33121), the scaling factors do not show any consistent ordering. All three indicators for iron and steel mills (NAICS 33111) are both the largest and the smallest at points in the time series 1992–2012. NAICS 33121 demonstrate slightly more stability, with employment consistently lower than shipment value and value added, although the latter soars to 35% in the mid-2000s. All three indicators tail off rapidly after 2007, suggesting (if the data is correct) an abandonment of that activity in Pennsylvania mills.

These scaling factors are with few exceptions larger than the scaling factor based on raw steel production. The ranges of scaling factors for the three industry subsectors in the year 2010 are presented in Table 5-16.



Figure 5-36. Pennsylvania iron and steel facilities reporting to the PARW program, 1992–2012.

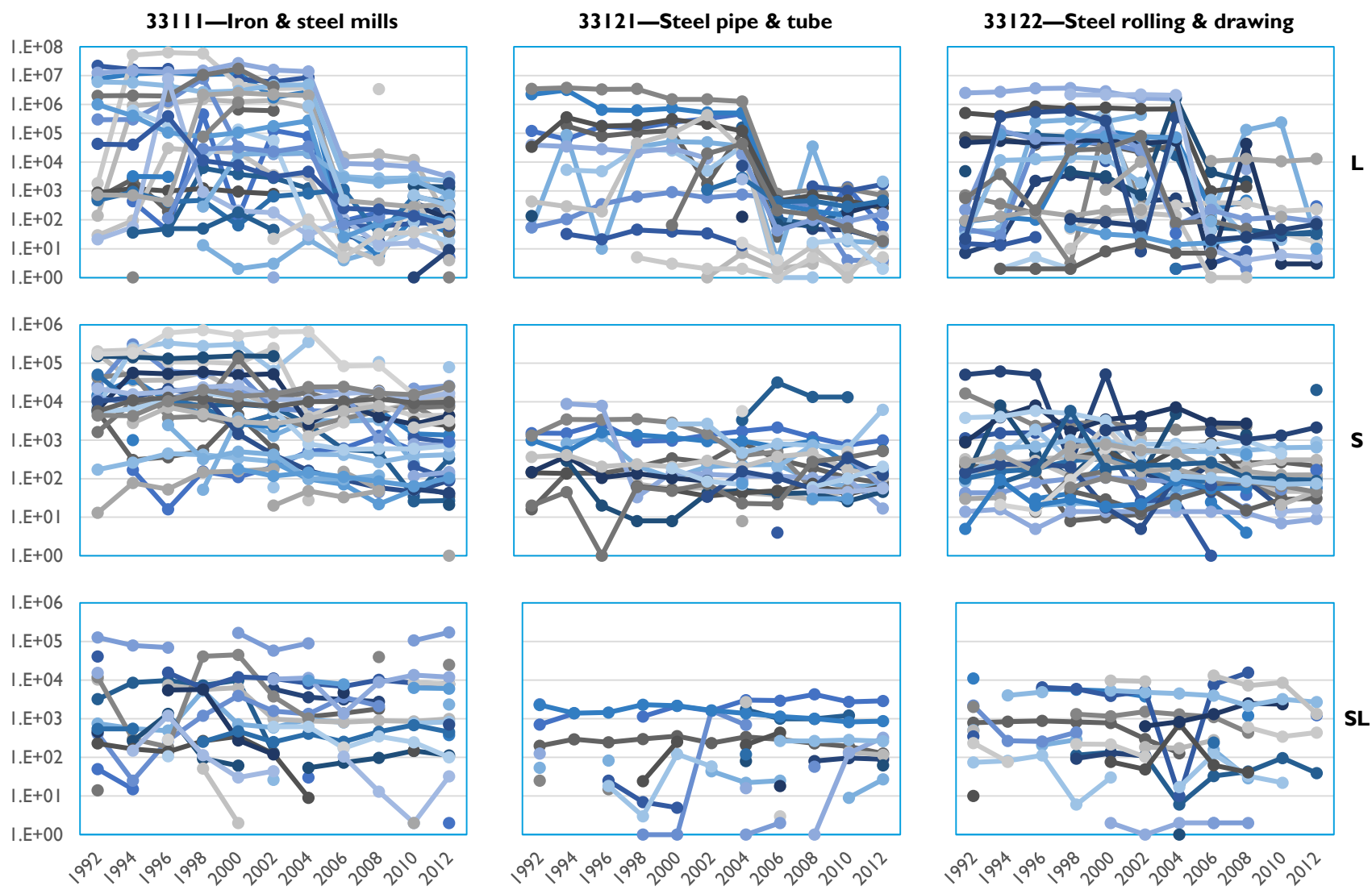


Figure 5-37. Raw residual waste data (in Mg) from the PARW database reported by facilities in the PA iron and steel industry by subsector and medium of discharge, L=liquid, S=solid, SL=sludge, 1992–2012.

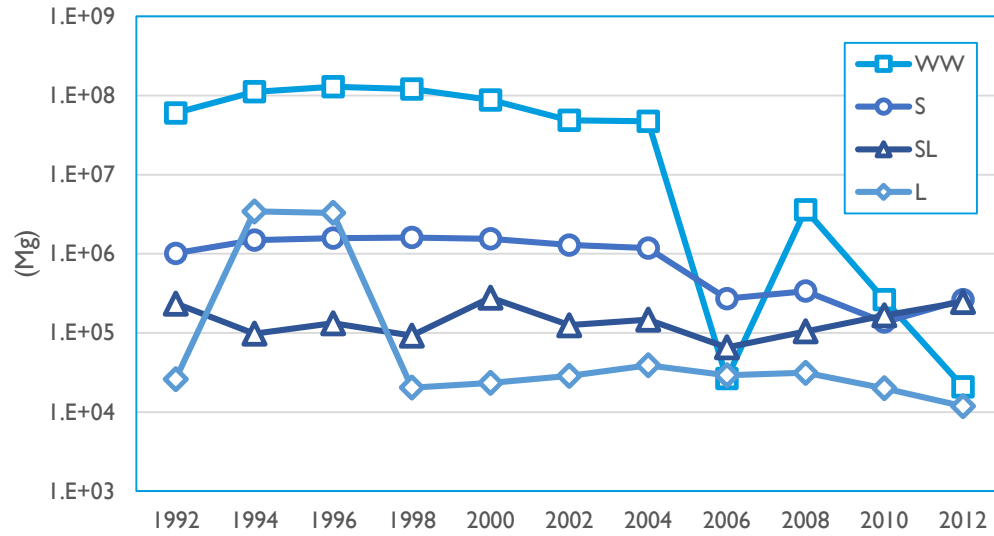


Figure 5-38. PARW data from the iron and steel industry subsectors 33111, 33121, and 33122 aggregated by medium of discharge, 1992–2012. Liquid wastes are separated into process wastewaters (420–422) and others.

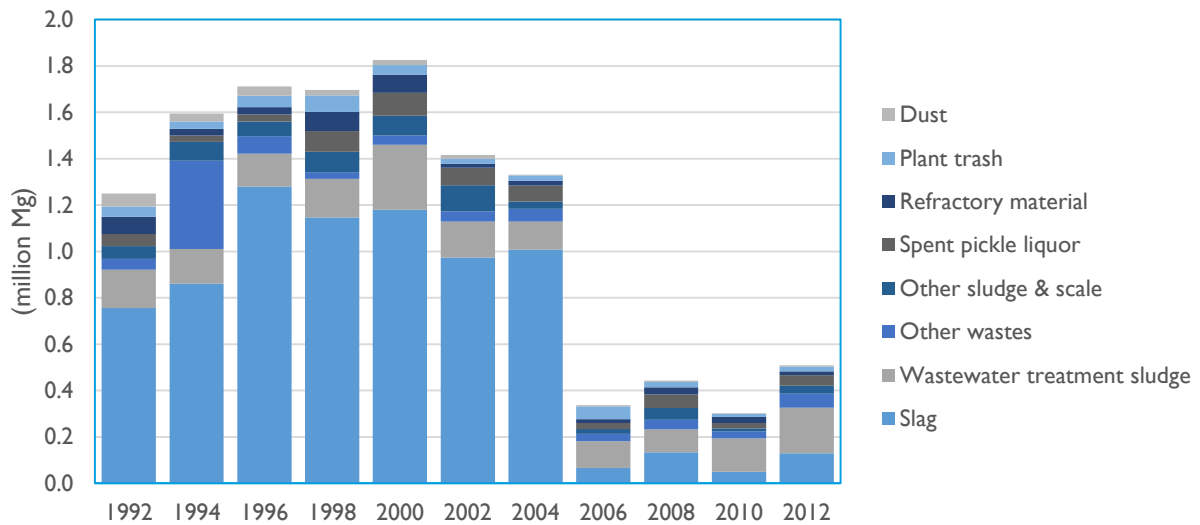


Figure 5-39. NHIW from the PA iron and steel industry, disaggregated by waste type, 1992–2012.

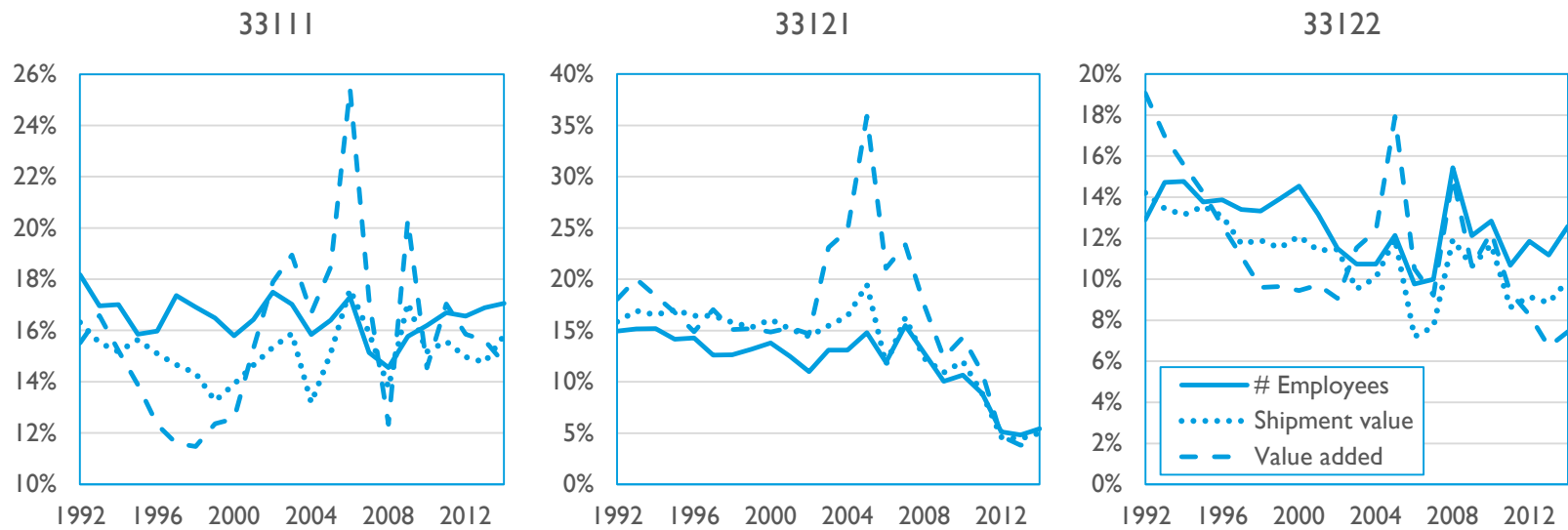


Figure 5-40. Scaling factors for PA iron and steel subsectors 33111, 33121, and 33122 (ASM, EC)

Table 5-16. Scaling factors for the three iron and steel industry subsectors for the year 2010

	33111	33121	33122
Raw steel production	7.1%	7.1%	7.1%
# Employees	16.2%	10.6%	12.8%
Shipment value	15.2%	12.0%	11.7%
Value added	14.5%	14.3%	12.3%

5.4.3 Results

Based on the state-level waste data and scaling factors above, the results of the spatial up-scaling estimation method for the year 2010 are presented in Table 5-17. The largest contributor, with nearly half of the total, is wastewater sludge, followed by slag, refractory material, and spent pickle liquor. The vast majority of the waste comes from iron and steel mills (NAICS 33111), although nearly half of the waste refractory material does come from pipe and tube manufacturing (NAICS 33121).

The estimate range was developed by using the smallest and largest scaling factor for each subsector from Table 5-16. The smallest scaling factor, consistently “raw steel production” (7.1%), is used to estimate the “high” side of the range and vice versa. At first glance, the results from the upscaling method, 1.92–4.27 million Mg, seem awfully small, compared with, for example, SAIC’s estimate of 46 million Mg. Recall, however, that the PARW reporting requirements were changed in 2006 to exclude not just process wastewater but also waste materials that were sold as byproducts, like slag. Looking back at pre-2006 data can help to determine the missing mass.

Figure 5-41 shows up-scaled NHIW from 1998–2010 using the raw steel production scaling factor. That factor was chosen because there is a direct physical relationship between raw steel production and slag generation and because it would yield the largest up-scaled estimates. This analysis shows that there is approximately 15 million Mg of slag “missing” from the 2010 up-scaled waste account. It also reinforces the observation that non-slag waste generation may be decreasing steadily.

The results from this analysis are in line with those of the other two estimation methods, that slag generation in 2010 is more or less 15 million Mg. To stay true to my methodology, this value will be excluded from the up-scaled results, but will serve as evidence to use the slag figure from one of the other two estimates. The agreement between Figure 5-41 and the other estimates also helps to justify the use of raw steel production as the main scaling factor (the “high” column from Table 5-17). Using the economic scaling factors for iron and steel mills (NAICS 33111) yields a value for slag generation less than half as large, a value that is more difficult to defend.

Table 5-17. Results from the upscaling method for iron and steel, 2010.

PARW waste code and description	PA (Mg)			US (million Mg)		
	33111	33121	33122	Low	High	%
203 Wastewater sludge	128,584	5,918	9,494	0.91	2.03	48%
102 Slag	49,152	–	488	0.31	0.70	16%
103 Refractory material	13,707	12,283	110	0.17	0.37	9%
213 Spent pickle liquor	19,615	–	3,175	0.15	0.32	8%
710 Plant trash	11,613	1,673	1,396	0.09	0.21	5%
105 Ferrous Baghouse Dust	2,679	–	209	0.02	0.04	1%
a Other sludge and scale	10,851	73	1,934	0.08	0.18	4%
b Other waste	25,473	3,034	1,622	0.19	0.42	10%
Total	261,674	22,981	18,428	1.92	4.27	

- a. Includes 209—oily sludge, petroleum derived; 210—air emission control sludge; 211—other industrial sludge; 112—mill & heat treat scales; and six others (minor)
- b. Includes 799—other maintenance waste; 499—other generic waste; 101—foundry sand; 506—contaminated soil/debris/spill residue; and 34 others

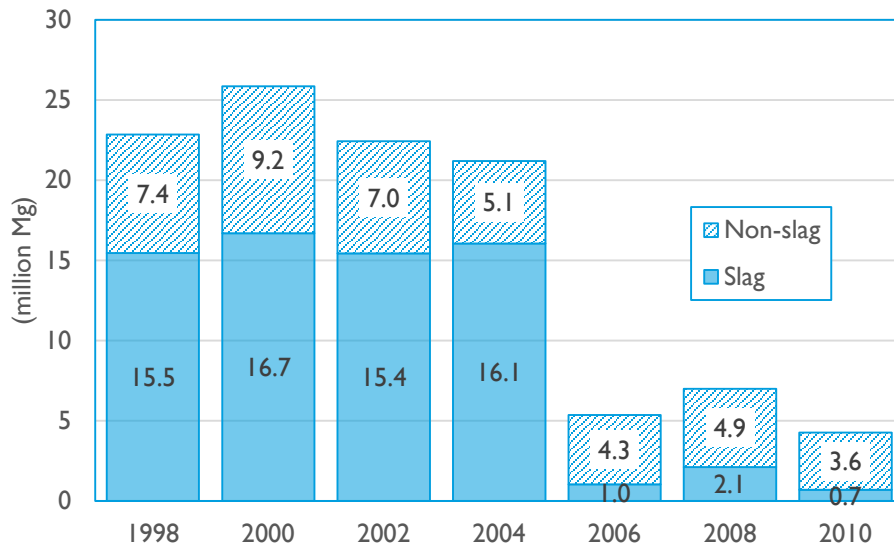


Figure 5-41. Scaled-up NHIW using factor of raw steel production, 1998–2010.

5.5 Triangulation summary

The results from each of the three estimation methods are summarized in Table 5-18. In aggregate, the forecasted and materials balance results largely agree, while the scale-up results are lower by an order of magnitude. The agreement between the first two methods holds at the next level down, slag vs. non-slag, but falls apart somewhat with a waste-by-waste analysis. The scale-up results are low almost everywhere, but especially for slag, due to the beneficial use exclusion in the PARW program.

For the specific slag categories, the materials balance results roughly agree with the 1997-basis forecast, both of which are lower than the 1985-basis forecast. Reasons for the difference may include improved process control or technology and market shifts away from integrated steel mills towards mini-mills. In any event, the earlier-basis forecast results are shown to be less reliable.

Table 5-18. Results from the three estimation methods for the US iron and steel industry, 2010

Waste Category	Forecast		Mat-Bal (million Mg)	Scale-up	
	(1985)	(1997)		Low	High
Slag					
BF	9.3	6.4	7.5		
EAF	5.9	4.8	8.3	0.3	0.7
BOF	4.5	4.0			
<i>Total slag</i>	<i>19.7</i>	<i>15.2</i>	<i>15.8</i>	<i>0.3</i>	<i>0.7</i>
Coke breeze			1.1		
Sludge	1.6	1.1		0.9	2.0
Dust	1.2	1.4		0.0	0.1
Refractory material				0.2	0.4
Scale	2.2	2.6		0.1	0.2
Spent pickle liquor	0	4.4		0.2	0.3
Other (steelmaking)	0.5	0	4.7	0.3	0.6
Other (finishing)			4.8		
<i>Total non-slag</i>	<i>5.5</i>	<i>9.5</i>	<i>10.6</i>	<i>1.7</i>	<i>3.6</i>
Total	25.2	24.7	26.3	2.0	4.3

As for the non-slag wastes, the three methods offer somewhat different stories, even if, again, the 1997-basis forecast agrees with the materials balance results in aggregate. With the exception of sludge and other wastes, the forecast results exceed the scale-up results. There is likely some category-shifting at play, with waste categorized as dust in the forecast showing up in sludge in the scale-up, for example. Like slag, scale waste can be beneficially used in many cases, which

might explain why it shows up in the historical forecast results but not the scale-up results. I would expect that the material is generated in the PA mills, but excluded from the database for its beneficial use. Spent pickle liquor is an aqueous waste, and so the 4.4 million Mg resulting from the 1997-basis scale-up is most likely a wet-basis value. The scale-up results are more realistic.

The “other” categories are on the surface highly distorted, with the materials balance results an order of magnitude larger than that produced by either other method. But, recall, that all of the non-slag wastes except for coke breeze are included as lost mass, and so that total 9.5 million Mg can be disregarded. In summary, the results of the triangulation are as follows (in million Mg):

- Blast furnace slag: 6.4-7.5
- Steel furnace slag: 8.3-8.8
- Coke breeze: 1.1
- Sludge: 1.1-2.0
- Dust: 1.2-1.4
- Refractory material: 0.2-0.4
- Scale: 2.2-2.6
- Spent pickle liquor: 0.2-0.3
- Other: 0.5-0.6
- TOTAL: 21.2-24.7

As it turns out, the upper end of the estimated range is exactly the same as the 1997-basis forecast results. Of course, the specific composition of the account differs. Otherwise, the range is lower than the aggregated results from the materials balance and 1985-basis forecast, but still substantially larger than the scale-up.

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6 Petroleum Refining

Waste from the petroleum refining industry is not considered to be a major contributor to the total NHIW account of the US. In fact, the industry is much more well known for its hazardous waste generation. It is nevertheless prudent to examine this mid-range industry through the triangulation lens both to evaluate both the of the method for a chemicals industry like this one and to challenge the perception of the industry as contributing little to NHIW generation. The historical forecasting yields an estimate of 1.15–1.24 million Mg of dry NHIW. The spatial up-scaling yields an estimate of 0.96–1.12 million Mg. The materials balance method did not yield a reliable estimate because available data for the industry offered just a single activity with which to balance the model. Arguments can be made to push the NHIW value up or down, but this order of magnitude is a marked improvement on the 153 million Mg estimate currently used by the EPA.

6.1 Introduction

This section introduces the petroleum refining industry in the US and key characteristics necessary for effective completion of the triangulation methods and interpretation of results.

6.1.1 Motivations

Of the myriad environmental concerns relating to the petroleum industry—oil spills, toxic waste, VOCs, and of course the CO₂ emissions from its primary product, gasoline, to name but a few—NHIW barely registers. In fact, it seems odd to even consider solid waste as a product of petroleum refining in the first place, as an industry with liquid feedstock and liquid products would seem an unlikely candidate to be producing solid wastes.⁵⁵ Nevertheless, the industry was ranked in the midrange of both of the motivating waste accounts for this research: eleventh out of 22 industries studied by SAIC (US EPA, 1985) and ninth out of the 17 industries surveyed in the industrial facilities survey (US EPA, 1988). SAIC estimated the industry produces approximately 1.3 million Mg (dry basis) NHIW, while the industrial facilities survey found that refineries dispose of 153 million Mg (wet basis) of NHIW on site.

From these figures, the petroleum refining industry is not a major contributor to the total, especially considering the large skewness of the distribution, where the top industries contribute an outsized amount. It is, however, a representative case, much more similar to a vast swath of

⁵⁵ The broadest classification of industrial waste is that waste material flow that is land-disposed (contrasting with water- and air-disposed waste), rather than requiring it be specifically solid, dry material.

American industry than are the top contributing sectors. Therefore, this chapter can be seen as both contributing an understanding of a specific industry and as a test of the applicability of the triangulation method to the mid-range industries, for which data on NHIW may be elusive.

6.1.2 Petroleum refining sector in the US

The US is a major global producer (and consumer) of energy in all forms, including petroleum. In the US, petroleum refining is classified as the NAICS code 324110—Petroleum Refineries. This is one of five six-digit industries comprising NAICS 324—Petroleum and Coal Products Manufacturing. NAICS 324110 corresponds with SIC 291—Petroleum Refining.

The industrial activities classified within NAICS 324110 are numerous, including no fewer than 40 different product categories (Table 4-2). Petroleum refining is the largest of the five industries within NAICS 324, contributing around 90% of the total value of shipments and value added (Figure 6-1). Petroleum refineries have comparatively fewer employees than establishments in the other six-digit industries, which are further down the value chain.

6.1.2.1 Consumption & production

The throughput of US refineries has been growing at a steady pace for decades, at just over 1% per year, from 4.9 billion barrels in 1981 to 6.8 billion barrels in 2014. Petroleum refineries consume mainly crude oil, with a small but growing quantity of non-crude oil inputs (Figure 6-2). The three major historical products of refineries are motor gasoline, distillate fuel oil (DFO), and residual fuel oil (RFO). Production of gasoline and DFO (primary diesel fuel) has grown steadily since the end of WWII, except for a period of rapid growth and then correction in the late 1960s and 1970s; RFO production has declined over that same time period (Figure 6-3).

In 2010, fully half of the volumetric output of US refineries was motor gasoline, nearly another quarter was DFO, with the remaining volume comprised of jet fuel, petroleum coke (petcoke), refinery (still) gas, liquefied petroleum gases, RFO, and other products (Figure 6-4).

6.1.2.2 Economic indicators

The value of shipments from petroleum refineries (NAICS 324110) has increased as production has increased, 0.8% per year on average (in real \$ terms) since 1987 (Figure 6-5). Value added, which economists look to as a better indicator of the health of the sector because it avoids the double counting associated with value of shipments by subtracting the cost of purchased materials, supplies, energy, etc., exposes a highly volatile industry (which should not come as a surprise to anyone). In 2010, value added from the industry was \$81.5 billion, while value of shipments was \$588 billion—this indicates that the cost of crude oil is both the largest component of the price of

petroleum products and the driver of volatility. Employment in the industry has declined steadily at a pace of 0.5% per year. This trend is reflected in the consolidation of the industry (Figure 6-6). The total number of establishments in the industry has declined from 308 in 1987 to 146 in 2012, with the vast majority of the decline as a result of small and medium facilities closing. At the same time, the number of distinct companies has also shrunk, from 200 in 1987 to just 59 in 2012.

6.1.2.3 Geographic distribution

Petroleum refining industry is unevenly distributed around the country. More than a quarter of the value of shipments from the industry come from refineries in Texas, with another 15–20% from Louisiana. California, Illinois, Pennsylvania, and New Jersey round out the top six states (Figure 6-7). The petroleum refining industry is a major if volatile economic driver in many states as well. In 2010, the industry contributed more than a quarter of the state gross product (value added) in Wyoming, Montana, and Louisiana, and more than 10% in Oklahoma, Texas, and Alaska. The US average was approximately 5% (Figure 6-8).

The EIA tracks refining capacity and petroleum product shipments at the regional level. “Petroleum Administration for Defense Districts” (PADD) were originally defined in 1942 to support gasoline rationing during WWII (US EIA, 2012). There are five primary PADDs, along with two additional districts for US territories (Figure 6-9). Half of national refining capacity is concentrated in PADD 3 (Gulf Coast), which has also seen nearly all of the absolute growth over the past two decades (Figure 6-10).

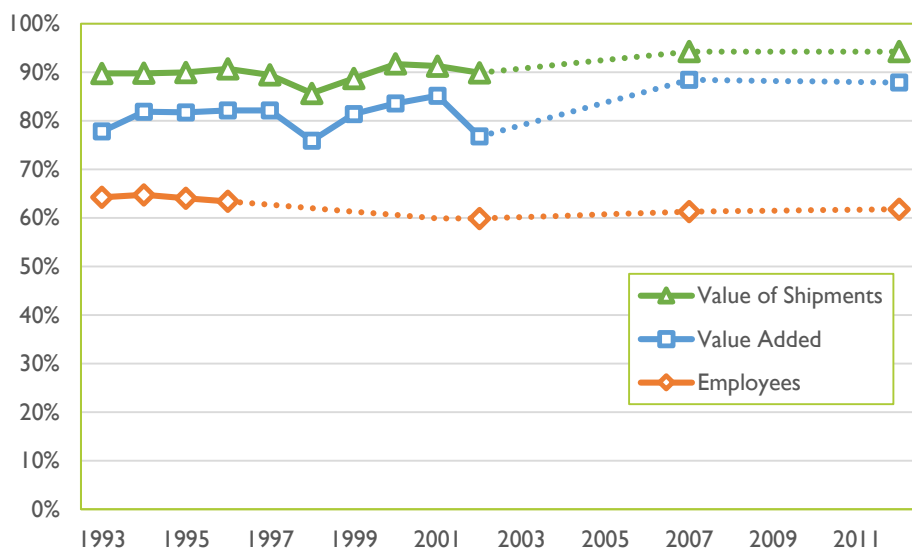


Figure 6-1. Economic characteristics of NAICS 324110—Petroleum Refineries as a percent of 324—Petroleum and Coal Products Manufacturing in the US, 1993–2012. (ASM, EC)

Table 6-I. 2012 NAICS Index entries for NAICS 324, including detail for NAICS 324110 (US CB, 2013)

324110: Petroleum Refineries

- Acid oils
- Aliphatic chemicals (i.e., acyclic)
- Alkylates
- Asphalt and asphaltic materials
- Asphalt paving mixtures
- Aviation fuels
- Benzene
- Butylene (i.e., butene)
- Cumene
- Cyclic aromatic hydrocarbons
- Diesel fuels
- Ethylene
- Fuel oils
- Gasoline
- Heating oils
- Hydraulic fluids
- Jet fuels
- Kerosene
- Liquefied petroleum gas (LPG)
- Lubricating oils and greases
- Naphtha
- Naphthenic acids
- Oil additives
- Paraffin waxes
- Petrochemical feedstocks
- Petrochemicals
- Petroleum coke
- Petroleum jelly
- Petroleum lubricating oils
- Petroleum waxes
- Propane gases
- Propylene (i.e., propene)
- Refinery gases
- Road oils
- Solvents
- Still gases
- Styrene
- Tar
- Toluene
- Xylene

324121: Asphalt Paving Mixture and Block Manufacturing

324122: Asphalt Shingle and Coating Materials Manufacturing

324191: Petroleum Lubricating Oil and Grease Manufacturing

324199: All Other Petroleum and Coal Products Manufacturing

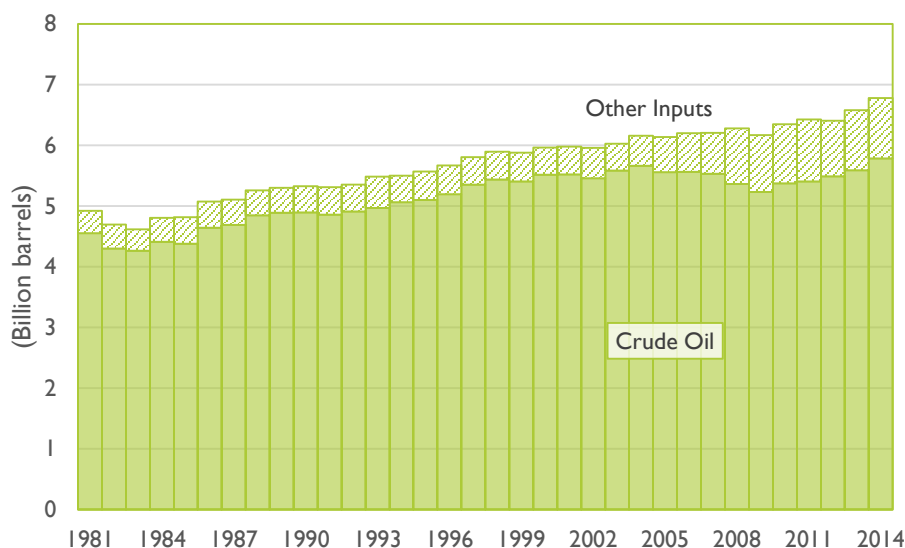


Figure 6-2. Net inputs of raw materials to US petroleum refineries and blenders, 1981–2014 (EIA Petroleum). Other inputs include natural gas liquids, liquid refinery gases, oxygenates, ethanol, unfinished oils, and gasoline blending components.

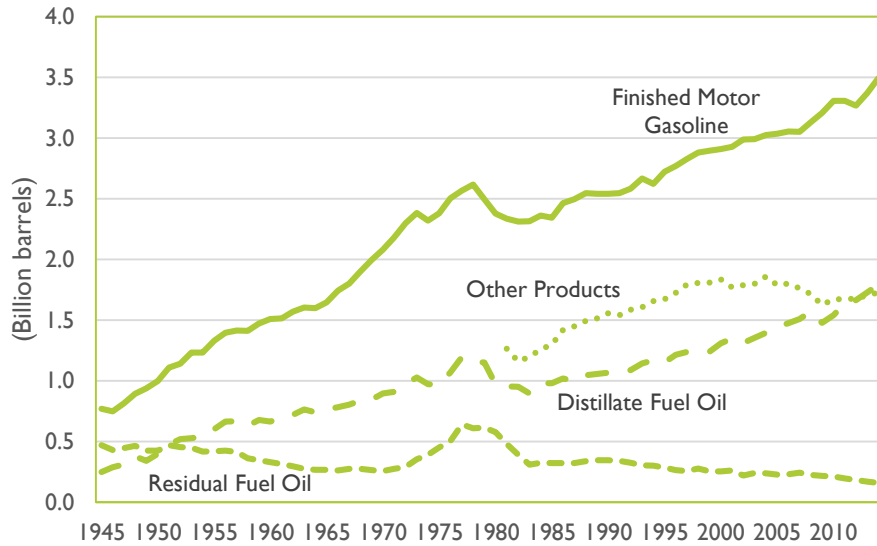


Figure 6-3. Net production of US petroleum refineries and blenders, 1945–2014 (EIA Petroleum). Documentation of other products begins in 1981, and includes jet fuel, petroleum coke, still gas, liquefied petroleum gases, and other minor products.

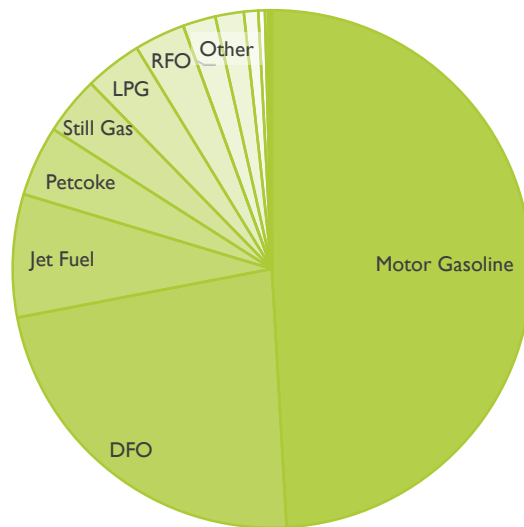


Figure 6-4. Distribution of production outputs from US refineries and blenders in 2010 (EIA Petroleum). Other products include asphalt and road oil, petrochemical feedstocks, lubricants, special naphthas, kerosene, aviation gasoline, and waxes.

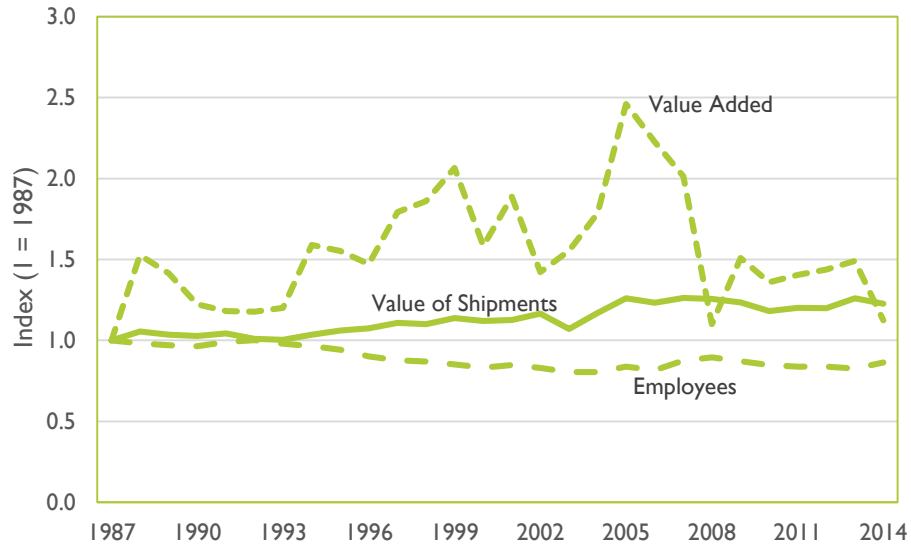


Figure 6-5. Economic indices of the US petroleum refining industry (NAICS 324110), 1987–2014 (1.0=1987). Value added and value of shipments in real 2010 dollars (ASM, EC, PPI).

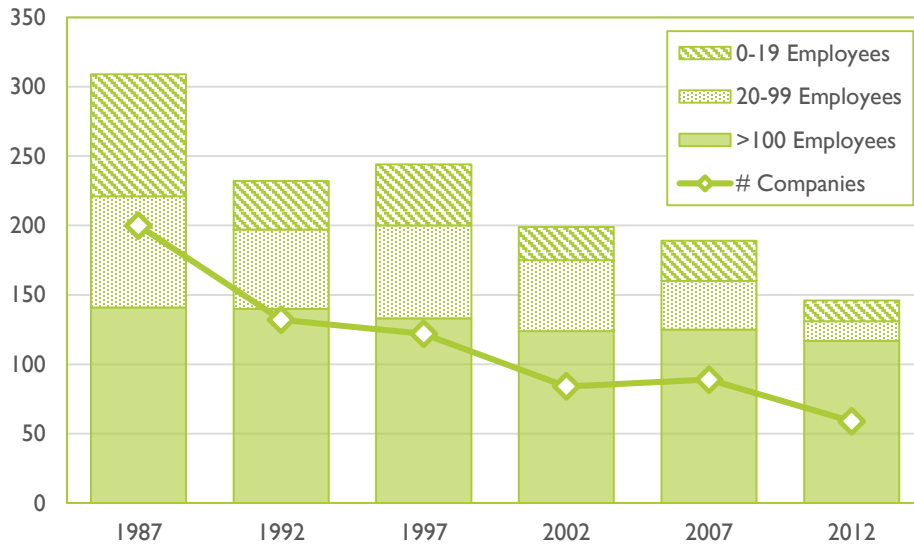


Figure 6-6. US refining industry establishments by number of employees; number of companies, 1987–2012. (EC)

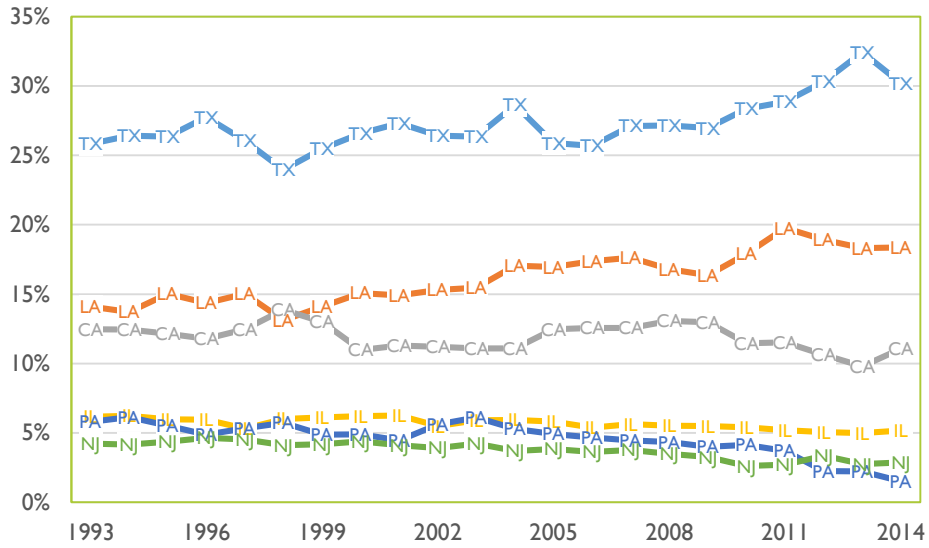


Figure 6-7. State refining industry as a fraction of US refining industry (by value of shipments), 1993–2014. (ASM, EC)

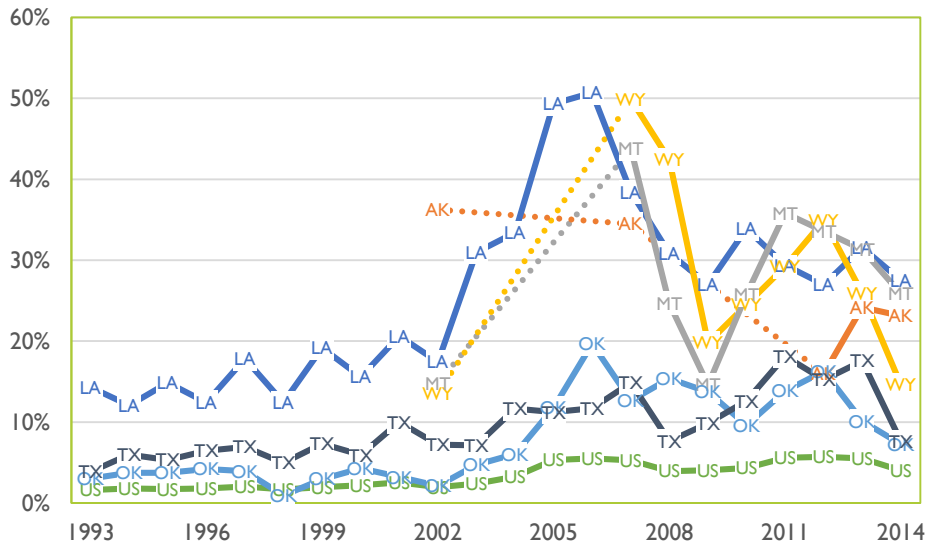


Figure 6-8. State refining industry as a fraction of total state manufacturing industry (by value added), 1993–2014. (ASM, EC)

Petroleum Administration for Defense Districts

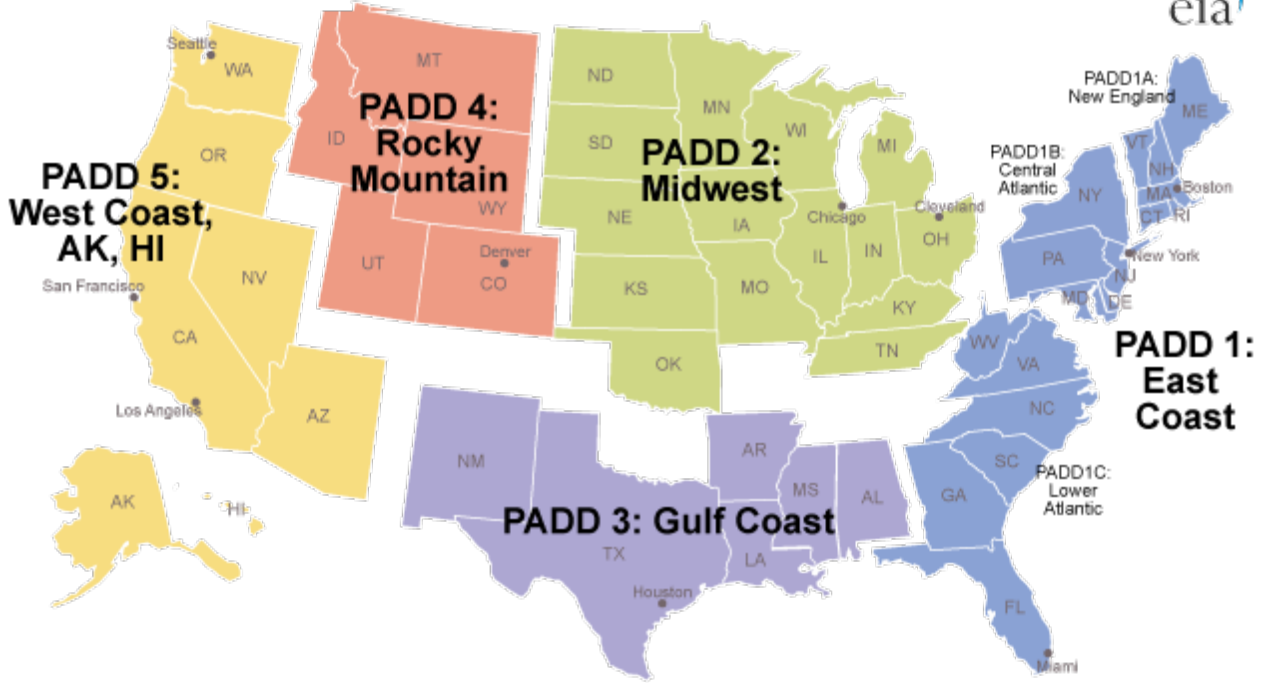


Figure 6-9. Petroleum Administration for Defense Districts (PADD) in the US. (US EIA, 2012)

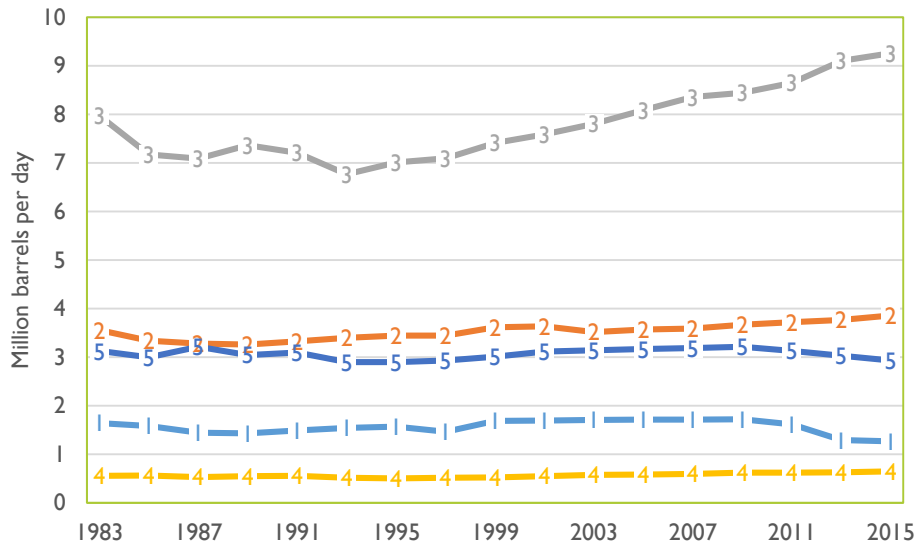


Figure 6-10. Refining capacity by PADD, 1983–2015. (EIA Petroleum)

6.1.3 Overview of petroleum refining processes

The main objective of a petroleum refinery is to separate crude oil into its hydrocarbon constituents. Although there is a variation in size and complexity among refineries, most perform the same set of standard operations, described in Table 6-2 and Figure 6-11. More detailed descriptions of petroleum refinery operations can be found in any number of engineering texts (e.g. Speight, 2014). Process descriptions written from the perspective of energy and environmental concerns can be found in US EPA (1995b) and US DOE (2007).

Table 6-2. Refinery process overview (US EPA, 1996, pp. 23–25)

Storage Facilities: Large storage capacities are needed for refinery feed and products. Sediments from corrosion and impurities accumulate in these storage tanks.

Crude Desalting: Clay, salt, and other suspended solids must be removed from the crude prior to distillation to prevent corrosion and deposits. These materials are removed by water washing and electrostatic separation.

Distillation: After being desalted, the crude is subjected to atmospheric distillation, separating the crude by boiling point into light ends, naphtha, middle distillate (light and heavy gas oil), and a bottoms fraction. The bottoms fraction is frequently subjected to further distillation under vacuum to increase gas oil yield.

Catalytic Cracking: Catalytic cracking converts heavy distillate to compounds with lower boiling points (e.g., naphthas), which are fractionated. Cracking is typically conducted in a fluidized bed reactor with a regenerator to continuously reactivate the catalyst. Cracking catalysts are typically zeolites. The flue gas from the regenerator typically passes through dry or wet fines removal equipment and carbon monoxide oxidation prior to being released to the atmosphere.

Hydroprocessing: Hydroprocessing includes (1) hydrotreating and hydrorefining (or hydrodesulfurization), which improve the quality of various products (e.g., by removing sulfur, nitrogen, oxygen, metals, and waxes and by converting olefins to saturated compounds); and (2) hydrocracking, which cracks heavy materials, creating lower-boiling, more valuable products. Hydrotreating is typically less severe than hydrorefining and is applied to lighter cuts. Hydrocracking is a more severe operation than hydrorefining, using higher temperature and longer contact time, resulting in significant reduction in feed molecular size. Hydroprocessing catalysts are typically some combination of nickel, molybdenum, and cobalt. Typical applications of hydroprocessing include treating distillate to produce low-sulfur diesel fuel, treating naphtha reformer feed to remove catalyst poisons, and treating catalytic cracking unit feed to reduce catalyst deactivation.

Thermal Processes: Thermal cracking uses the application of heat to reduce high-boiling compounds to lower-boiling products. Delayed (batch) or fluid (continuous) coking is essentially high-severity thermal cracking and is used on very heavy residuum (e.g., vacuum bottoms) to obtain lower-boiling cracked products. (Residuum feeds are not amenable to catalytic processes because of fouling and deactivation.) Products are olefinic and include gas, naphtha, gas oils, and coke. Visbreaking is also thermal cracking; its purpose is to decrease the viscosity of heavy fuel oil so that it can be atomized and burned at lower temperatures than would otherwise be necessary. Other processes conducting thermal cracking also would be designated as thermal processes.

Table 6-2. (Cont.)

Catalytic Reforming: Straight run naphtha is upgraded via reforming to improve octane for use as motor gasoline. Reforming reactions consist of (1) dehydrogenation of cycloparaffins to form aromatics and (2) cyclization and dehydrogenation of straight chain aliphatics to form aromatics. Feeds are hydrotreated to prevent catalyst poisoning. Operations may be semiregenerative (cyclic), fully-regenerative, or continuous (moving bed) catalyst systems. Precious metal catalysts are used in this process.

Polymerization: Polymerization units convert olefins (e.g., propylene) into higher octane polymers. Two principal types of polymerization units include fixed-bed reactors, which typically use solid-supported phosphoric acid as the catalyst, and Dimersol[®] units, which typically use liquid organometallic compounds as the catalyst.

Alkylation: Olefins of 3 to 5 carbon atoms (e.g., from catalytic cracking and coking) react with isobutane (e.g., from catalytic cracking) to give high octane products. Sulfuric (H₂SO₄) or hydrofluoric (HF) acid act as catalysts.

Isomerization: Isomerization converts straight chain paraffins in gasoline stocks into higher octane isomers. Isomer and normal paraffins are separated; normal paraffins are then catalytically isomerized. Precious metal catalysts are used in this process.

Extraction: Extraction is a separation process using differences in solubility to separate, or extract, a specific group of compounds. A common application of extraction is the separation of benzene from reformate.

Lube Oil Processing: Vacuum distillates are treated and refined to produce a variety of lubricants. Wax, aromatics, and asphalts are removed by unit operations such as solvent extraction and hydroprocessing; clay may also be used. Various additives are used to meet product specifications for thermal stability, oxidation resistances, viscosity, pour point, etc.

Residual Upgrading: Vacuum tower distillation bottoms and other residuum feeds can be upgraded to higher value products such as higher grade asphalt or feed to catalytic cracking processes. Residual upgrading includes processes where asphalt components are separated from gas oil components by the use of a solvent. It also includes processes where the asphalt value of the residuum is upgraded (e.g., by oxidation) prior to sale.

Blending and Treating: Various petroleum components and additives are blended to different product (e.g., gasoline) specifications. Clay and caustic may be used to remove sulfur, improve color, and improve other product qualities.

Sulfur Recovery: Some types of crude typically contain high levels of sulfur, which must be removed at various points of the refining process. Sulfur compounds are converted to H₂S and are removed by amine scrubbing. The H₂S often is converted to pure sulfur in a Claus plant. Off-gases from the Claus plant typically are subject to tail gas treating in a unit such as a SCOT[®] treater for additional sulfur recovery.

Light Ends (Vapor) Recovery: Valuable light ends from various processes are recovered and separated. Fractionation can produce light olefins and isobutane for alkylation, n-butane for gasoline, and propane for liquid petroleum gas (LPG). Caustic may be used to remove sulfur compounds.

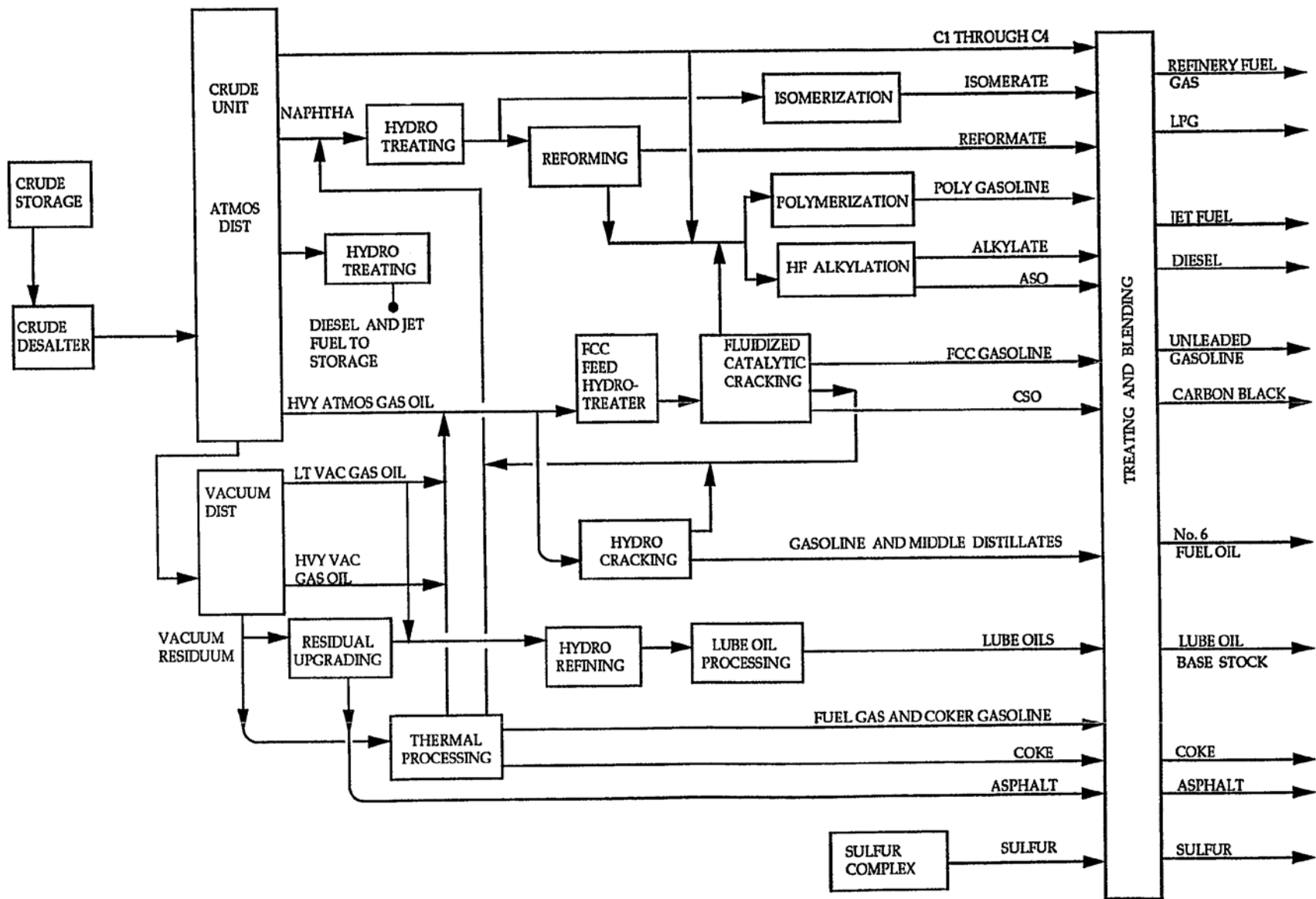


Figure 6-11. "Simplified refinery process flow diagram" (US EPA, 1996)

6.1.4 Refinery NHIW categories

According to SAIC, “refinery solid wastes consist primarily of processing residual sludges. They are categorized according to constituent materials and generating processes and are classified generally as 1) oily process sludges, 2) non-oily wastes, 3) biological sludges, 4) miscellaneous, and 5) sanitary wastes. Various classification systems have been devised for refinery solid wastes, but because of the large diversity within the industry, none is complete or accurate enough to satisfy all industry members and regulating agencies” (US EPA, 1985).

Solid residual wastes and the refinery process steps that produce them are listed in Table 6-3. Descriptions of the residual wastes used by API and SAIC in their studies published in the 1980s are listed in Table 6-4; certain wastes that were considered non-hazardous then but later listed are excluded.

Table 6-3. Summary of residual wastes from petroleum refining (Cheremisinoff & Rosenfeld, 2009, pp. 33–34).

Refinery Process	Residual waste stream
Crude oil desalting	Crude oil/desalter sludge—includes iron rust, clay, sand, water, emulsified wax, metals
Atmospheric distillation / vacuum distillation	Minimal to no residual waste stream
Thermal cracking / visbreaking	Minimal to no residual waste stream
Coking	Coke dust—hydrocarbons and carbon particles
Catalytic cracking	Spent catalysts (metals from crude oil and hydrocarbons), spent catalyst fines from electrostatic precipitators (aluminum silicate and metals)
Catalytic hydrocracking	Spent catalyst fines—includes metals from crude oil and hydrocarbons
Hydrotreating / hydroprocessing	Spent catalyst fines—includes aluminum silicate and metals
Alkylation	Neutralized alkylation sludge—includes sulfuric acid, calcium fluoride, and hydrocarbons
Isomerization	Calcium chloride sludge from neutralized HCL gas
Polymerization	Spent catalyst containing phosphoric acid
Catalytic reforming	Spent catalyst fines from electrostatic precipitators—includes alumina silicate and metals
Solvent extraction / dewaxing / propane deasphalting	Little to no residual waste generated
Mercox treating	Spent caustic solution, waste oil—disulfide mixtures
Wastewater treatment	API separator sludge (phenols, metals, oil), chemical precipitation sludge (chemical coagulants, oil), DAF floats, biological sludge, spent lime

Table 6-4. Descriptions of non-hazardous wastes from petroleum refining (US EPA, 1985)

Crude oil tank bottoms: Accumulations of fine inorganic materials, clay, silt, sand, tank scale, occluded oil, and wax, form sludge in the bottoms of crude oil storage tanks. The composition and buildup rates vary with the nature of the crude oil, added chemicals, detection time, and the type of storage system incorporated. Some installations have stirring mechanisms that keep solids in suspension until transfer to refining operations. Cleaning of storage tanks varies from every year to every 10 years.

Distillate and residual product storage tank bottoms: Similar sludges form in storage tanks holding intermediate and final products. The characteristics of the sediment that forms in these tanks also is dependent upon the type of crude, chemical additives used, and whether or not tank mixers are incorporated. Additional factors are the distillate cut, recovered oil processing methods, the metallurgy of tanks and processing equipment used upstream from the tanks, and processes used to produce gasoline blend components.

Once through cooling water sludge: Cooling waters are used in large quantities. Occasionally, source water is not of sufficient quality to be used directly and must be treated both before and after system flow-through. Settling ponds are used to allow suspended solids to precipitate from the water, forming a sludge that requires periodic removal and disposal. The sludge is made up of solids from the system source water, corrosion products, and occasionally residual flocculent chemicals such as alum used to settle colloidal organics and silts.

Cooling tower sludge: Suspended particulates settle out of cooling tower effluent in settling basins and are removed periodically either by washing into the process sewer system or by direct removal and disposal. Cooling tower sludge typically have contained a significant amount of chromium resulting from use of chromium-bearing corrosion inhibiting additives, although these additives now are being replaced by polymer type rust inhibitors.

Biological sludge: Secondary wastewater treatment processes, including activated sludge, rotating biological contractors, trickling filters, aerated lagoons, and stabilization ponds produce large quantities of organic residuum synthesized by micro-organisms in the course of aerobic degradation of hydrocarbon-contaminated wastewaters. The primary collection method is in secondary clarifiers. Generation rates vary with different types of biological treatment processes, desired levels of purification, and raw waste load. Bio-sludge can contain up to 80 to 90 percent water prior to dewatering. Chromium and zinc values in bio-sludge are often quite high.

Fluid catalytic cracker catalyst fines: Flue gases from cracking operations contain fine particles of catalyst, most of which are captured in cyclone filters and returned to the furnace. Electrostatic and other type precipitators remove remaining catalyst fines from emissions. These are recovered sometimes, but usually are disposed.

Spent catalyst: Processes such as catalytic reforming, hydrodesulfurization, hydrotreating, hydrocracking, steam hydrocarbon reforming, and others require fixed-load catalysts, which become inactive after a certain amount of time, usually 6 months to 3 years. Most of these catalysts contain significant amounts of precious metals and are shipped to an off-site facility for recovery, or are sold. The remaining spent catalyst is disposed as solid waste.

Table 6-4. (Cont.)

Treating clays: Clay minerals are added to various stocks of gasoline, kerosene, jet fuels, and light fuel oil to absorb moisture and impurities. Much larger volumes of clays are used similarly to treat lube oils, waxes, and polymers. The clay particles are removed from product fluids by filtering. Periodic cleaning of filters produces material that is regenerated, treated prior to disposal, or disposed directly. Quantities and characteristics of the final disposed waste are affected by the type of clay used, the type of treating process, and the quantities and characteristics of the products treated.

HF alkylation sludge: Hydrofluoric alkylation generates residual spent acid, which is neutralized either with lime or with spent lime solution from boiler feedwater and disposed.

Storm water runoff: periods of precipitation, surface runoff carries oily films and other contaminants washed from refinery surfaces into storm drains, where it normally is channeled to water treatment operations or settling ponds. Factors that affect the quantities and characteristics of the resulting sludge are climate, topography, the type of process operations conducted in the refinery, facility size, and housekeeping practices.

6.1.5 Hazardous waste generation in the US

Petroleum refining is the second-largest generator of hazardous wastes in the US (6 million Mg in 2011),⁵⁶ behind NAICS 3251—Basic chemical manufacturing (BR). The triangulation method used in this research does not strictly require the consideration of hazardous wastes, but in this case, such a large tonnage of hazardous waste is generated by the industry that it must be acknowledged, even if the data are not formally incorporated into any of the estimation methods.

RCRA Subtitle C gives the EPA the authority to designate wastes as hazardous. “A waste may be considered hazardous if it exhibits certain hazardous properties (‘characteristics’) or if it is included on a specific list of wastes EPA has determined are hazardous (‘listing’ a waste as hazardous) because [they were found] to pose substantial present or potential hazards to human health or the environment” (US EPA, 2008, p. 5). Characteristic wastes (“D” wastes) are defined according to four properties: ignitability (D001), corrosivity (D002), reactivity (D003), and toxicity (D004–D043). Listed wastes are further classified as non-source-specific wastes (“F”), source-specific wastes (“K”), and discarded commercial chemical products (“P” and “U”). For the petroleum refining industry, the EPA had originally listed five K-wastes (API, 1983):

- Dissolved air flotation (DAF) float (K048): Flotation waste generated from treatment of refinery wastewater.
- Slop oil emulsion solids (K049): The residual left in the emulsion layer after treatment in the slop oil tank, i.e. the emulsion which cannot be broken.
- Heat exchanger bundle cleaning sludge (K050): Sludge from the cleaning of heat exchanger bundles within the refinery used in cooling.
- API separator sludge (K051): Wastewater treatment sludge generated from the oil/water/solids separator.
- Leaded tank bottoms (K052): The waste generated from cleaning out a leaded gasoline storage tank.

RCRA has a mechanism for ongoing review of industrial wastes to determine whether or not they should be listed. The EPA was not performing this obligation, and was sued by the Environmental Defense Fund in 1989, resulting in a consent decree requiring the EPA consider an additional 29 wastes from the petroleum industry (US EPA, 1996b). Following extensive study, four more wastes were listed (K169–K172). The entire list of hazardous wastes from the petroleum refining industry, including source- and non-source-specific listed wastes and relevant characteristic wastes, can be found in Table 6-5.

⁵⁶ This tonnage is most likely reported on a wet basis.

Table 6-5. “Hazardous wastes associated with petroleum refining (US DOE, 2007, p. 33)

EPA Waste Classification	Summary Description	Hazardous Constituents
<i>Characteristic: Corrosivity</i>		
D002	Spent sulfuric acid (from alkylation process)	Sulfuric acid
<i>Characteristic: Reactivity</i>		
D003	Sulfur (on spent catalyst surfaces)	Sulfur
<i>Characteristic: Toxicity</i>		
D007	Non-specific residuals containing chromium	Chromium
D008	Non-specific residuals containing lead	Lead
D018	Non-specific residuals containing benzene	Benzene
<i>Listed: Non-source-specific</i>		
F037	Petroleum refinery primary oil/water/solids separation sludge from gravitational separation of process waters and oily cooling waters	Benzene, benzo(a)pyrene, chrysene, lead, chromium
F038	Petroleum refinery secondary (emulsified) oil/water/solids separation sludge from physical and/or chemical separation of process wastewaters and oily cooling waters	Benzene, benzo(a)pyrene, chrysene, lead, chromium
<i>Listed: Source-specific</i>		
K048	Dissolved air flotation (DAF) float	Hexavalent chromium, lead
K049	Slop oil emulsion solids	Hexavalent chromium, lead
K050	Heat exchanger bundle cleaning sludge	Hexavalent chromium
K051	API separator sludge	Hexavalent chromium, lead
K052	Leaded tank bottom corrosion solids	Lead
K169	Crude oil storage tank sediment from petroleum refining operations	Benzene
K170	Clarified slurry oil tank sediment and/or in-line filter/separation solids from petroleum refining operations	Benzene, benzo(a)pyrene, dibenz(a,h)anthracene, benzo(a)-anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, 3-methylcholanthrene, 7,12-dimethylbenz(a)anthracene
K171	Spent hydrotreating catalyst from petroleum refining (does not include inert support media)	Benzene, arsenic
K172	Spent hydrotreating catalyst from petroleum refining	Benzene, arsenic

6.2 Historical forecasting

The historical forecasting estimation method is applied in this section to the petroleum refining industry. First, seven distinct data sources on waste from 1967–1992 are presented. Of these, the baseline data are selected and forecasted to the year 2010 by tracking the change in total refinery input (volumetric). The results of the forecasting are discussed in the context of waste hazard, wet vs. dry mass, and waste composition.

6.2.1 Data sources

The first post-EPA-era studies of petroleum refining industry waste were conducted to better understand the risk of industrial hazardous wastes. A 1973 report commissioned by the EPA under its authority provided by the Resource Recovery Act of 1970 to “quantif[y] the hazardous waste problem” in the US (US EPA, 1974a, p. 1) estimated a total of 2.1 million Mg of industrial waste generated by facilities classified under SIC code 2911—Petroleum Refining in the year 1967 (US EPA, 1973b). The wastes included in this estimate were almost all discharged to waterways, and were most likely reported in wet-basis tons.

In 1974, as part of a 13-industry series of studies designed to ultimately support the EPA’s “technical assistance efforts or preparation of hazardous waste guidelines” (Lehman, 1976, p. 10), the EPA contracted with the Jacobs Engineering Co. to “assess the hazardous waste practices of the petroleum refining industry” (US EPA, 1976a, p. 1). Based on a detailed analysis of 16 refineries and 21 waste categories⁵⁷ (17 of which were quantified and tabulated), Jacobs estimated that the industry generated about 0.72 million Mg (dry basis) of waste in 1974, containing 0.61 million Mg of inert solids, 0.11 million Mg of oil, and just 1,000 Mg of hazardous substances (see Table 6-6). The largest components of this waste were spent lime (from boiler feedwater treatment), non-leaded tank bottoms, filter clays, FCC catalyst fines, and API separator sludge. The study also estimated the waste was generated in about 1.1 million Mg of process water, yielding a total of 1.8 million Mg⁵⁸ (US EPA, 1976a, p. 14).⁵⁹

⁵⁷ Page 10 of the report lists 20 waste categories, but #2, “leader or non-leaded tank bottoms” is split into two in the analysis. The report explains why the remaining four wastes types were excluded from analysis. Only one, silica gel was excluded due to expected lack of hazardous substances.

⁵⁸ The missing 0.1 million Mg is due to rounding.

⁵⁹ There is some confusion about the precise results from this study. In the executive summary (p. 14), Jacobs reports 1,132,092 Mg of water and 624,541 Mg of solids including hazardous constituents, on a wet weight basis. On the other hand, the results of the data extrapolation (pp. 108–109), reproduced in Table 6-6, claim a total 723,028 Mg (dry basis) of hazardous components, inert solids, and oil. Using the reported values of “% water,” this waste was generated in 812,459 Mg of process water. Further complicating things, Lehman (1975) reports 674,000 Mg (dry) and 1,440,000 Mg (wet) of hazardous waste from what must have been a draft version of the Jacobs study. The Jacobs report includes multiple appendices, including detailed waste data from four of the 16 refineries studied,

At this time, there was not a uniform standard for assessing waste hazard; the EPA left that task up to the contractors conducting each of the industry studies. Jacobs considered the hazard of each refinery waste category based on the concentration of 20 toxic substances—14 metal elements, two inorganic compounds, and four organic compounds (including oil). Hazardous materials were found in all of the studied waste streams, albeit at varying concentrations. Because the hazardous substances were so pervasive, it is not inconceivable that all of the waste generated by this industry in 1974 would be considered hazardous under RCRA today. But then again, that highlights the point of the law. Responsible handling and disposal of hazardous waste represents a substantial financial burden to the waste generator; an economically rational industrial actor would see those costs and make the necessary investments in the plant to at least isolate, if not reduce, the hazardous materials, thereby reducing cost of RCRA compliance.

Even though the objective of the Jacobs study was to estimate hazardous waste generation, the exploratory nature of the research and pervasiveness of hazardous substances actually make this a pretty good estimate for NHIW, at the time. One simply has to take total waste generation and subtract the amount of hazardous substances to arrive at the inert component. The data from the study suggests that a relatively small amount of hazardous and toxic material is enough to contaminate a much larger tonnage of total industrial waste.

In 1976, the API conducted its own survey of waste from the U.S. refinery fleet, collecting data on generation, oil and solids content, and heavy metals composition of 10 waste types (API, 1980). The survey resulted in a national estimate of 0.36 million Mg (dry) of industrial waste. In the Jacobs study, this same subset of wastes is responsible for just 0.24 million Mg out of a total 0.72 million Mg (dry), suggesting that the wastes overlooked by the API survey are actually quite important to painting the whole waste picture of the industry.⁶⁰

The next survey of refinery waste was motivated by an unlikely source. In 1978, the EPA Office of Air Quality Planning and Standards (OAQPS) contracted with Radian Corp. to determine “the need to control volatile organic carbon (VOC) emissions from the handling and disposal of wastes from the U.S. Petroleum Refining Industry” (US EPA, 1979b, p. 1). Just as Jacobs surveyed the entire refinery waste stream to determine hazard, Radian surveyed a broad swath of the refinery waste stream to determine any sources of VOC. Radian’s sample size was 34 refineries. The survey inquired about tonnage and composition of 20 waste categories, then calculated waste intensity for each based on reported or tabulated refinery capacity data. The authors also calculated a 95% confidence interval of these intensity factors. The intensity factors were used to estimate the industry-wide waste generation to be about 0.69 million Mg (dry basis)

which may be capable of explain the different numbers, but this is merely a context-setting section, so I let the mystery go.

⁶⁰ I was unable to locate a copy of the *1976 API Refinery Solid Waste Survey* (API, 1978), so there may in fact be more information contained therein that I have been able to ascertain.

(Table 6-7). The 95% confidence interval is almost comically wide: 0.14 million Mg to 3.7 million Mg. This range reflects the variation in waste generation (or at least reported generation) from refinery to refinery.

Although the Radian report concluded that existing data was insufficient to satisfy the particular request of OAQPS, it does serve adequately as another data point about waste generation. The total results closely resemble those of Jacobs: 0.72 million Mg (Jacobs) vs. 0.69 million Mg (Radian). However, the specifics of waste composition are different between the two studies, with storm silt, waste FCC catalyst, and biosludge contributing the most according to Radian and spent lime, non-lead tank bottoms, and filter clays the most according to Jacobs. Isolating the list to the same few examined by API in 1976, the differences become starker, with Jacobs reporting 0.24 million Mg, API reporting 0.36 million Mg, and Radian reporting 0.55 million Mg (albeit with a 95% confidence interval from 0.13 million Mg to 2.5 million Mg), all dry basis.

Following the passage of RCRA and implementation of the other environmental laws of the 1970s, the petroleum refining industry underwent considerable changes that “significantly affected the actual or perceived volume and composition of [its] solid and hazardous waste streams” (API, 1983, p. 1-1). This prompted API to conduct another survey of the industry, with a number of key changes and improvements on the surveys of the previous decade. Being the first post-RCRA survey, API distinguished between listed and non-listed wastes, referring to those waste flows that were designated categorically by the EPA as being hazardous (in part as a result of some of the studies discussed above) vs. others whose hazard needed to be considered characteristic by characteristic (i.e. toxicity, ignitability, reactivity, and corrosivity). The 1982 API survey inquired about five listed wastes and 10 non-listed wastes.

Another change was to distinguish between waste at point of generation and waste at point of disposal. Not only are there storage options in between the generation and ultimate disposal of industrial waste, there is also the possibility of recycling, dewatering, and other on-site treatment that would change the tonnage and composition of the waste flows.

The survey received responses from facilities representing 76% of total U.S. refining capacity, with most of the remaining 24% representing small-to-medium refineries. Reported waste tonnages were then scaled up by this figure. The results from the scaling are presented in Table 6-8. On a wet basis, there is approximately 25% more listed waste than non-listed waste generated by the industry, but that ratio is reversed for disposal. This swing is some evidence that RCRA works. The elevated cost of hazardous waste disposal caused the refineries to more aggressively pre-treat the listed wastes, all of which are hazardous, as compared with the non-listed wastes, less of which are intended to be hazardous. On the other hand, much of the swing can also be explained by a single outlier data point: one mill reporting 1 million Mg of API separator sludge generated, but after dewatering, just 25,000 wet Mg disposed.

The survey asked for mass data on waste generated/disposed and compositional fraction of water, solids, and oil. I used these fractions to estimate the tonnage of water, solids, and oil of each waste type. The total of these three components exceeds the total reported wet mass because the sum of the reported fractions exceeded unity. But proportionally, the results should hold. In total, this survey reveals that the industry generated 1.9 million Mg (dry-basis) and disposed 0.64 million Mg of waste. These mass flows include 44% listed waste in generation and 43% listed waste in disposal. The estimated disposal value from this survey lines up well with results from the previous surveys discussed above. The difference between generation and disposal is considerable, with the largest change apparently due to on-site catalyst regeneration.

There is insufficient data here to determine how much of the waste reported is non-hazardous. Certainly the listed wastes are treated as hazardous, but the results of the characteristic testing procedure conducted in this study suggest that the listed wastes were not necessarily that much more hazardous than non-listed wastes.

The 1982 API survey was the primary data source used by SAIC in their 1985 report to the EPA (US EPA, 1985). However, somehow SAIC did not realize that the figures reported by API were already representative of 100% of national refining capacity, not just the 76% that responded to the survey. So, SAIC scaled the figures up again, which makes them represent an industry a full 24% larger than actually existed in 1981, and they should be disregarded.

API conducted its next survey of refinery waste generation and management in 1989, collecting data from the previous two years (API, 1991). The objective of the study was to “generate data that could be used in a variety of contexts, including waste minimization,” and so defined waste quite broadly, “including hazardous and non-hazardous waste and secondary materials that might otherwise be considered byproducts or recyclable materials” (Bush & Levine, 1992, p. 73). The survey was completed by refineries representing 80% of domestic refining capacity, and yielded a top-line estimate of 14.5 million Mg (wet basis) of waste per year, which amounts to less than 3% of the total crude oil input.

The results of the 1987–1988 API survey are presented in Table 6-9. Having two years of data provides the analyst with the opportunity to identify outlier waste flows that might only occur once and skew the results; as it turns out this precaution was unnecessary. The actual outlier data came in the form of four refineries reporting vast quantities of “other aqueous wastes NOS.” These same refineries reported use of deep well injection disposal, which, according to API, does not require any wastewater treatment. Excluding these outliers, the results become 4.4–4.5 million Mg (wet-basis) per year, very close to the reported generation rates from the 1982 API survey above.

Listed wastes that were represented in the survey are indicated in the table. Wastes K048–K052 were listed at the time of the survey, but K171–2 were added later. For the three large volume listed wastes, API separator sludge, DAF float, and slop oil emulsion solids, the wet tonnage is lower than that reported in the 1982 API survey. The 1987–1988 survey did not ask about waste

characteristics, so there is no way to determine the relative hazard of the non-listed wastes. This survey also did not ask about water and oil composition, making it difficult to assess the dry mass of the reported waste flows. A back-of-the-envelope estimate is possible using the fractions reported in 1982: 62% water, 30% solid, 8% oil. Using these factors, 1988 waste totals 1.7 million Mg (dry).

The final data point available for historical forecasting comes with a poetic sense of recapitulation, as it again follows from the EPA's effort to better characterize hazardous waste from the petroleum refining industry. As the result of a lawsuit from the Environmental Defense Fund, the EPA consented to study a list of petroleum refining wastes and consider them for listing (US EPA, 1996b). The EPA distributed a survey to 180 domestic refineries under their RCRA §3007 inspection authority asking about the management of 29 waste categories (data is reported for 31 categories because two of the original categories were each split in two). The survey revealed a total of 3.3 million Mg (wet) for the year 1992 (Table 6-10). However, the survey excluded the five previously listed wastes (K048-K052), which totaled 1.1–1.2 million Mg (wet) in the 1987–1988 API survey.

These seven studies can be stitched together into a narrative about the evolution of the petroleum industry, the regulatory apparatus, waste accounting, and waste generation and treatment. They also provide ample raw data for the historical forecasting task.

Throughout the 1990s, API conducted a series of annual refining residual studies that started with the 1987–1988 study. It appears as if the series ended with the 1997 study published in 1999.⁶¹ These reports are not owned by the MIT Libraries, and were not located in time to integrate them into this analysis.

⁶¹ API publications catalog: <http://www.api.org/Publications-Standards-and-Statistics/Publications/Publications-Catalog>

Table 6-6. Results from the Jacobs study of solid and hazardous wastes from the petroleum refining industry in the US, 1974 (US EPA, 1976a, pp. 108–109).

Waste stream	Hazardous components	Inert solids	Oil	H ₂ O
	<i>Mg (dry)</i>			(%)
API Separator Sludge	45.7	32,624	24,900	53
Coke Fines	3.7	3,466	0	0
Cooling Tower Sludge	0.7	111	2	75
Crude Tank Bottoms	0.3	650	356	13
Dissolved Air Flotation (DAF) Float	17.5	10,814	8,660	82
Exchanger Bundle Cleaning Sludge	0.9	619	138	53
FCC Catalyst Fines	21.6	30,978	65	0
Kerosene Filter Clays	0.4	4,140	153	0
Leaded Tank Bottoms	6.0	1,654	335	1
Lube Oil Filter Clays	13.1	51,237	3,627	45
Neutralized HF Alkylation Sludge	812.0	6,858	1,200	54
Non-Leaded Tank Bottoms	18.1	68,452	53,200	18
Once-through Cooling Water Sludge	18.4	28,112	161	25
Slop Oil Emulsion Solids	31.2	20,269	12,180	40
Spent Lime from Boiler Feedwater Treatment	20.1	319,980	2,500	59
Storm Water Silt	25.2	22,600	1,145	25
Waste Bio Sludge	36.7	10,543	228	87
TOTAL	1,071.6	613,106	108,850	

Table 6-7. Results from the Radian study of “solid waste generation of the entire U.S. petroleum refining industry,” 1978 (US EPA, 1979b, p. 23)

Waste stream	Mg (dry)	95% confidence interval
Slop Oil Emulsion Solids	59,380	9,690 – 28,720
Silt from Storm Water Runoff	139,900	16,390 – 923,200
Exchanger Bundle Cleaning Sludge	690	90 – 3,700
API Separator Sludge	51,090	21,500 – 94,090
Nonleaded Gasoline Tank Bottoms	900	80 – 72,200
Crude Tank Bottoms	14,450	2,470 – 56,460
Other Storage Tank Bottoms	21,500	230 – 149,800
Leaded Gasoline Tank Bottoms	4,400	1,070 – 13,920
Dissolved Air Flotation Skimmings	76,110	24,670 – 174,400
Kerosene Filter Clays	2,470	550 – 8,100
Other Filter Clays	44,930	4,230 – 378,800
HF Alkylation Sludge	34,180	2,100 – 421,100
Waste Bio-Sludge	97,790	22,380 – 361,200
Once-Through Cooling Water Sludge	2,470	0 – 47,570
FCC Catalyst	99,370	37,000 – 123,300
Coke Fines	35,770	880 – 815,800
Spent Amines	18	0 – 350
Salts from Regeneration	-	-
Ship and Barge Ballast	-	-
Other	2,290	140 – 23,300
TOTAL	687,708	143,470 – 3,695,950

Table 6-8. Waste from the US petroleum refining industry, 1981 (API, 1983). Total waste disposed includes net removals from storage. Inconsistency between wet- and dry-basis mass is due to the total of the reported composition fractions >100%. The “characteristics” columns include the percent of wastes tested that exceed the EPA hazard threshold. (T = Extraction Procedure Toxicity; I = Ignitability; R = Reactivity; C = Corrosivity)

Waste Stream	Total waste		Waste composition (Gg-dry basis)						Characteristics			
	(Gg-wet basis)		Generation			Disposal			(% of total)			
	Gener.	Disp.	H ₂ O	Solids	Oil	H ₂ O	Solids	Oil	T	I	R	C
Listed												
API Separator Sludge	1,886	358	1,271	398	238	211	100	47	13	20	8	0
DAF Float	652	281	534	61	57	211	39	31	12	18	13	0
Slop Oil Emulsion Solids	236	131	149	37	51	79	30	25	18	19	5	0
Leaded Tank Bottoms	5	5	2	3	0	2	3	0	26	29	14	0
Heat Exch. Bundle Cleaning Solids	1	1	0	1	0	0	1	0	11	19	12	5
<i>Listed Waste Total</i>	<i>2,779</i>	<i>776</i>	<i>1,956</i>	<i>500</i>	<i>346</i>	<i>503</i>	<i>173</i>	<i>103</i>	<i>16</i>	<i>21</i>	<i>10</i>	<i>1</i>
Non-listed												
Primary oil/solids/water separator sludge	70	63	40	21	10	34	22	8	12	54	0	8
Secondary oil/solids/water separator sludge	9	6	5	3	0	2	3	1	0	0	0	0
Biological Sludge	1,013	637	927	83	10	544	91	6	14	0	9	4
Cooling tower sludge	16	13	11	5	0	9	4	0	19	0	0	6
HF Alkylation sludge	31	28	22	9	2	17	11	1	0	0	0	11
FCC Catalyst	871	120	131	839	9	23	113	1	13	4	4	4
Other spent catalysts	16	15	2	15	1	2	14	1	29	0	6	30
Stretford Solution	43	35	41	2	0	33	2	0	40	0	0	0
Non-leaded tank bottoms	113	107	40	52	26	36	53	21	9	47	4	0
Treating clays	11	11	2	9	1	2	9	1	14	17	9	7
<i>Non-listed Waste Total</i>	<i>2,195</i>	<i>1,036</i>	<i>1,221</i>	<i>1,038</i>	<i>59</i>	<i>701</i>	<i>322</i>	<i>41</i>	<i>15</i>	<i>17</i>	<i>5</i>	<i>8</i>
TOTAL	4,974	1,718	3,177	1,538	405	1,204	495	144				

Table 6-9. Results from the 1987–1988 API survey on waste generation in the US petroleum refining industry (API, 1991).

Waste Stream	1987	1988	RCRA Listing
	<i>(Gg-wet basis)</i>		
Oily Sludges and Other Organic Wastes			
API Separator Sludge	363	322	K051
DAF Float	591	594	K048
Slop Oil Emulsion Solids	189	203	K049
Leaded Tank Bottoms	8	7	K052
Other Separator Sludges	72	94	
Pond Sediments	306	241	
Nonleaded Tank Bottoms	196	117	
Waste Oils/Spent Solvents	4	6	
Other Oily Sludges/Inorg Wastes	34	55	
Contaminated soil/solids			
Heat Exch Bundle Cleaning Solids	3	5	K050
Contaminated Soil/Solids	150	218	
Waste Coke/Carbon/Charcoal	39	61	
Waste Sulfur	15	20	
Other Contaminated Soils NOS	74	62	
Spent catalysts			
FCC Catalyst or Equivalent	157	175	
Hydroprocessing Catalysts	36	33	K171-2
Other Spent Catalysts NOS	30	34	
Aqueous wastes			
Biomass	687	713	
Oil Contaminated Water NOT Wastewater	25	33	
High pH/Low pH Waters	131	125	
Spent Sulfite Solution	38	36	
Spent Stretford Solution	32	44	
Other aqueous wastes NOS	26	25	
<i>Other aqueous wastes NOS outliers</i>	<i>10,219</i>	<i>10,021</i>	
Chemicals/inorganics wastes			
Spent Caustics	612	595	
Spent Acids	114	135	
Waste Amines	12	13	
Other Inorganic Wastes NOS	295	193	
Other Wastes NOS	184	374	
TOTAL	4,423	4,533	
<i>With outliers</i>	<i>14,643</i>	<i>14,553</i>	

Table 6-10. Waste from the US petroleum refining industry, 1992 (US EPA, 1996b; 1996c)

Waste Stream	Gg (wet)	RCRA Listing
Sludges/Sediments		
Clarified slurry oil (CSO) sludge from catalytic cracking	24	K170
Unleaded gasoline storage tank sludge	4	
Crude oil storage tank sludge	22	K169
Process sludge from sulfur complex and H ₂ S removal facilities	9	
Sludge from HF alkylation	11	
Sludge from H ₂ SO ₄ alkylation	1	
Desalting sludge from crude desalting	5	
Residual oil storage tank sludge	9	
Process sludge from residual upgrading	0	
Catalysts		
Catalyst from catalytic hydrotreating	6	K171
Catalyst from catalytic reforming	4	
Catalyst from catalytic cracking (FCC catalyst)	124	
Fines from catalytic cracking (FCC fines)	68	
Catalyst from catalytic hydrorefining	19	K172
Catalyst from H ₂ SO ₄ alkylation	1,760	
Catalyst from sulfur complex and H ₂ S removal facilities (Claus)	4	
Catalyst from sulfur complex and H ₂ S removal facilities (Tail gas treating catalysts)	0	
Catalyst from extraction/isomerization processes	0	
Catalyst from catalytic hydrocracking	18	
Catalyst from polymerization	4	
Catalyst from HF alkylation	0	
Off-spec Products		
Off-spec product and fines from thermal processes (Off-spec coke and fines)	194	
Off-spec product and fines from residual upgrading	1	
Off-spec product from sulfur complex and H ₂ S removal facilities (Off-spec sulfur)	10	
Treating clays		
Treating clay from clay filtering	9	
Treating clay from lube oil processing	1	
Treating clay from the extraction/isomerization process	3	
Treating clay from alkylation	3	
Miscellaneous Residuals		
Spent caustic from liquid treating	918	
Spent amine and spent Stretford solution	24	
Acid-soluble oil from HF alkylation (ASO)	34	
TOTAL	3,286	

6.2.2 Baseline

As it turns out, neither EPA estimate that was explicitly focused on NHIW is a sufficient baseline for the forecasting analysis. The SAIC report arbitrarily increases empirical data by 24%, while, as we have seen repeatedly, the Survey of Industrial Subtitle D sites almost categorically vastly overstates disposal tonnages, not to mention lacking any compositional differentiation.

Conceivably, any of the other estimates above could serve as adequate baseline data. Many of the totals agree with one another, at least if examined with consistent system boundaries. There are remain open questions regarding the specific tradeoffs between hazardous and non-hazardous wastes, listed vs. characteristic wastes, wet vs. dry basis mass, and generation vs. disposal.

The general heuristic is to use the most recent assessment of waste to generate a forecast, but as presented above, it is unclear which of the many surveys is the most accurate. Certainly, it would be prudent to select one (or more) of the studies conducted after the early 1980s, as the effects of EPA regulation will have dramatically changed waste generation patterns from the 1970s. Nevertheless, details from those early studies regarding hazardous substances and composition can still be useful.

6.2.3 Forecast

Using the change in total refinery volumetric inputs as the tracking indicator (Figure 6-2), the results from the last four industry-wide estimates of waste from the petroleum refining industry are forecast to the year 2010. These surveys yielded data on listed and non-listed wastes in wet-basis tons. The forecast was based on non-listed wastes only, correcting for the hazardous wastes that were listed after the surveys were conducted. The forecast is presented in Figure 6-12.

By isolating the data to non-listed wastes, the forecasts based on the 1987, 1988, and 1992 surveys agree well with each other, at least in aggregated terms, totaling about 4 million Mg (wet basis). The earlier baseline, from 1981, is in less agreement with the other three. This is possibly due to changes in survey scope, and possibly due to a shift in the generation of listed to non-listed wastes as refineries better isolated the hazardous substances. The compositions of the waste as forecasted by the 1987–1988 API survey and the 1992 RCRA §3007 survey are very different, as illustrated in Table 6-11, which presents composition at level of categories as defined in each of the survey reports. The API survey identifies aqueous wastes and chemicals/inorganics wastes as the largest contributors to refining waste generation, while the RCRA survey identifies waste catalysts and miscellaneous residuals as the largest. Referring back to Table 6-9 and Table 6-10, the largest individual waste streams from 1987–1988 were spent caustics and biomass, while the largest from 1992 were catalysts from H₂SO₄ alkylation and spent caustics. This suggests that there is at least some agreement between the surveys, even if the classification and categorization of the wastes differ substantially.

The two later surveys also do not provide any guidance as to the contained dry mass of the waste. For this, I turn to the last survey to have that information, the 1982 API survey. Forecasting the dry weight of non-listed waste from 1981 yields an estimate of 1.4 million Mg (dry) of solids and oils (. That survey also suggests that, on average, total refinery wastes (listed and non-listed) were 62% water, 30% solid, and 8% oil, fractions that can be used to estimate dry weight from subsequent surveys. Although the non-listed wastes from 1981 were reported to have a different composition of water, solid, and oil, I use the total breakdown (including listed wastes) for two reasons. First, using data representative of the largest system boundary seems the most representative of general industry activity. Second, there is some evidence that in 1981 non-hazardous materials in listed wastes may have been diverted to non-listed wastes through process improvements, possibly without changing the liquid/solid ratios. A third ex post justification for the selection of the 62/30/8 breakdown comes from examining the results of the composition analysis, which shows remarkable agreement among results from all four baseline years, between 1.4 and 1.6 million Mg (dry) of solids and oil. Of course, this could all be a coincidence as well.

The application of the generic, high level composition ratio is not appropriate for any specific, lower level waste categories. It might be possible to extract more detailed information from the 1982 API survey to facilitate estimating dry mass of particular waste streams, but that was deemed out of scope here.

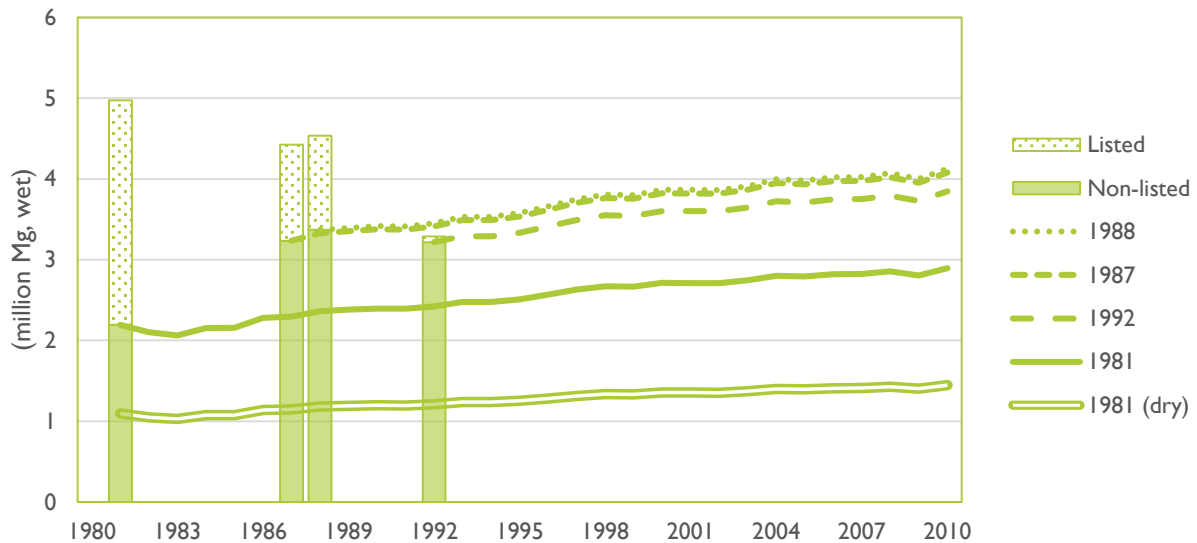


Figure 6-12. Forecast of petroleum refining industry waste to 2010.

Table 6-11. Results of the forecast broken down by waste category defined by source surveys.

Waste Category	2010			Waste Category	2010
	(1985)	(1987)	(1988)		(1992)
	Gg (wet)				Gg (wet)
Oily sludges and other organic wastes		772	628	Sludges/sediments	47
Contaminated soil/solids		351	442	Catalysts	2,369
Spent catalysts		236	256	Off-spec products	245
Aqueous wastes		1,185	1,196	Treating clays	19
Chemicals/inorganics wastes		1,303	1,147	Miscellaneous residuals	1,166
Other wastes NOS		232	458		
TOTAL	153,000	4,079	4,127		3,846

Table 6-12. Wet and dry composition of forecasted wastes. 1981 baseline uses empirical data from the 1982 API survey, and the other three baselines use the fractions indicated in the table, which are the weighted averages of all wastes from 1981, listed and non-listed.

		2010	2010	2010	2010
		(1981)	(1987)	(1988)	(1992)
		Gg (dry)			
Solid	30%	1,369	1,224	1,238	1,154
Oil	8%	78	326	330	308
<i>Subtotal</i>		<i>1,447</i>	<i>1,550</i>	<i>1,568</i>	<i>1,461</i>
H ₂ O	62%	1,610	2,529	2,559	2,384
Total		3,057	4,079	4,127	3,846

6.2.4 Discussion

The main source of uncertainty and error in this forecasting study has to do with the degree non-hazardousness of the waste streams. The forecast above already dealt with listed wastes, but did not address characteristic wastes. The 1982 API survey suggests that even non-listed wastes would be highly hazardous, some even more so than listed wastes. The Jacobs study suggests that that hazard is likely caused by a very small weight fraction of the total waste flow. This reality is part of what motivated the API's 1987-1988 survey system boundaries, which more or less ignored the EPA's hazard criteria in order to better understand the broader set of possibilities with waste management and resource recovery. The motivations of this research is not to characterize current waste management practice, but account for waste generation so as to inform, among other things, the potential for eco-industrial transformation. So, while noting the current hazardousness of a

particular waste is important, condemning an entire waste flow to the hazardous waste landfill because of the characteristics of a small and potentially isolatable fraction of waste material seems shortsighted. The results of this forecast should therefore be given with an asterisk, explaining that strictly speaking, the waste flows are not NHIW but, with some processing, it could be made non-hazardous with essentially no change in mass.

Better clarification of the hazardous waste picture of the petroleum refining industry could be attained by exploring the RCRA biennial report data, which is freely available online.⁶² Tackling that particular analytical challenge was deemed out of scope for this research at this time.

Another source of potential error comes from a change in industry structure, specifically, the trend towards consolidation and integration in the refining industry. Most of the survey data over-represented large facilities and under-represented small facilities, a source of error noted in every report. However, considering that the small, non-reporting facilities have been the ones going out of business, what was once a source of extrapolation error is now less so, and the data representing mainly large facility waste is even more representative today.

The technology mix in the refining industry has changed considerably in the past decades as a result of changing demand for different petroleum products and changing environmental requirements. The only evidence of this change in the waste data is confounded by an ever-increasing list of waste streams surveyed. For example, are the 10 catalyst waste categories from the 1992 survey simply a result of better waste accounting compared with, say the two categories from the 1982 API survey, or is it a result of more catalytic processes? While this is an interesting question, it is unclear what the implications of a particular answer would be.

Finally, there is a common tendency throughout the referenced literature for the authors to use what was reported in the conclusions or summary of the previous study without looking much deeper at the conditions or motivations of the research. This leads to errors being propagated throughout time, sometimes in a damaging way, and other times just in a misleading way. For example, in comparing their results to past studies, Radian referenced a version of the Jacobs survey results that had been considerably abridged by API for purposes of comparability between those two studies. Similarly, SAIC embarrassingly misunderstood the results of the 1982 API survey, reporting numbers nearly 25% higher than they should have been. While there is no evidence that these mistakes adversely impacted industrial policy or the environment, it does suggest that the misuse of the results from industrial subtitle D survey as representing NHIW generation is not a fluke, and that particular error has had considerable effect, if not on real policy, then on the general understanding of waste in America.

⁶² US EPA, "National Biennial RCRA Hazardous Waste Report: Documents and Data," <https://www3.epa.gov/epawaste/inforesources/data/biennialreport/>

6.3 Materials balance

This section describes the application of materials balance principles to the petroleum refining industry for the estimation of lost mass.

6.3.1 Background

As a chemical process industry, petroleum refineries operate under strict mass balance constraints. Mass balance monitoring is used in refineries as a component of process control (Lyons, Plisga & Lorenz, 2016, pp. 2-144-2-146). Mathematical process models exist to help engineers understand plant operations and improve performance (Erokhin, Laptev & Lisitsyn, 2010). Although pollution outputs must be included in models used in refinery control by virtue of the mass balance constraint, solid and residual waste generation would be of secondary concern to efficient plant operations.

On the other hand, the RFF industrial residuals research program constructed a materials balanced model of a 150,000 bbl/day refinery to “predict how residuals discharges from a petroleum refinery will vary with changes in various direct policies and underlying conditions” (Russell, 1973, p. 101). This model specifies at a very detailed level the individual residuals emanating from each refinery sub-process, and how those sub-processes are linked together and controlled at the refinery level. The model focused mainly on airborne and waterborne residuals; the only solid residuals considered were “the collected particulates from the modification processes attached to the catalyst regenerator and boilers and the ash from sludge incineration” (p. 86). However, the study authors did emphasize “that the reduction in discharge of BOD [or other waterborne residuals] results in the generation of secondary residuals, particularly “solids” formed in the standard activated sludge process” (Bower, 1975, p. 297). As it turns out, in the years immediately following the RFF study, many of the effluent and air pollution controls explored in the study came into effect, in one form or another, making the model and its specific albeit exploratory results obsolete.

In their expansive efforts to characterize lost mass from the US economy as a whole, Ayres & Ayres balanced inputs to and outputs from the petroleum refining industry. In their initial working paper, which focused on the year 1988, the Ayreses stayed at the highest level of industry aggregation, considering the effective supply of crude oil, natural gas liquids, and intermediate feedstocks as industry inputs and refinery gases and saleable products as industry outputs (Ayres & Ayres, 1993). The difference, 4.3 million Mg, was attributed completely to “fugitive hydrocarbon emissions (VOC)” (p. 12).

In their revision and expansion of the 1988 analysis, the authors delved into much greater detail about inputs, outputs, and intermediate transformations of material in the industry (Ayres & Ayres, 1999). Here, lost mass is calculated to be 55.6 million Mg, including airborne

combustion products (CO and CO₂) that were excluded from the earlier version. The authors use an EPA estimate (i.e. not proceeding from the materials balance calculations) to attribute just two million Mg of lost mass to VOC emission. They also account for the fraction of input crude oil that is sulfur and ash; they state, “assuming the crude oil contains 0.1 percent ash, there would be some 0.7 [million Mg] of solid waste” (p. 123). They also estimate 2.1 million Mg of neutralized spent sulfuric acid (H₂SO₄).

The 1993 case study, which Ayres & Ayres (1998) take an entire book to explore, operates largely at the same level of detail as the 1999 publication,⁶³ with updated figures. The change in industry throughput was not so great in the intervening five years, so, while total lost mass was estimated to increase to 69.5 million Mg, the residuals excluding combustion products remained the same: 0.7 million Mg of solid waste from the ash content of crude oil⁶⁴ and 2.1 million Mg of spent sulfuric acid. New to this analysis is data on the consumption of non-hydrocarbon materials, 0.72 million Mg of salt and 0.122 million Mg of kaolin clay (used to manufacture catalysts). The authors state, “since these materials do not appear in products, they must be part of the waste stream” (p. 78). This very well might be true, but another explanation is that the materials were purchased to accommodate growth in the industry, and then remained in stock.

Despite the progressively more detailed models of the industry, Ayres & Ayres were not able to achieve much more refined estimates of solid waste from petroleum refining, at least not using materials balance logic. Instead, they relied on dubious compositional claims to better attribute the lost mass calculation. The Ayreses do not address the shortcoming of the method as it applies to this industry. Below, I follow the Ayreses’ lead in model construction, with similarly limited results.

6.3.2 Model

The great complexity of the modern petroleum refinery (see Figure 6-11) would seem to offer a perfect scenario for a well-constrained materials balance model of the industry. Numerous interconnected process steps, each linked by local and global materials balance constraints, would enable the development of a material flow account without needing empirical observations for every flow. However, in reality, the information that is available only enables model specificity to the degree employed by Ayres & Ayres (1998): refinery inputs linked with refinery outputs through a single process step, barely enough to estimate lost mass with any confidence. The model employed here is illustrated in Figure 6-13. Inputs are classified as crude oil, other, and fuel, while

⁶³ If you recall, the 1999 publication is a refinement of the 1988 case study originally published in 1993, despite being published later than the 1993 case study.

⁶⁴ The Ayreses acknowledge the dubious provenance of this figure with characteristic dismissiveness: “The actual figure may be higher or lower” (p. 78).

outputs are petroleum products, lost mass, and fuel combustion products (emissions). The conversion of fuel to emissions does not yield any NHIW, and so can be safely disregarded for these purposes.

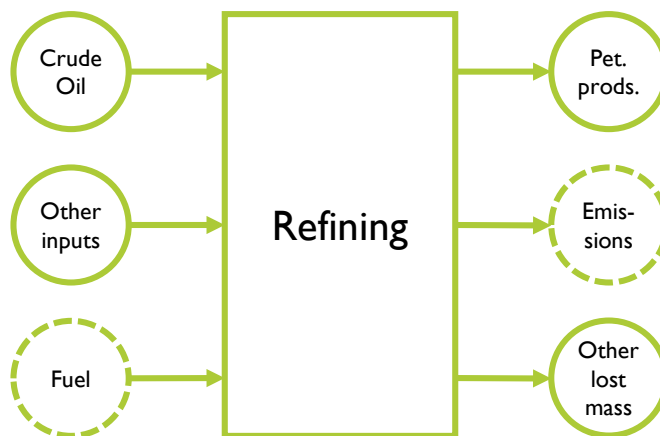


Figure 6-13. High-level model of the petroleum refining industry for the material balance estimation method.

6.3.3 Data & Material Flows

The US Energy Information Administration conducts monthly surveys of a wide range of energy-related facilities. One of these, EIA-810 “Monthly Refinery Report”⁶⁵ contains copious data on the consumption of crude oil, other feedstocks, and fuels, and outputs of petroleum refineries (EIA Petroleum). This data can be used to populate a material balance model of the US petroleum refining industry for the subject year. One challenge to this is that nearly all of the data is reported in volumetric terms. Volume does not obey conservation laws,⁶⁶ so reliable density values are needed to convert these data into a mass basis.

The petroleum industry differs from the other two case studies in many ways; a major one is that the vast majority of the inputs and outputs in this industry are in liquid form, with gases a distant second and solids largely unrepresented (at least on the input side). As a result, the industry has developed its own evaluation criteria for important physical properties of its liquid feedstocks. Two of these will be referenced commonly below. First is the standard unit of oil volume, the *barrel*, equivalent to 42 gallons (0.159 m³). Second is a density measure called API gravity, which is

⁶⁵ EIA Survey Forms, <http://www.eia.gov/survey/#eia-810>

⁶⁶ The EIA recognizes this, and even includes a line “Processing Gain (Loss)” in their data reports, which reflects the “processing of crude oil into products which, in total, have a lower [or higher] specific gravity than the crude oil processed.”

“a measure of the lightness or heaviness of petroleum that is related to density and specific gravity” (Speight, 2005, p. 323). It is measured in units of “degrees,” calculated as: $^{\circ}\text{API} = 141.5/G - 131.5$, where G is the liquid’s specific gravity at 60°F in relation to water at 60°F. Combining these two units, one can calculate a density as:

$$\frac{\text{barrels}}{\text{metric ton}} = \frac{^{\circ}\text{API} + 131.5}{141.5 \times 0.159}$$

For other petroleum products, volumetric density (or sometimes specific gravity) is available from numerous sources, including engineering handbooks and government reports. The density of petroleum products is a function of temperature, so it is important to have a consistent standard. It is, for some products, also a function of production technology, with average density of certain products having changed over time. For these reasons, I have chosen to use a reliable, transparent, contemporary source of densities that more or less lines up with the list of products tabulated by the EIA (US EPA, 2009, pp. 3–5). This list was compiled by the EPA in support of the national greenhouse gas reporting regulation. Details on the source of each value are available in the reference. See Table 6-13 for the density values used here to convert volumes reported by the EIA to mass values subject to the materials balance constraint.

Ayres & Ayres (1998) cite an IEA/OECD publication that reports similar data in mass units. The contemporary equivalent of that publication (OECD/IEA, 2013) seems to present energy flow data at a higher level of aggregation that is desired here, making it a challenge in and of itself to evaluate. Since I have access to the same raw EIA data that the OECD/IEA team used in their publication, I have chosen to use that instead. The subsequent sections are arranged according to how the data is presented from EIA.

6.3.3.1 *Inputs*

The primary input to petroleum refineries by a wide margin is crude oil. Refineries consumed 5.4 billion barrels of crude oil in 2010, 2.2 billion barrels from domestic resources and 3.2 billion barrels from imports. For domestically produced crude, the EIA reports the API gravity and sulfur content (Figure 6-14). The density of imported crude is more difficult to ascertain. Figure 6-15 displays the inputs of crude oil to US refineries in mass terms, calculated using a range of densities of 0.13–0.15 Mg/barrel, which is a general range of crude oils on the market (Speight, 2014). The mass of US crude calculated using reported API gravity is overlaid starting in 1985, which is the first year of data availability. In 2010, the API gravity figure of 30.71 degrees, corresponding to a density of 0.139 Mg/barrel, yields 745.39 million Mg of crude oil consumed in US refineries. This is just below the average of the high and low range reported in the literature. OECD/IEA (2013) reports a slightly higher figure: 748.52 million Mg of crude oil in 2010.

Table 6-13. Density factors for petroleum products. (US EPA, 2009, Table 1)

Product	Density (Mg/bbl)	Product	Density (Mg/bbl)
<i>Finished Motor Gasoline</i>		<i>Unfinished Oils</i>	
• Conventional	0.1155–0.1185	• Heavy Gas Oils	0.1476
• Reformulated	0.1164–0.1167	• Residuum	0.1622
• Other	0.1185	<i>Other Petroleum Products</i>	
<i>Blendstocks</i>		• Aviation Gasoline	0.1120
• CBOB	0.1155–0.1185	• Special Naphthas	0.1222
• RBOB	0.1164–0.1167	• Lubricants	0.1428
• Other	0.1185	• Waxes	0.1285
<i>Oxygenates</i>		• Petroleum Coke	0.1818
• Methanol	0.1268	• Asphalt and Road Oil	0.1634
• GTBA	0.1257	• Still Gas	0.1405
• MTBE	0.1181	• Ethane	0.0866
• ETBE	0.1182	• Ethylene	0.0903
• TAME	0.1229	• Propane	0.0784
• DIPE	0.1156	• Propylene	0.0803
<i>Distillate Fuel Oil</i>		• Butane	0.0911
• DFO No. 1	0.1346	• Butylene	0.0935
• DFO No. 2	0.1342	• Isobutane	0.0876
• DFO No. 4	0.1452	• Isobutylene	0.0936
<i>Residual Fuel Oil</i>		• Pentanes Plus	0.1055
• RFO No. 5	0.1365	• Miscellaneous Products	0.1380
• RFO No. 6	0.1528	<i>Biomass-Based Fuel and Biomass</i>	
Kerosene-Type Jet Fuel	0.1294	• Ethanol (100%)	0.1267
Kerosene	0.1346	• Biodiesel (100%)	0.1396
Diesel—Other	0.1452	• Rendered Animal Fat	0.1333
<i>Petrochemical Feedstocks</i>		• Vegetable Oil	0.1460
• Naphthas (< 401 °F)	0.1158	• Pentanes Plus	0.1055
• Other Oils (> 401 °F)	0.1390		

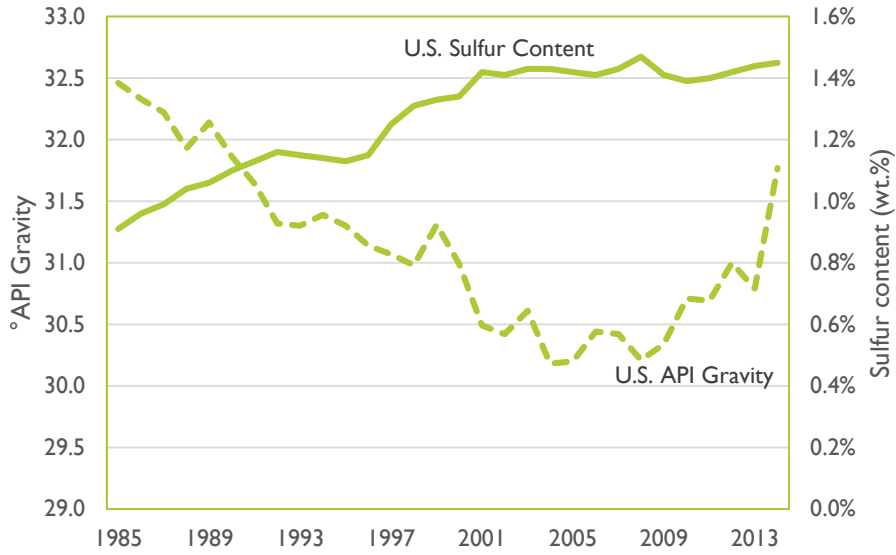


Figure 6-14. API gravity and sulfur content of US crude oil inputs to refineries, 1985–2013 (EIA Petroleum)

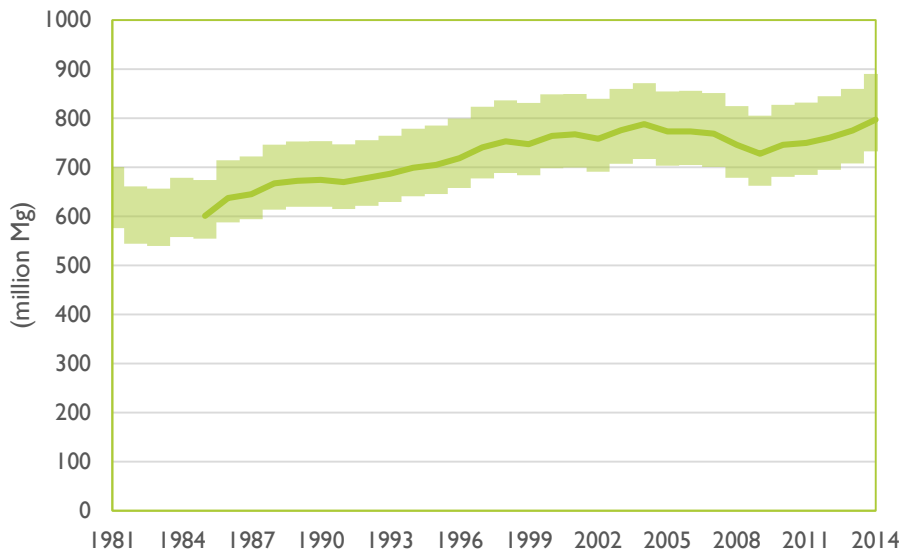


Figure 6-15. Crude oil inputs to US refineries, 1981–2014 (EIA Petroleum)

The EIA reports quantities of many other types of hydrocarbons consumed in refineries. There is less variability around the densities of these materials; I simply used the EPA reported figures tabulated above. Natural gas liquids include a variety of hydrocarbons extracted from natural gas that are predominantly pentanes (C₅H₁₂), hexanes (C₆H₁₄), and heavier. This mixture is also called “pentanes plus” and “natural gasoline.” Liquefied refinery gases are comprised overwhelmingly of butane (C₄H₁₀), butylene (C₄H₈) and their isomers isobutene and isobutylene. Historically, refineries also consumed a small quantity of ethane (C₂H₆) and ethylene (C₂H₄), but this seems to no longer be the case today. These refinery gases are reported in pairs; the mass conversion depends on the specific mixture of each pair of butane-butylene and isobutene-isobutylene. Consumption of pentanes plus in 2010 totaled 5.98 million Mg; the other liquefied refinery gases totaled between 9.33 and 9.80 million Mg (Figure 6-16).

Oxygenates are gasoline additives that increase the amount of oxygen present in the gasoline blend. MTBE (methyl tertiary butyl ether) was the most common oxygenate used through the 1990s; it has since been nearly completely replaced by fuel ethanol, the consumption of which in 2010 totaled 39.63 million Mg (Figure 6-17).

The remaining hydrocarbon inputs to refineries accounted by the EIA are also refinery products; their input is recorded in net terms, where more is consumed than produced because they either need more processing or are added to other products. Unfinished oils are partially refined petroleum products that require further processing. Specific components of this material flow are defined by specific gravity, from lightest to heaviest, naphthas, kerosene and light oils, heavy gas oils, and residuum. Most of the unfinished oils that are consumed by refineries are in the form of heavy gas oils. Gasoline blending components are specific naphthas added to gasoline to achieve a desired chemical composition of the fuel. Net inputs of unfinished oils in 2010 totaled 31.95 million Mg (72% of which was heavy gas oils, 20% was residuum, and the remaining 8% lighter oils and naphtha) and gasoline blending components totaled between 28.39 and 28.90 million Mg, depending on whether or not the blendstocks were for summer or winter gasoline blends (Figure 6-18). The sharp growth in consumption of gasoline blending components and ethanol since 2008 is a bit of a mystery. It might be due to improved accounting by the EIA, or it might be due to tightening of regulatory requirements for gasoline performance.

Data on other non-hydrocarbon input materials are available from two sources, the USGS *Minerals Yearbooks* (MYB) and the Census Bureau’s *Economic Census* (EC). The MYB includes data on the consumption of sulfur and sulfuric acid by the petroleum refining industry. In 2010, total sulfur inputs were 2.42 million Mg: 2.05 million Mg of elemental sulfur and an additional 0.37 million Mg of sulfur contained within 1.13 million Mg of H₂SO₄ (Figure 6-19). From Figure 6-14, sulfur contained within input crude oil totaled 10.36–10.40 million Mg. Ayres & Ayres (1998) claim ash content of crude oil to be 0.1%; this number is validated by Speight (2014, p. 187), who claims the metals content of petroleum to not exceed 1000 ppm (< 0.1%). This would put ash content of crude oil consumed in 2010 at no more than 0.75 million Mg.

The *Economic Census* of the years 1997–2012 list a number of both hydrocarbon and non-hydrocarbon materials purchased by the petroleum refining industry from other sectors. The non-hydrocarbon materials include sodium hydroxide (NaOH), sulfuric acid (H₂SO₄), chemical catalytic preparations, and plastic, paper, and metal containers. Most of these census entries lack physical quantity; the 2012 EC indicates 0.06 million Mg of NaOH was consumed in 2012, but that is barely enough to justify further exploration of this material flow. It might be possible to estimate mass of the catalyst materials from dollar figures, but even those were redacted to protected industry confidentiality. The data on kaolin clay and salt that Ayres & Ayres located for the 1993 case study were not available for 2010 (nor did they identify their data source). The packaging is intriguing because those materials would contribute to a non-process-based waste flow.

The final input flow is that of hydrocarbon materials for fuel. Many fuel materials are simply recirculated from products (e.g. still gas and petroleum coke), while others (natural gas) are brought in from the outside. This model assumes that all fuels are consumed in combustion, yielding no solid residuals, and so they are excluded from the materials balance model. They are included here for completeness sake: in 2010 between 61.73 and 66.01 million Mg of fuels were consumed in petroleum refineries in the US (Figure 6-20), the variation stemming from uncertainty around the heat content of the natural gas.

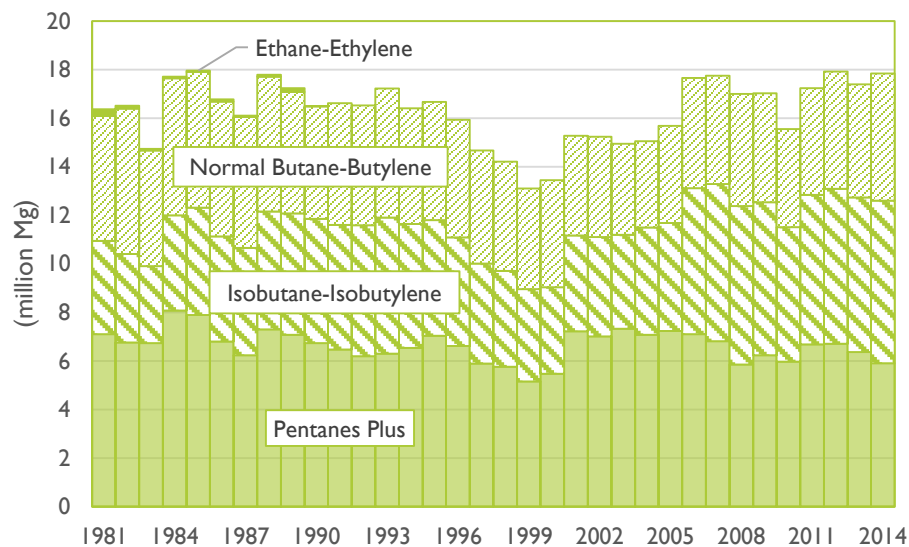


Figure 6-16. Natural gas liquids (pentanes plus) and liquid refinery gases inputs to US refineries, 1981–2014 (EIA Petroleum)

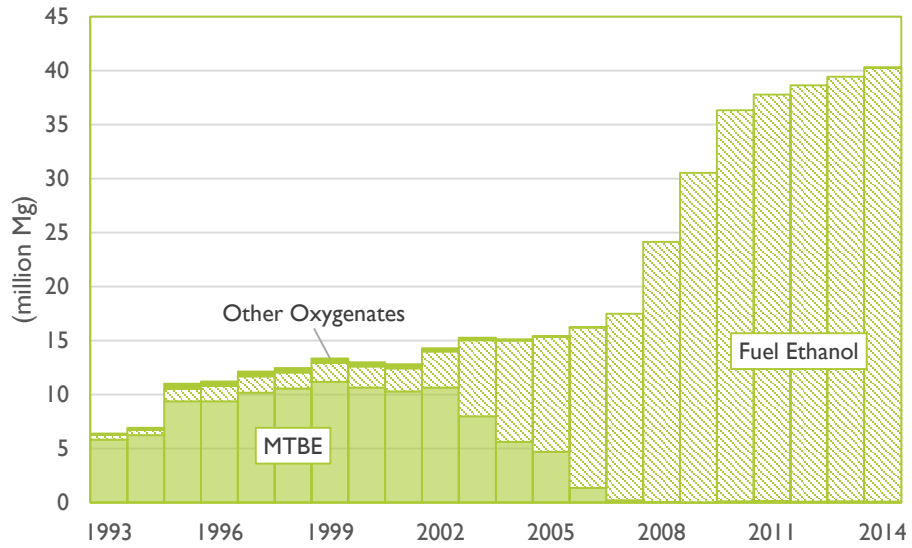


Figure 6-17. Inputs of oxygenates to US refineries, 1993–2014 (EIA Petroleum)

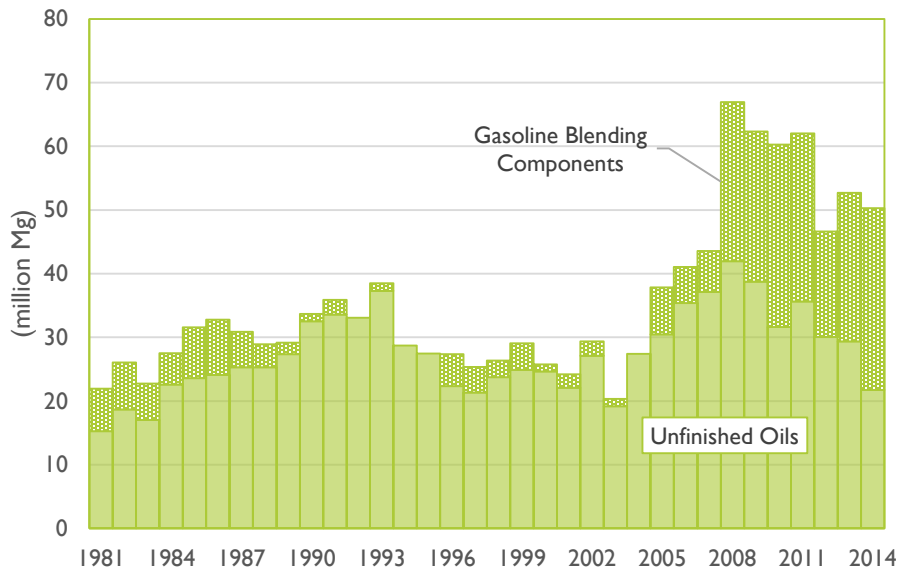


Figure 6-18. Other hydrocarbon net inputs to US refineries, 1981–2014 (EIA Petroleum)

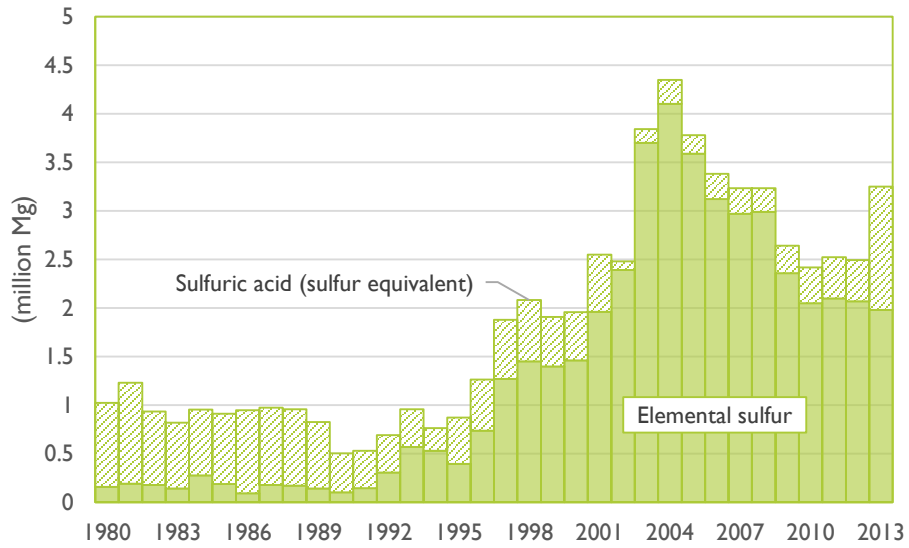


Figure 6-19. Sulfur inputs to US refineries, 1980–2013 (MYB)

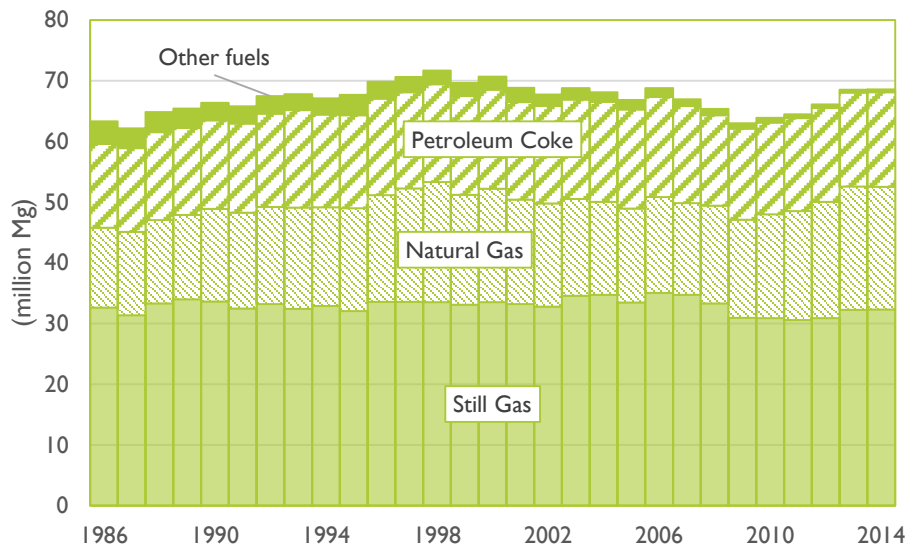


Figure 6-20. Fuel inputs to US refineries, 1986–2014 (EIA Petroleum)

6.3.3.3 *Outputs*

The outputs of petroleum refineries are overwhelmingly finished (or unfinished) petroleum products. Refineries also recover some sulfur. Whatever is left over in the materials balance is in one way or another an industrial residual, either an emission or industrial waste.

The largest fractions of petroleum refinery production are the big four fuels: motor gasoline, distillate fuel oil, jet fuel, and residual fuel oil (Figure 6-21). Motor gasoline is the primary product, 382.89–389.80 million Mg in 2010, the variation due to the difference between summer and winter gasoline blend densities. (Aviation gasoline can be included here too because of its chemical similarity to motor gasoline: 0.60 million Mg in 2010). Distillate fuel oils include diesel fuel and heating fuels; in 2010 US refineries produced 206.87–207.49 million Mg, depending on the ratio of no. 1 to no. 2 oil. Jet fuel and residual fuel oil (used as a heating and electric power generating fuel) were produced in 2010 in quantities of 66.96 million Mg and 29.14–32.62 million Mg, respectively. Uncertainty in the latter is from the ratio of no. 5 to no. 6 oil.

Minor products include fuels for use in on-site and industrial energy generation, heavy petroleum products, petrochemical feedstocks, and specialty products (Figure 6-22). Fuels include petroleum coke (66.96 million Mg in 2010), refinery still gas (34.46 million Mg), and liquefied petroleum gases (19.41 million Mg). Other products include asphalt and road oil (22.55 million Mg in 2010), petrochemical feedstocks (14.82 million Mg), lubricants and waxes (8.98 million Mg), and miscellaneous products (6.41 million Mg). Sulfur recovered from refineries is tabulated by MYB: 7.14 million Mg in 2010.

6.3.3.4 *Lost mass & Materials balance*

The remaining mass, calculated as the difference between inputs and outputs, is classified by Ayres & Ayres as lost mass. For 2010, total (non-fuel) inputs sum to 863.08–867.21 million Mg and total (non-combustion product) outputs sum to 854.12–865.13 million Mg. The difference is 2.08–8.96 million Mg.⁶⁷ Like Ayres & Ayres, it is difficult to say exactly what this lost mass is made of. Based on the discussion above, somewhat less than 0.75 million Mg of the lost mass is ash that was contained within the crude oil. Another fraction of the lost mass is lost sulfur. The sulfur balance of the model is as follows: on the input side is sulfur contained within crude oil and sulfur purchased by refineries as elemental sulfur and H₂SO₄; on the output side is recovered sulfur and sulfur contained within petroleum products, specifically in residual fuel oil, the majority produced of which contains >1% sulfur content. The difference between inputs and outputs (indicates sulfur

⁶⁷ This difference is calculated as In (low) - Out (low) and In (high) - Out (high) because the uncertainties of many of the values are not independent.

is lost in a residual waste stream or, perhaps, contained within other products (Figure 6-23). Without knowing which, it is difficult to confidently include sulfur in the lost mass fraction.

The materials balance diagram for the petroleum refining industry in the US in the year 2010 is shown in Figure 6-24.

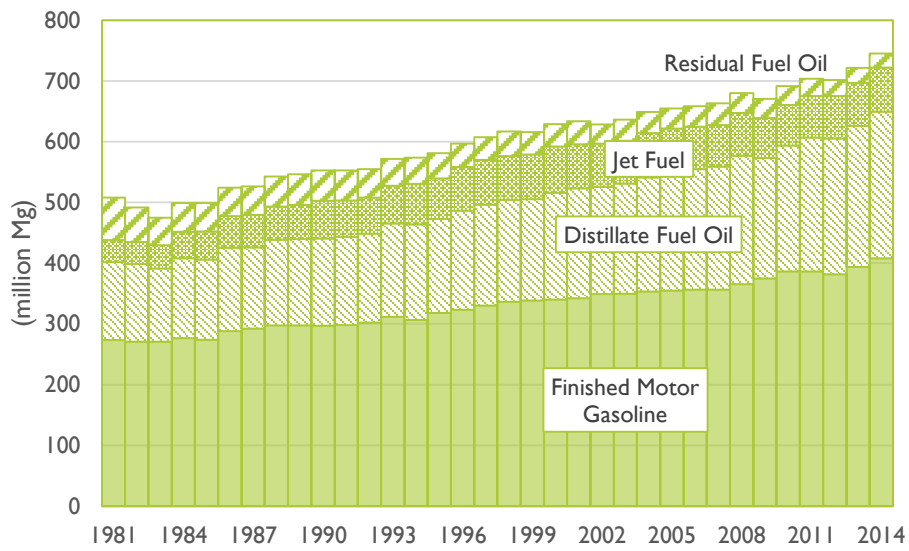


Figure 6-21. Major products of US petroleum refineries, 1981–2014 (EIA Petroleum)

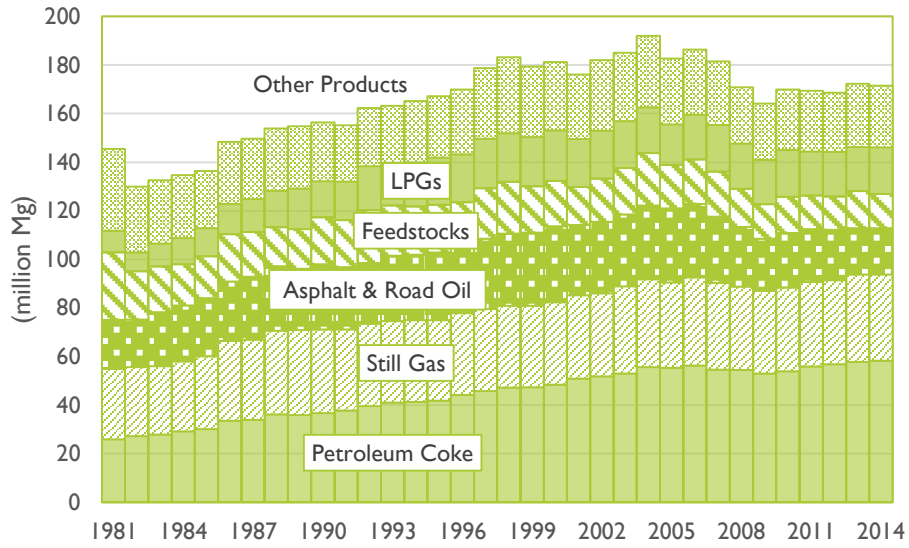


Figure 6-22. Minor products of US petroleum refineries, 1981–2014 (EIA Petroleum)

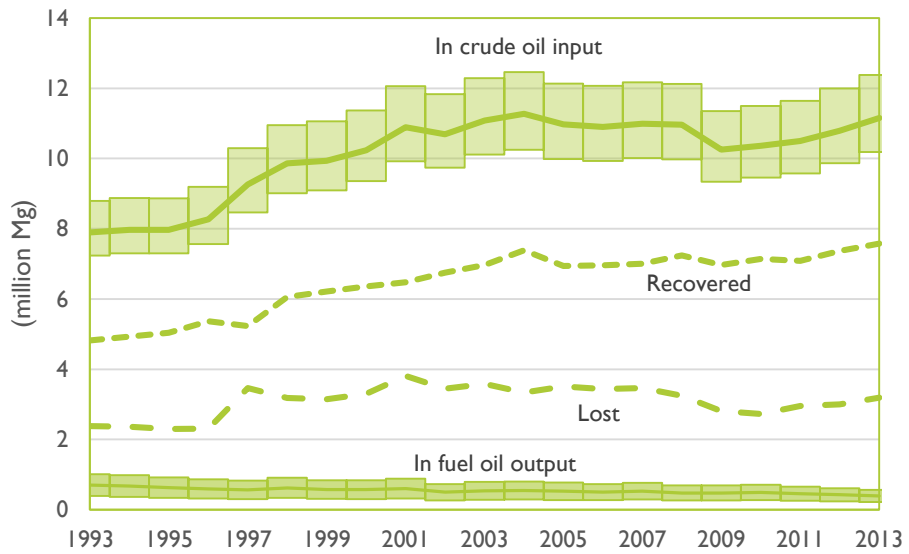


Figure 6-23. Sulfur materials balance in US petroleum refineries, 1993–2013

6.3.4 Discussion

Despite the abundance of data available for industry-wide inputs and outputs, the materials balance method for the estimation of NHIW from petroleum refining falls severely short. Having just a single balancing activity limits the ability of the model to perform any sort of self-corroboration; the closest thing to this is the internal sulfur substance balance, but even then there is sufficient uncertainty regarding the data to make it useless. The range of lost mass calculated, 2–9 million Mg, is incredibly broad, and likely mostly made of air emissions, as similarly concluded by Ayres & Ayres. The other types of solid wastes identified by surveys of refineries, such as catalyst wastes and wastewater separator sludges, are nowhere to be found, except perhaps in the 0.75 million Mg figure that marks a high value on possible heavy metals & ash content.

So, it seems that despite the availability of data and a constructed model, the estimate from materials balance is not a useful contribution to the triangulation effort. This puts a greater onus for corroboration on the remaining two estimation method.

There are possibly other paths to improve the usefulness or at least the reliability of this model. The EPA publishes other data on air, water, and hazardous waste pollution from refineries. These data sources could be mined for specific values of VOC, SO_x, and particulate emissions from the industry, being pollution flows that are linked with the throughput of specific materials. Other data, such as hazardous waste and CO, would be less useful, as they confound the model with process water and oxygen flows, respectively.

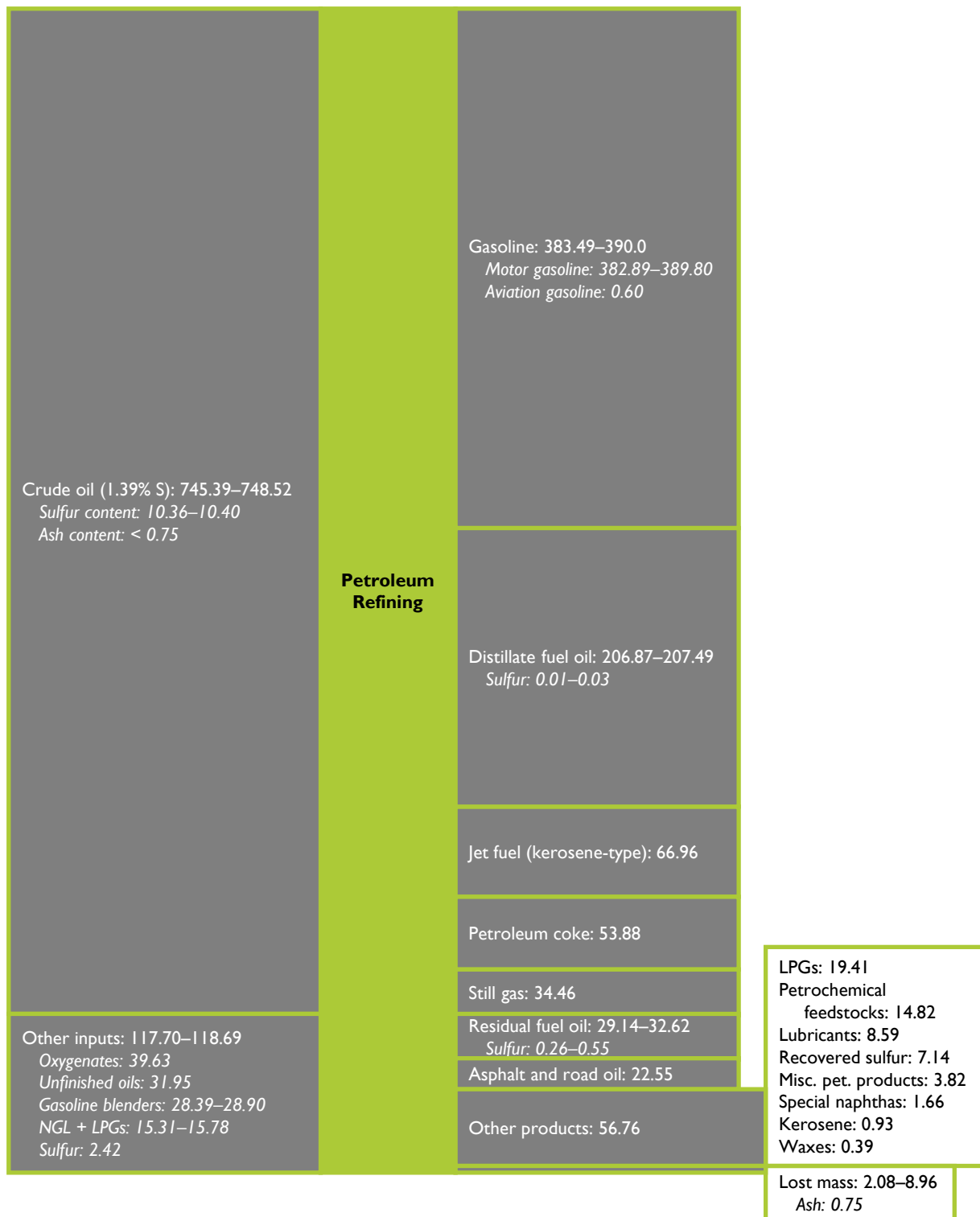


Figure 6-24. Material balance of the US petroleum refining industry, 2010, excluding fuels consumed in the refineries.

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6.4 Spatial scale-up

As with paper and steel, national generation rates of NHIW from petroleum refining can be estimated using data from the PA residual waste (PARW) program. Also like those other two industries, petroleum has a storied history in the commonwealth, being the site in 1859 of the nation's first oil well (Strauss, 2015). Today, Pennsylvania is all but insignificant to national crude oil production but maintains a respectable, if minor, refining capacity of 596,000 barrels per calendar day, 3.4% of the national operating capacity as of January 1, 2015 (down from 773,000 barrels per calendar day and 4.6% of the national operating capacity as of 2010). For most of the past thirty years, Pennsylvania has had the fifth largest refining capacity in the country (behind Texas, Louisiana, California, and Illinois); facility closures and reorganizations in very recent years now puts it sixth behind Washington state.

The availability of data on production capacity at the state level provides a physical dimension to the scaling method that is limited to economic factors in most other cases. Pennsylvania's refining capacity was more or less stable in recent history through 2010 (with a possible exception in the years 1996–1998, where data is sparse), this despite a steady decline in the number of operable refineries from 10 in the early 1980s to just five in 2010 (Figure 6-25). The value of shipments from these refineries has fluctuated over the years (as oil prices are wont to do), but has experienced a steady decline since a peak in the year 2002 (Figure 6-26).

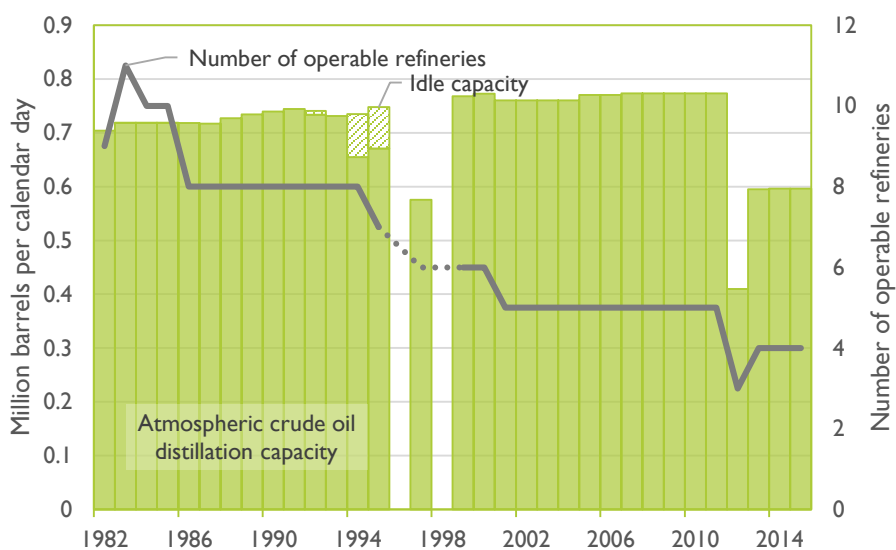


Figure 6-25. Number and daily capacity of oil refineries in Pennsylvania, 1982–2015 (EIA Petroleum). Data was not collected in the years 1996 and 1998, and 1997 is suspect.

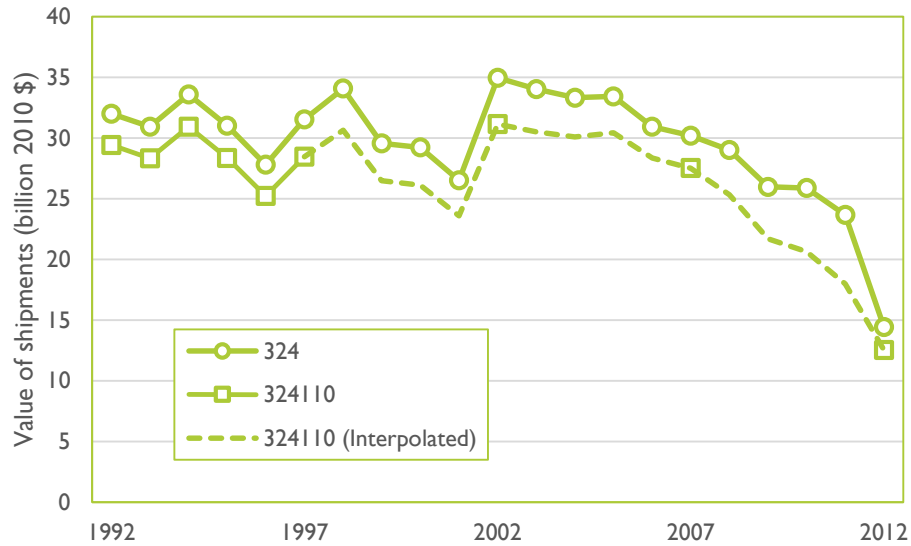


Figure 6-26. Value of shipments from NAICS 324—Petroleum and Coal Products Manufacturing and NAICS 324110—Petroleum Refineries, in real 2010 \$, 1992–2012 (ASM, EC, PPI). Six-digit NAICS codes at the state level are serviced only every five years; interpolation was performed by tracking annual change in three-digit code values and the ratio between the two codes.

6.4.1 History of petroleum refining in Pennsylvania

“The birth of the petroleum industry took place in the northwest corner of Pennsylvania, where the mountain ranges of the Alleghenies begin to flatten out toward the central plains” (Giddens, 1938, p. 30). Petroleum was known to Native Americans living along the Alleghany River and its tributaries for centuries before the European colonization of North America. They would skim oil produced in natural seeps from the surface of the river for use in medicine, skin ointments, religious ceremonies, and other purposes (Black & Ladson, 2010). By 1755, the word “petroleum” began appearing on maps above this region and by 1791, the tributary that was known as the “greatest source of petroleum prior to 1845” was named “Oyl [Oil] Creek” (Giddens, 1938).⁶⁸

Salt wells were known throughout the Appalachian region to sometimes yield petroleum, some of which was captured and sold as little more than a curiosity by enterprising salt miners, but most of which was seen as a nuisance and contaminant. In 1846, a salt well owned by a Mr. Kier began producing oil in unusually large quantities. His son Samuel brought a sample of the oil to a chemist in Philadelphia, who designed a distillation process to convert the crude oil into a passable

⁶⁸ Giddens references an account of General Benjamin Lincoln’s encounter with Oil Creek. On a march through western Pennsylvania in 1783, General Lincoln’s troops bathed in the creek, which “gave great relief and freed many of them immediately from rheumatic complaints. They also drank freely of the waters, which acted as a ‘gentle purge’” (pp. 11–12).

illumination fuel, which Kier implemented via a one-barrel still in Pittsburgh in 1850. This act placed Samuel Kier, and Pennsylvania, at the birth of an industry.

The first well drilled with the intention of producing petroleum was also in Pennsylvania. On August 27, 1859, a well drilled by “Colonel” Edwin L. Drake in Titusville, a town on Oil Creek, struck oil. The demonstrable success of the Drake well ushered in a bonanza that would come to be called the Pennsylvania Oil Rush, and by the end of the decade, Pennsylvania oil wells were producing over 13,000 barrels per day. By the end of the nineteenth century, Western Pennsylvania was producing fully half of the world’s crude oil (Davé, 2008). The construction of refineries and the development of increasingly sophisticated refining processes would follow, with the first industrial-scale refinery built in Titusville in 1860.⁶⁹ Others early in that decade would be built near the wells along Oil Creek and the Allegheny River as well as slightly farther afield, at Union Mills, Corry, and Erie, PA. By 1867, there were 58 oil refineries in Pittsburgh alone (Dougherty, 2013). That city’s early supremacy “lasted only eight years after Drake’s oil strike of 1859,” losing refining capacity to both Cleveland and Philadelphia (Sulman, 1966, p. 69)

Many of the refineries that remain in operation in the state trace their origins to this period or just shortly thereafter. In 1866, the Atlantic Refining Company built storage tanks at Point Breeze, Philadelphia, to connect the oil fields and refining capacity of Western Pennsylvania with the rapidly growing export market (Mayer, 1990). The company added its own refining capacity in 1870, was bought by Standard Oil in 1874, and by 1882 it was one of the largest oil refineries in the world (Wyatt, 2006). When Standard Oil was dissolved in 1911, Atlantic returned to independence.

On June 11, 1879, a lightning strike caused a fire that decimated the Point Breeze facility, a tragedy foreshadowing the multitude of environmental harms that urban refineries continue to cause today (Quivik, 2015). Fires at Point Breeze became regular occurrences; the destruction of three ships docked at the refinery in 1919 was memorialized by Christopher Morley in his 1920 poem, “Penn Treaty Park,” which includes the following stanza (p. 154):

“The *Roald Amundsen* was Larsen’s ship.
She lay at the refinery, Point Breeze,
Taking on oil for Liverpool. The day
She was to sail, somehow she caught on fire.
A petaled rose of hell, she roared in flame—
The burning liquid overflowed her decks,
The dock and oil-scummed river blazing, too.

⁶⁹ This first refinery left much to be desired, according to Giddens, “The first run of oil was made on January 22, 1861, and the yield did not exceed 50 per cent of the crude. Not knowing how to utilize the by-products, they either dumped into Oil Creek or burned all tar and naphtha.

Her men had little chance. They leaped for life
Into the river, but the paraffin
Blazing along the surface, hemmed them in.
They either burned or drowned, and Alf was one.”

Point Breeze experienced so many fires that “Atlantic employees learned to read the long and short whistle codes to determine the location and severity of these conflagrations” (Dougherty, 2013). It was, tragically, not alone, even in Philadelphia. In 1975, the Girard Point refinery built in 1920 by Gulf Oil on a site adjacent to Point Breeze, was consumed in a fire that claimed the lives of eight firefighters, and this was just one of 10 fires at that site in 15 years (Doyle, 2015).

Both of these refineries have undergone numerous changes in ownership. Gulf Oil, which also had built a storage tank farm across the Schuylkill River from Girard Point was purchased by Chevron in 1982 (PES, 2016). In 1966, Atlantic, along with its Point Breeze refinery, merged with Richfield Oil Co. to become ARCO. Sunoco, Inc. purchased Point Breeze in 1988 and Girard Point in 1994, consolidating them into a single facility, at least administratively. The operation of the facilities was taken over in 2012 by PES in partnership with Sunoco.

Sunoco also operates the Marcus Hook refinery on the Delaware River, south of Philadelphia, founded in 1901. Just upstream is the Trainer refinery, built by the Union Petroleum Company in 1900 (PA DEP, n.d.). This facility has also changed ownership numerous times: Sinclair Oil in 1925, BP in 1969, Tosco in 1995, Phillips/ConocoPhillips in 2001, and Monroe Energy in 2012.

Philadelphia became a refining center due to its intermediacy between the Western PA oil fields and European markets. The other center of refining in PA sprang up much closer to the oil fields and looked inwards towards domestic markets. Few of the small refineries that were built during the Oil Rush survived the ruthless growth of the Standard Oil trust. Some that did have managed to survive to this day. The Kendall Refinery was built in 1881 along the Kendall Creek on the border of Bradford and Foster Townships, near the New York state line. After more than a century of growth, diversification, and what seems like the requisite number of changes in ownership for an oil refinery, including to Witco Chemical in 1966, the American Refining Group (ARG) purchased the facility in 1997, which today has a daily refining capacity in excess of 10,000 barrels (McElwee, 2009). Interestingly, ARG claims that it procures two thirds of its crude oil inputs from wells within a hundred-mile radius (Costik, 2006).

The largest refinery in western PA is the Warren refinery, owned by the United Refining Company, which was founded by ten independent refining operations in Warren, PA in 1902. In 1971, URC built a pipeline from West Seneca, New York to open up access to Canadian crude oil. Today, the refinery has a capacity of 70,000 barrels per day (McElwee, 2009).

The last refinery to operate on the Oil Creek seems to have been the Pennzoil Quaker State facility in Rouseville, PA, just 13 miles down Route 8 from Drake’s original oil well in Titusville. Pennzoil and Quaker State were both iconic Pennsylvania petroleum products brands, and Pennzoil had operated a refinery in Rouseville since the 1880s (Forsthoffer, 2000). The companies merged in 1998 and were then acquired by Shell Oil in 2002. One of the two refinery units on the site was shut down in 2000, while the other was shut down a few years later.

Pennsylvania’s pivotal role in the domestic fossil fuel industry is far from over. The use of hydraulic fracturing to exploit the Marcellus shale gas field has produced sizeable quantities of natural gas and small amounts of oil, even if its economic and environmental impacts remain areas of active debate (Maykuth, 2013). The much larger production of oil from the North Dakota Bakken field has also reinvigorated Pennsylvania refineries, even while posing new environmental and safety threats from the transport of crude oil by rail (Tate, 2014). Field production of crude oil in PA declined to just 4,000 barrels per day in 1997 (1.3 million barrels/year), but is up to historical highs today: 20,000 barrels per day in 2015 (EIA Petroleum). As a fraction of national production, PA remains insignificant, although the Marcellus has pushed its contribution to nearly 0.22% (Figure 6-27). The current geography of petroleum industry infrastructure is displayed in Figure 6-28.

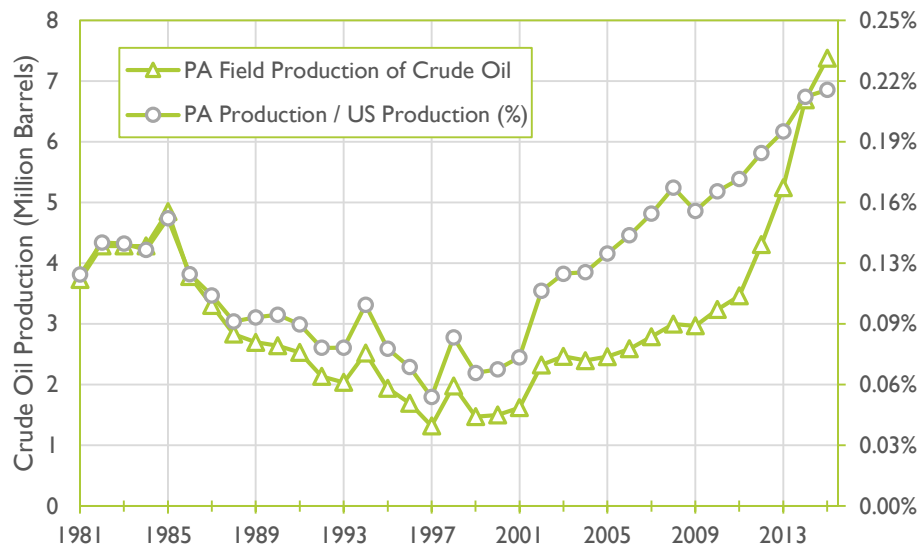


Figure 6-27. Crude oil production in PA and the fraction of total US production in PA (EIA Petroleum)

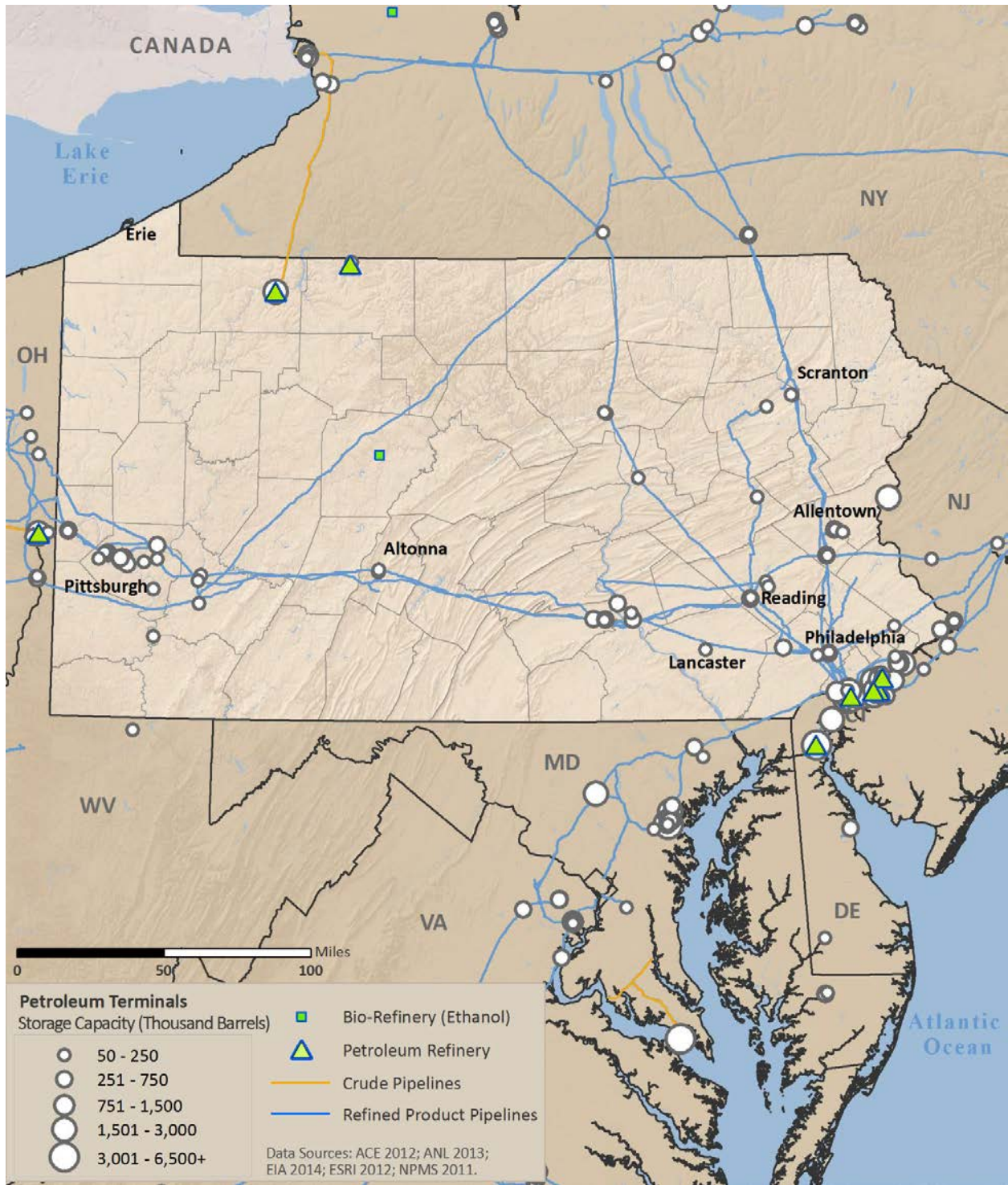


Figure 6-28. Petroleum infrastructure in Pennsylvania, as of 2010. (US DOE, 2015)

6.4.2 Data

Thirteen facilities comprising Pennsylvania’s petroleum refining industry (NAICS 324110) reported to the PA DEP under the residual waste program over the course of its history, 1992–2012 (Figure 6-29). The reported residual waste generation from each reporter was largely relatively stable over the time period, although there were a few examples of reported waste quantities jumping an order of magnitude or more up or down from year to year (Figure 6-30). The reporting patterns reflect what I have learned about the recent history of the state’s refining industry (see above), including consolidation, sale, and decommissioning. The high exposure of this industry to environmental oversight gives me greater confidence than usual in the reliability of the reported data.

Liquid wastes include both wastewaters and aqueous process residuals. The change in reporting requirements around wastewater is apparent in the reported data, while non-wastewater aqueous wastes continued to be generated at stable rates (Figure 6-31). The 100x jump in sludge reporting from 2004 to 2006 seems to be due to a single facility reporting the disposal of large quantities of contaminated soil—this waste flow was reported in three consecutive periods, and then ceased.

Reported solid wastes from this sector is composed of a number of different waste materials, including wastewater treatment plant sludge, tank bottoms, spent catalysts, ash, plant trash, and a variety of oil-containing wastes (Figure 6-32).

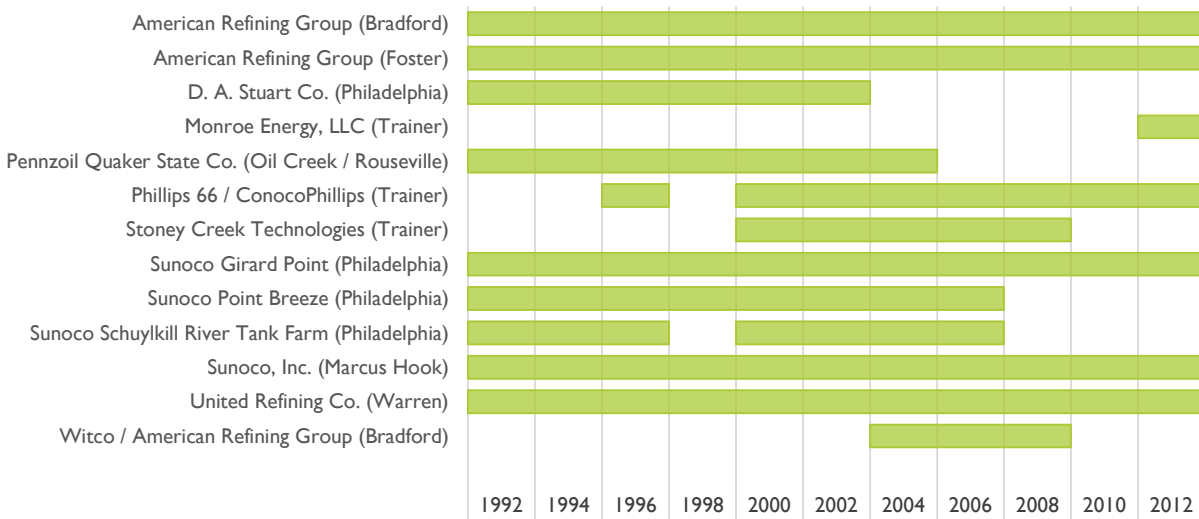


Figure 6-29. Refineries and other NAICS—324110 facilities reporting to the PARW program

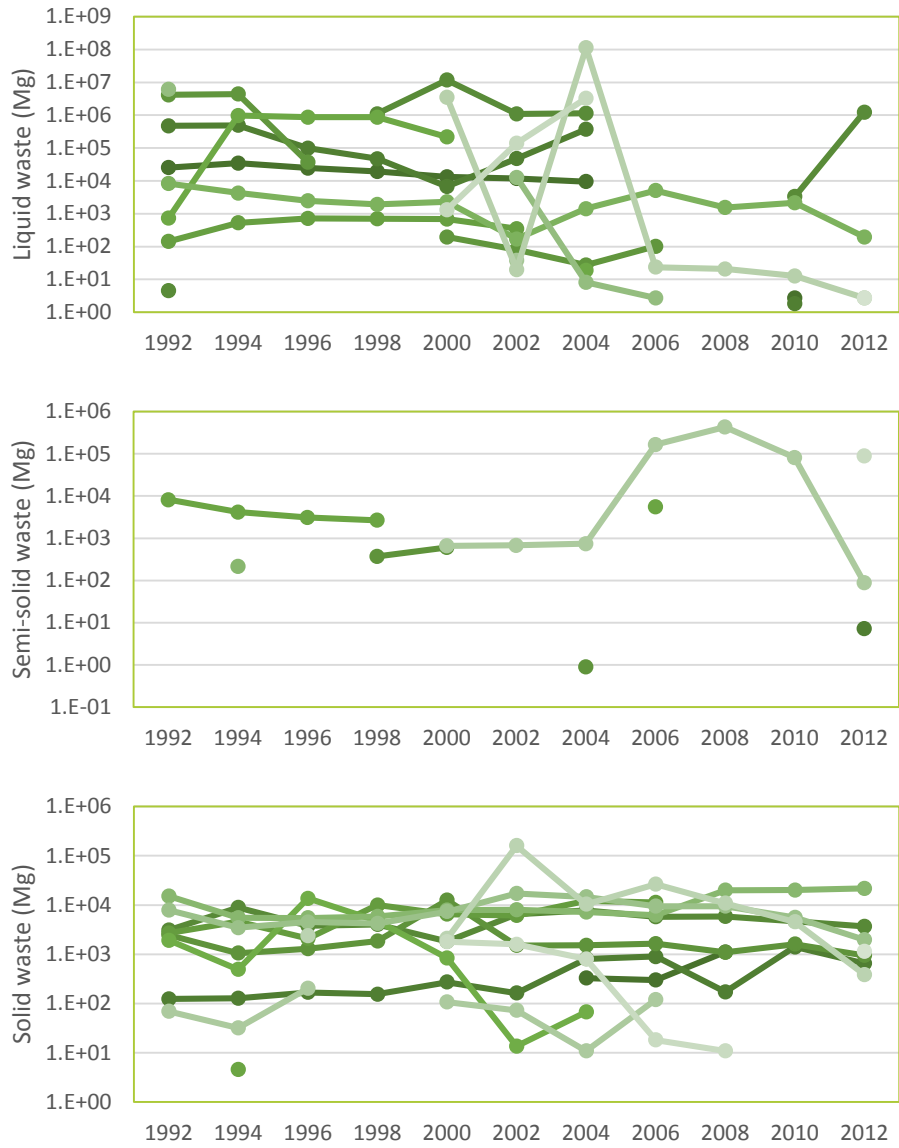


Figure 6-30. Raw residual waste data from NAICS—324110 in the PARW database, by individual facility, medium of discharge, and year.

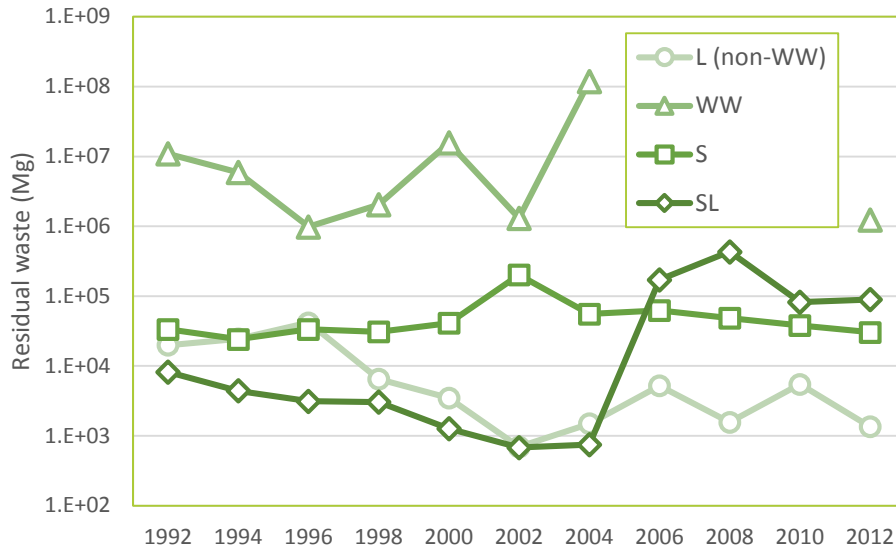


Figure 6-31. Total residual waste from NAICS—324110 in the PARW, by medium of discharge, 1992–2012. Liquid wastes have been split into wastewater and non-wastewater fractions.

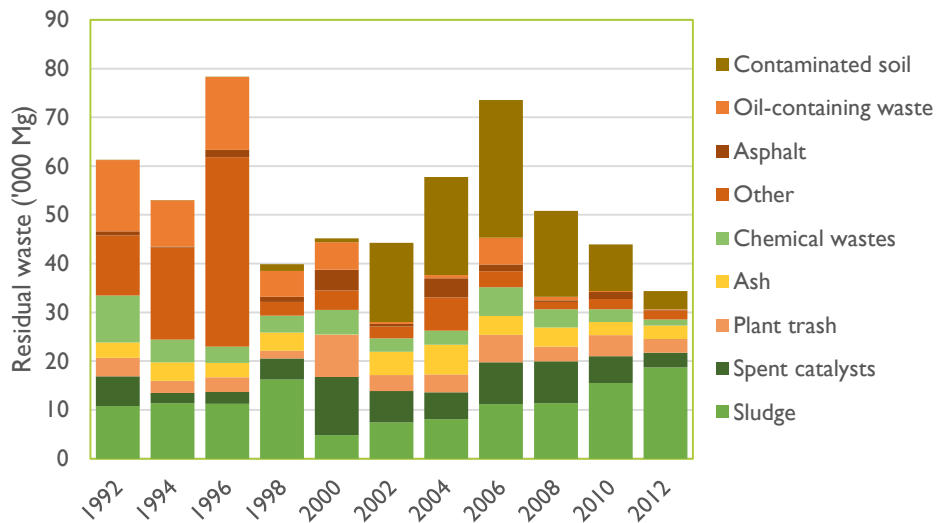


Figure 6-32. Tonnage and composition of non-wastewater residual wastes from NAICS—324110 in the PARW, 1992–2012.

6.4.3 Scale-up

Four scaling factors were identified for the petroleum refining industry: the standard four economic indicators (employment, value added, and total value of shipments) as well as built refinery capacity, which is data published by the EIA Petroleum database. Ratios were calculated by dividing the value of each indicator at the PA level by its equivalent at the US level. The economic indicators are for NAICS—324110, which are only published in the EC (except for the years 1992–1997, in which the equivalent state level SIC codes were available in the ASM as well). For the ASM years after 1997, PA values were estimated by tracking the change in the state-level indicators for NAICS—324.

The scaling options are presented in Figure 6-33. Excluding the highly volatile “value added” indicator, the scale-up factors are tightly bounded over the entire time period 1992–2012. The range of scale-up ratios is relatively consistent, between 4–6%, for most of the time period, but has dropped quickly in the last few years of recorded data. The employment ratio is consistently higher than the shipments ratio, indicating refineries in Pennsylvania are more labor intensive than the average national refinery.

In 2010, the possible scaling factors range from a low of 1.3% (value added) to a high of 4.9% (refinery capacity). It appears as if value added is an outlier, and not an accurate measure of relative industry size. The results of scaling up the 2010 waste data by the available factors are presented in Table 6-14.

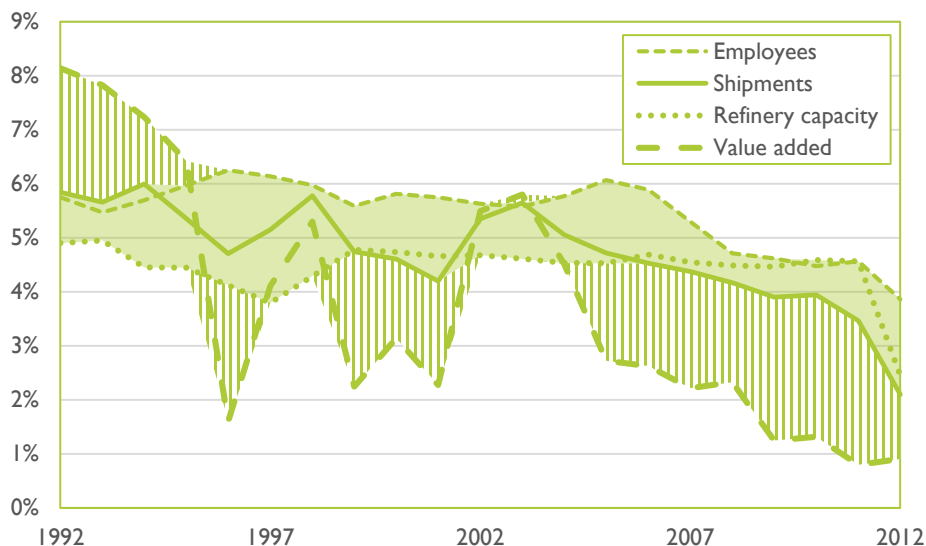


Figure 6-33. Scaling factors available for NAICS—324110 in the PARW, 1992–2012 (EC, EIA Petroleum). The shaded region indicates the range of possible scaling factors.

Table 6-14. Scaled-up waste from petroleum refineries in the PARW database, 2010.

Waste stream	Gg (dry) by scaling factors:			
	<i>Refinery Capacity</i> 4.6%	<i>Employees</i> 4.5%	<i>Shipments</i> 3.9%	<i>Value Added</i> 1.3%
Ash	59	60	68	205
Asphalt	31	32	36	108
Chemical wastes (aqueous)	47	48	55	164
Chemical wastes (solid)	10	11	12	36
Inorganic and refractory wastes	27	28	32	96
Oil containing waste, contaminated soil/debris	215	220	250	750
Plant trash and other waste	110	113	129	385
Sludge/sediment, incl. tank and still bottoms	339	348	395	1,183
Spent catalysts	120	123	140	420
Total	959	983	1,117	3,346

The largest waste category, irrespective of the scaling indicator, is sludge/sediment, including tank and still bottoms. Oil containing wastes are the next largest, followed by spent catalysts. Although the PARW reporting rules exclude hazardous wastes, there is overlap between some of the RW categories and those that might be considered hazardous under RCRA, such as spent catalysts and oil containing wastes. PARW designates these “special handling wastes,” and even though they are not hazardous enough to be regulated by RCRA, they still contain sufficient hazardous materials to require special care, and as such might be inadequate for recycling or reuse.

6.5 Triangulation summary

The three estimation methods each provide a very different picture of NHIW in the petroleum refining industry. The historical forecasting suggests the industry generates between 3.85–4.13 million Mg of non-listed wastes, equivalent to about 1.15–1.24 million Mg of solid content and another 0.31–0.33 million Mg of oil; the remaining tonnage is water. The materials balance offers a minimum tonnage of 0.75 million Mg. The spatial up-scaling method suggests generation between 0.96–1.12 (or as high as 3.35) million Mg of residual waste. I could be tempted to simply report the waste from this industry at 0.75–4.13 million Mg and leave it at that; it certainly would be an improvement on the EPA estimate of 153 million Mg from the industrial facilities survey. But the value of the triangulation method is that it enables corroboration between the figures, which in turn can help narrow the uncertainty band.

The first issue is that of wet vs. dry mass. The historical forecasting results are reported in wet mass; compositional data from a much earlier survey was used to estimate crudely the solids and oil composition. The PARW data, on the other hand, reports the medium of each of the waste flows. Evidence from the other industries has drawn some question as to the accuracy of the waste medium designation, but after examining the data, it appears as if the 2010 designations are plausible, if not correct. With the exception of the aqueous chemical wastes (0.05–0.06 million Mg), all of the rest of the mass is reported as solid, even the “sludge/sediment” waste. (The data that was discarded as outliers was contaminated soil reported as sludge.) There is therefore some agreement between the solid waste estimated by scale-up and by forecast, between 0.96–1.24 million Mg. There is an alternative explanation, which is that the PARW data is biased low due to A) the effect of the PARW program itself driving down waste generation, or B) the exclusion of some wastes from the record, such as the wastewater sludge that would be the responsibility of a downstream POTW facility to report (as I observed in pulp and paper). Neither of these scenarios is particularly plausible for this industry, however.

The second issue is that of hazardous vs. non-hazardous waste. All of the results of the three estimation methods exclude the listed hazardous wastes; the PA data also likely excludes characteristic wastes generated at the refineries, while the forecasted estimates likely do not. This would bias the forecasted data on the high side, as some of those wastes would not strictly fall under the umbrella of NHIW (specifically, the first two letters). However, reporting an accurate waste account depends on the goal of the accounting scheme. If the objective were to characterize wastes flows that can be beneficially used without running afoul of federal environmental regulations, then the lower number from PARW is likely more accurate. But if the objective were to characterize the non-hazardous *fraction* of solid waste output, then the higher forecasted number is more compelling, considering the small mass fraction of hazardous substances that leads to a characteristic determination. In this second case, even including the listed wastes would be reasonable.

Echoing the SAIC observation that no waste classification system is “complete or accurate enough to satisfy all industry members and regulating agencies” (US EPA, 1985), the waste classifications of the three accounts of any reliability—API (1993), US EPA (1996b), and PARW—are not comparable, and therefore it is difficult to say precisely what the composition of the waste really is. The argument to go with the PARW classification and distribution because it is the newest holds some water. Additionally, the scaled-up data retains some internal consistency regarding wet-vs. dry. On the other hand, the PARW classification system is universal to all industries, while the API and EPA classifications from the historical forecasting are unique to the refining industry.

Consider the spent catalyst waste figures available. The forecast offers two distinct estimates of this value, either 0.23–0.26 million Mg (from API) or 2.37 million Mg (from EPA). Although both of these are reported with a wet-basis, waste catalysts do not come in contact with process water, and so will be largely dry at point of generation and point of disposal. This is validated by the water/solids/oil composition data from API (1982). The scale-up estimate of catalyst waste is just 0.12–0.14 (0.42). The bulk of the 2.37 million Mg from the forecasting method is from H₂SO₄ alkylation, a particular waste that does not appear in any of the other estimates. But even the remaining two numbers are separated by a factor of 2, which is not an unreasonable error, but one that we would hope could be reduced. Future work should do two things to try to address the waste composition question. First, the series of API environmental surveys that were not included in the historical forecasting could prove to be enlightening. Second, as petroleum refining is more or less a standard technology around the world, international waste data could be a helpful corroborative factor.

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7 Conclusions & Future Work

This chapter presents a synthesis of the research, a discussion of general and specific conclusions, a summary of key contributions, and thoughts on future work.

7.1 Summary & general conclusions

For thirty years, it has been accepted as truth that non-hazardous industrial waste (NHIW) is generated at a rate of 6.9 billion Mg per year in the U.S., making it the largest waste flow in the country by more than an order of magnitude. Often acknowledged but poorly appreciated is that the value was calculated in 1985 and not updated since. It also most likely includes vast quantities of dilute process wastewater, limiting its practical comparability with contemporary accounts of other waste flows like MSW, hazardous industrial waste, and construction and demolition debris. Furthermore, a nearly contemporaneous estimate of NHIW made by the firm SAIC for the EPA suggests a value closer to 390 million Mg. Nevertheless, for three decades the 6.9 billion Mg figure has persisted and even thrived with little direct interrogation, being used in federal policy language, influencing environmental and waste advocacy, motivating academic research in various fields including political science and industrial ecology, and even showing up on the walls of a museum in London.

Industrial ecology theory envisions strategies for environmental improvement based on the reuse and recycling of wastes throughout the economy. Research and practice alike have demonstrated that many of the waste materials classified as NHIW are ideal for use as substitutes for raw materials via industrial symbiosis, waste exchange, and/or other beneficial use schemes. Assessing the potential for eco-industrial transformation in this way therefore hinges on having accurate and up-to-date accounts of the quantity and composition of waste generated by industry.

Motivated by the glaring data gap around NHIW and the importance of a robust, repeatable waste account for nation-wide sustainability policy, this research was designed to provide just that: a method for constructing such an account at the national industry level, including both mass and composition of waste flows, and the results from its application to three characteristic industry sectors.

The research began with an extensive review of the history of NHIW accounts in the US, going back to the years immediately preceding the establishment of the EPA. Of the five estimates from 1965–1978 that I uncovered, no two relied on the same system boundaries or estimation methods. Nevertheless, the range, 86–301 million Mg, gives credence to the idea that the ultimate EPA estimate is actually highly misleading. Additionally, it seems as if the decision made by the

EPA to deemphasize the SAIC results in their 1988 Report to Congress due to concerns of accuracy and completeness, however legitimate seeming at the time, was a mistake. The review of relevant literature identified multiple attempts made throughout the intervening decades to either make sense of the official NHIW estimate or construct new accounts. Although the results of these studies further reinforce the plausibility of the SAIC estimate over the EPA estimate, at least in order of magnitude terms, the wide range of results (136–430 million Mg) means that none can be considered particularly reliable on its own. Nevertheless, the literature record suggests that sufficient data is available to attempt to study NHIW generation without needing new, empirical observation at the national scale.

Consequently, I propose a triangulation method by which three independent estimates of NHIW generation, each error-prone and incorrect in its own, unique way, are used to cross-corroborate each other at the industry sector level. Based on evidence from the literature, the three estimation methods are:

- Historical forecasting, by which estimates published in the past are extrapolated to the present taking into account changes in industry production, technology, market characteristics, and regulation;
- Materials balance, in which industry-wide material flow models are populated with data on raw material consumption and finished material production in order to assess the waste and other lost mass generated in each industrial process; and
- Spatial up-scaling, in which the unique state-level data of the Pennsylvania Residual Waste program are extrapolated to the national-level by finding the ratio of industrial production in Pennsylvania to industrial production in the entire US.

The specific results from each of the methods are compared to one another in the context of US industry structure and technological trends as well as details of each method and data source.

I applied the method to three industry sectors for the year 2010: pulp and paper manufacturing, iron and steel manufacturing, and petroleum refining. The specific cases were selected to test the feasibility and validity of the triangulation model. The three sectors differ in terms of their raw materials and waste burdens, process technologies, evolution since the 1980s, geographic distribution, and prominence in the SAIC and EPA NHIW accounts. The results from the triangulation method are as follows:

- Pulp & paper: 9.7–14.9 million Mg
- Iron & steel: 21.2–24.7 million Mg
- Petroleum refining: 0.96–1.24 million Mg

Although there is no reason to believe that the results of these three sectors are necessarily representative of the manufacturing sector as a whole, they can be used to bound a range of nationwide generation rates. Scaling factors are calculated as the ratio between the triangulated results

and the EPA and SAIC estimates. I calculated these factors for each industry sector separately and for the aggregated value for all three industries. The range of the aggregated factors is 0.9%–1.2% for the official EPA account and 57%–73% for the SAIC estimate.⁷⁰ From the EPA factors, we estimate a total NHIW generation range of just 65–84 million Mg, and from the SAIC factors a range of 224–287 million Mg (Figure 7-1).

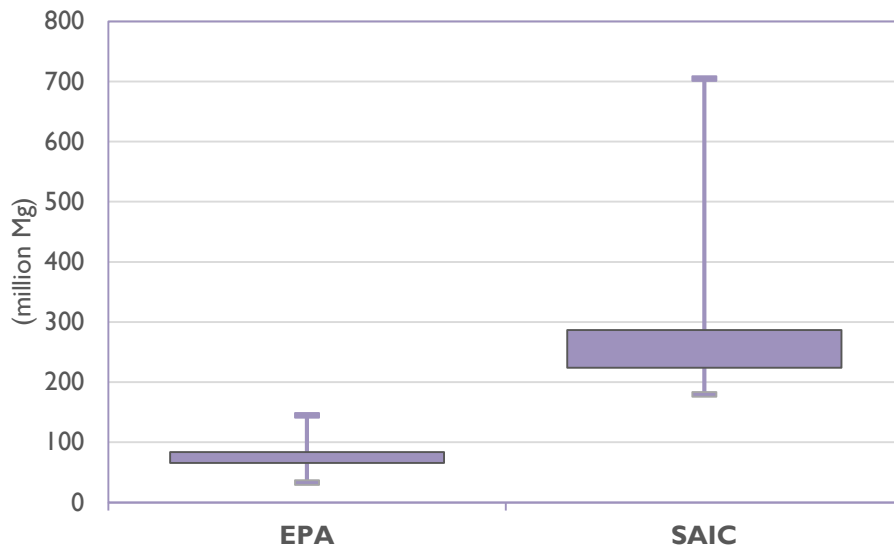


Figure 7-1. Extrapolation of the triangulation results to the whole manufacturing sector based on the EPA and SAIC estimates. The boxes represent the weighted scaling factors and the whiskers the absolute high and low factors.

This result is the last piece of evidence I need to discard the EPA's official NHIW value for good. For most of the last three decades, the 6.9 billion Mg value has been repeated and transformed and misapplied over and over again, often with the same two caveats: it is old and full of water. In the US OTA's revision, the exclusion of off-site waste disposal in the value was also acknowledged, but this was ignored by others, possibly because the on-site number was already so large, it seemed unnecessary to acknowledge that it could be in fact larger. My analysis suggests that the excluded waste material may in fact have been substantial, once the water weight was removed.

⁷⁰ The absolute range of scaling factors is much wider. The low triangulated estimate of pulp and paper waste is just 0.5% of the 2,040 million Mg from the EPA, while the high estimate of iron and steel waste is a whopping 2.1% of the respective 1,180 million Mg. Similarly, the low triangulated estimate for iron and steel is 46% of the SAIC estimate of 46.3 million Mg (after excluding the 14.4 million Mg of foundry sand in the original SAIC estimate) and the high triangulated estimate of pulp and paper waste is 80% larger than the SAIC estimate of 8.3 million Mg.

The logic is as follows. If, as the scaling factors show above, approximately 50% of the 6.9 billion Mg of EPA-reported waste is equivalent to just 32–41 million Mg of NHIW (triangulated here), and if the remaining 50% behaves the same way, then the total NHIW equivalent of the EPA account is 65–84 million Mg. This range is considerably lower than all but one estimate of total NHIW generation available in the literature or previous government reports. The difference must be waste disposed off-site.

The SAIC-extrapolation results point to a reduction in NHIW generation from 1985 to 2010, although with only middling confidence. The three industries contributed nearly 50% of the total NHIW estimated by the EPA, but just 14% of that by SAIC. Nonetheless, it places the economy-wide estimate squarely among every NHIW estimate from government, consulting, and academic sources going back to the late 1960s except that from the EPA’s 1988 Report to Congress. Interestingly, these extrapolated values, 224–287 million Mg also place NHIW generation rates on a par with the generation of MSW in the US for that year: 225 million Mg.

7.2 Discussion

The triangulation approach presented here is effective at generating new, up-to-date estimates of NHIW generation in the US. The three constituent estimation methods rarely agree, but the differences observed can be explained readily after examining industry characteristics and trends (Table 7-1). The case studies are the first step in populating a new account of NHIW, and taken together they also allow for an analysis of each of the three estimation methods and data themselves. In general, the historical forecasting overestimates waste quantities and the scale-up underestimates. Materials balance is less consistent, but instead provides a logical backstop to the analysis.

Table 7-1. Summary of conclusions from the estimation and triangulation method.

	Pulp & Paper NAICS 3221	Iron & Steel 3311–3312	Petroleum 324110
Forecast	12.10–12.33	24.7–25.2	1.15–1.24
Materials balance	8.49–14.66	26.3	>0.75
Scale-up	3.7–6.4	2.0–4.3	0.96–1.12
Triangulation	9.7–14.9	21.2–24.7	0.96–1.24

The forecasting method generally provides a slightly high estimate for a number of possible reasons. First, since the 1980s, process technology improvements have resulted in increased

utilization of raw materials and reduction in waste generation. Similarly, some industries, like steelmaking, have not only increased process efficiency but actually shifted the technology base towards one that is fundamentally less waste-generating, e.g. BOF to EAF. A similar trend can be observed in the increasing consumption of secondary fiber in the paper industry. Although deinking can be a wasteful process, it does not come close to comparing to the quantities of wood and black liquor solids that are generated from the kraft pulping process.

Second, there has been a move towards improved on-site utilization of waste materials. Specifically, processes for recovering chemicals and metals from waste sludge have improved, so the ultimate quantities of those wastes will have decreased. Based on the definition of waste used in this research, even if a waste material is used beneficially on site (e.g. ash used as a soil amendment), it still counts as waste. One exception to this is the use of wood waste as fuel. In this case, the waste material is seen to be the ash, not the wood. In the paper sector, increased on-site wood combustion has in fact led to decreased solid waste generation.

A third possible explanation has to do with the hazard criterion. NHIW is defined as material other than that which is explicitly classified as hazardous. As the number of RCRA Subtitle C listed wastes has increased over the years, some materials that were once non-hazardous must now be excluded. On the other hand, the total generation of hazardous waste has gone down over the decades, and contrary to my original hypothesis, the decrease did not seem to result in an increase in NHIW. Similarly, increasingly strict water and air pollution controls had an effect on waste generation when those regulatory programs were put into place in the 1970s, and no further effects have been explicitly noticed since.

The scale-up estimates from the Pennsylvania Residual Waste program underestimate waste generation. Again, there are multiple possible reasons for this. First and foremost, the reporting rules for the program allow generators to exclude materials that are beneficially used or sold as byproducts. In the definition of waste used here, these materials should be included, and before the rule change, were counted in the PARW data set as well. Another possible reason also has to do with classification. Each individual waste flow reported to the PARW program is given a NAICS code that most closely aligns with the activity that generates the waste, not necessarily the activity that best defines the industry of the generator. So, it is possible that some reporters assign waste generation associated with wastewater treatment with that NAICS code rather than, for example, steelmaking.

The materials balance estimation method was the least enlightening of the three. It does in many cases offer the physical baseline on which to compare the messy and sometimes confusing results from the other two methods. However, contrary to the Ayreses' contention it does not seem to be that effective of a method for waste estimation by itself. The reason for this is that unlike the large volumes of ore refining wastes and other lost masses that dominate the DPO, NHIW really is a small fraction of total industry output, and therefore is often difficult to distinguish from the

model noise. Many of the small waste flows that Ayres identifies do not proceed from model logic; rather certain input flows are simply averred to be fully converted to waste. By expanding the industrial metabolism model to incorporate a time series analysis, I no longer have great faith in the reliability of the reported consumption and production input data, further weakening the materials balance method.

Interestingly, although in many cases the aggregated NHIW estimates both from forecasts with different baselines and from different estimation methods would agree, while the compositions from those sources would not agree. For example, the two baselines for the pulp and paper forecast (1978 and 1995) generate very close, as do the forecast and materials balance estimates for iron and steel. However, the compositional differences among these are large. It is possible that the coherence of the different estimates is just coincidence. But it is also possible that it is a result of imprecise waste classification. Perhaps the same waste material would be classified as sludge by one reporter and dust by another. The incompatibility of the PARW waste classification scheme with those from historical reports and the materials balance poses a similar challenge.

The story of the decades-long search for the knowledge about industrial waste quantities and the percolation of information once an estimate was found teaches a lesson about how waste data is understood by the public. Put simply, we have no patience for nuance. We are not well-built to accommodate asterisks in our understanding of (probably everything) but particularly environmental impact. This is the mechanism of risk from incomplete accounting. The EPA's contractor reported about just one dimension of industrial waste management—disposal—but within a year that value was being used erroneously to represent generation as well. The distinction between the two stages in waste management are poorly appreciated by the public, but the EPA itself should have been more clear about what the data actually meant. The footnotes and explanations notwithstanding, it was just the top-line conclusion that entered the public consciousness about NHIW. Any public engagement around environmental issues and waste should heed this lesson. I do not believe that science and public policy must be dumbed down for public consumption, but complexity must be sold carefully, and if a simple story is all that is included in an executive summary, then it will be difficult to dislodge simply by claiming that it is actually more complex than people realize.

7.3 Summary of Contributions

This research offers intellectual contributions in multiple areas. Methodologically, this work contributes to material flow accounting and industrial metabolism studies. The domains of the research include industrial ecology and sustainable waste management. There are also practical implications of both the methods presented and the new waste accounts.

- Developed a method to estimate waste material flows from indirect observations

- Demonstrated the utility of triangulation to extract meaningful materials flow information from otherwise unreliable data and models
- Refined industrial metabolism models of three industry sectors
- Explained the data gap around NHIW in the US
- Populated a new account of NHIW
- Clarified the difference between generation- and disposal-based waste accounting
- Highlighted the value of returning to historical and primary documents for industrial ecology research
- Concluded that NHIW generation is an order of magnitude less than originally thought
- Enabled the regular accounting of NHIW to track change over time
- Identified the practical limitations of waste estimation, motivating improved, national-scale data collection

7.4 Future Work

The work presented in this dissertation represents just the beginning of a long process of improving and rectifying waste accounting in the US. Now that I have demonstrated the viability of the triangulation method for estimating contemporary NHIW generation and applied it successfully to three sectors, the same method can be used to complete the construction of an economy-wide NHIW account. The SAIC and EPA accounts had 22 and 17 sectors, respectively. Those studies suggest that an effectively complete account of NHIW could be accomplished with data from just 12–14 sectors.

The three industry cases chosen for this thesis vary in dimensions important for validating the triangulation method. It is possible, however, that there are characteristics of other sectors that would make them ineligible for triangulation using the three estimation methods developed here. For example, equipment manufacturing sectors are poor candidates for materials balance because there is not a set of fundamental physical processes at work. In these cases, other data should be explored, including life cycle inventories and international accounts. In general, there is other available data that can help to further flesh out the understanding of NHIW in the US, including the Toxics Release Inventory, the RCRA Subtitle C Biennial Reports, and the US GHG inventory.

Another extension of the work should be to add more dimensions to the waste account. Right now, the account is limited to just generation tonnage and composition. As we have seen, the distinction between generation and disposal is an important one. In addition, much of the NHIW generated in the iron and steel industry is already beneficially used. Integrating this type of data into the account takes it one step closer towards being able to be used to calculate waste reuse and industrial symbiosis potentials.

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Legal Citations

Current Federal Laws

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