Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii

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Summary

Home to the capital city and nearly a million people, the island of Oahu in the state of Hawaii, USA, is highly dependent on external resources. Over the past decade, large-scale agricultural production has diminished dramatically, leaving the island greatly reliant on imports for food and most other basic goods. A strong tourism sector and high levels of affluence contribute to per capita municipal waste generation rates exceeding all other U.S. states. The only municipal landfill requires immediate expansion if it is to remain in operation, and it has proven extremely difficult to find additional disposal sites. An island-wide material flow analysis (MFA) was performed as an innovative means of considering issues of import, export, consumption, and substitution, resulting in long-term strategies for diminishing the generation of waste that could complement current local conservation and recycling efforts. The findings indicate several opportunities for using domestic waste resources to substitute for imports and simultaneously reduce waste generation, particularly for construction materials. Legislative constraints and possible changes in this regard are also considered. Although past efforts by both the city and state governments to encourage on-island recycling and reuse have not achieved set goals, the MFA results suggest numerous opportunities that could be pursued to increase material self-sufficiency and/or reduce waste disposal by several hundred thousand short tons, enhancing the long-term sustainability of the island.

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Introduction

The island of Oahu, home to the state capital of Honolulu, is the most populous and developed of the Hawaiian Islands, which lie isolated in the middle of the Pacific Ocean. Like most islands, Oahu is heavily dependent on flows of imports such as food, fuel, and manufactured goods to satisfy its modern physical resource needs. Industrial ecology as a field is dedicated to the study of how these and other resources flow through human and industrial systems with an eye toward conserving energy, water, and materials. Given the acute waste disposal problem on Oahu and a variety of near-term interventions being explored, it seemed prudent to investigate longer-term solutions for resource conservation and waste reduction. An island-wide material flow analysis (MFA) was performed as an innovative means of considering issues of import, export, consumption, and substitution, resulting in long-term strategies for diminishing the generation of waste that could complement current local conservation and recycling efforts.

Many islands face physical material availability constraints, and these are exacerbated by the quantity and diversity of consumption present in the modern world. Oahu's economy, like that of the entire state, has progressed through a series of social and economic phases. Prior to significant outside influence, Oahu maintained a sophisticated agricultural economy that supported several hundred thousand native inhabitants (Stannard 1989). The islands were politically and economically divided into wedge-shaped areas called *ahupua'a*, which ran from the mountains to the sea along natural watershed boundaries. Within these boundaries, Hawaiians set up complementary farms of crops (mostly taro and banana) and aquaculture that used the slope of the land to emphasize water and nutrient cascading.

With the advent of foreign influence and commercial pressures, early large-scale industries were based on extractive harvesting such as whaling and sandalwood. At the turn of the 20th century, plantations were established to produce large monocultures such as sugarcane and pineapple for export. In the past several decades, the processes of globalization and, in particular, the lowering of tariffs and trade barriers, have made these plantations unprofitable as suppliers of raw materials. In the latest phase, tourism has become the dominant feature of the economic landscape. The tourism shift began in the late 1950s, taking off in earnest when Hawaii was made the 50th U.S. state. Tourism today represents approximately a quarter of the Hawaiian economy and a third of its jobs (DBEDT 2006).

The military presence on Oahu also remains significant today. Currently some 44,000 armed forces personnel and 53,000 military dependents reside on the island, and military land holdings account for more than 20% of Oahu's land area. The Pearl Harbor naval base alone pumps an estimated $4 billion into Honolulu's economy. The large military presence has many material flow consequences; for example, many aspects of waste management are run in parallel with the municipal system, and imports of petroleum to service the military make up a large portion of the overall demand for this fuel.

Oahu faces significant barriers to economic diversification. The first among these is the island's remoteness and the resulting high cost of shipping. This raises prices for any sort of industrial process involving raw materials, or any agricultural business requiring fertilizer or feed, and makes exports from Oahu less competitive. Another factor is that Oahu's economy is of an intermediate size: it is large enough to demand a diverse stream of products and materials but can be too small to provide economies of scale or adequate market competition. From the perspective of material utilization, on the collection end, this size makes it difficult for reuse and recycling businesses to secure a consistent waste stream and, on the market end, may be insufficient to find enough uses for secondary materials.

Just as islands have proven to be valuable units of study in the biological sciences, they have emerged as a useful type of system for industrial ecology as well (Deschenes and Chertow 2004). The borders of landlocked cities are poorly defined and porous, usually containing numerous major entry points by car, rail, ship, or air. Materials can flow freely through these casual borders without being officially noted. Islands represent physically constrained systems with unique challenges and opportunities, making questions of sustainability more immediate than in locations with greater resource availability and diversity. A fortunate side effect for research is that the physical constraints of islands and their limited number of entry points also have translated into a simplified paper trail for tracking the movement of materials. Individual countries have this same advantage in the form of customs bureaus, and most MFA research has been carried out on a country level, in part because MFA was envisioned early on as an indicator for national-level environmental planning (Kleijn 2000; Matthews et al. 2000).

Material flow research specifically for islands is limited. Singh and colleagues (2001) examined the social metabolism of the island of Trinket, in the Indian Nicobars. This small, remote, and relatively undeveloped island was found to be nearly self-sufficient, relying on local biomass and minerals for all basic necessities. Small amounts of fossil fuels and final products were imported to supplement indigenous resources. In addition, a large quantity of sand was being exported for use in concrete production on a nearby island as well as a small amount of dried coconut. This work demonstrated clearly and quantitatively the differences in per capita material requirements between rural Trinket and more developed regions.

Islands also have been a main focus of study for the Yale University Center for Industrial Ecology. Research in Puerto Rico between 2001–2008 focused on material flows and industrial symbiosis (Chertow et al. 2008). On the Island of Hawaii,[1] teams of Yale researchers completed a preliminary island-wide MFA (Houseknecht et al. 2006) as well as additional studies on waste (Houseknecht 2006), water (Fugate 2008), and energy (Johnson et al. 2006; Johnson et al. 2007). The Rocky Mountain Institute compiled a complementary report on some food flows for the Island of Hawaii (Page et al. 2007). Figure 1 shows preliminary material flow results for the Island of Hawaii. As on Oahu, waste disposal options on that island are few, highlighting the trade-offs between waste management practices and land use.

Oahu's 906,000 residents and 22,100 businesses generate nearly 1.8 million short tons[2] of waste annually before recycling, about two thirds of which is municipal solid waste (MSW) (R.W. Beck 2007a; U.S. Census Bureau 2007). Though Hawaii's consumer price index is well above the national average, suggesting higher prices with consequent lower consumption, this is not the case. The large tourism sector and a relatively high level of affluence means that islanders generate 1.5 tons of MSW annually per capita, well above the national average of 0.8 to 1.2 tons per capita, which does not include hazardous or construction wastes (Kaufman et al. 2004; U.S. EPA 2007). Rising population and waste generation rates have put waste management officials in a difficult bind: there is only one municipal landfill on the island operating under a short extension, and a lengthy repermitting process would be required if use is to be continued (Boylan 2009). Regulations restrict siting landfills over groundwater supplies, which exist in the interior of the island; this constraint limits possible sites to areas close to the ocean, where population densities are higher, and there are many competing land uses. Combined with local concerns surrounding odors, traffic, and other quality-of-life issues, it is extremely difficult to find new landfill sites. A waste-to-energy plant on the island also has reached capacity, and a third boiler is being considered. The waste disposal problems are so acute that officials are planning to ship 100,000 tons of MSW nearly 2,700 miles away to a landfill in Washington state (Yap 2008; Boylan 2009).

The current study of waste and material flows on Oahu began with the recognition that incremental improvements to the existing waste management system would not offer a long-term solution to Oahu's disposal problems. The study was designed to tie together all material flows with waste, under the hypothesis that understanding material flows would provide a longer-term perspective on the generation of waste and how it could be modified over time. Through a grant provided by the Hawaii Community Foundation in 2008, four groups of Yale University graduate students conducted studies of material flows on Oahu. Each group focused on a portion of the overall material flow analysis, discussed in the next section, as follows:

1. Imports, exports, and resource extraction (Famely et al. 2008);
2. Military (Espinoza et al. 2008);
3. Private sector (Parthasarathy et al. 2008); and

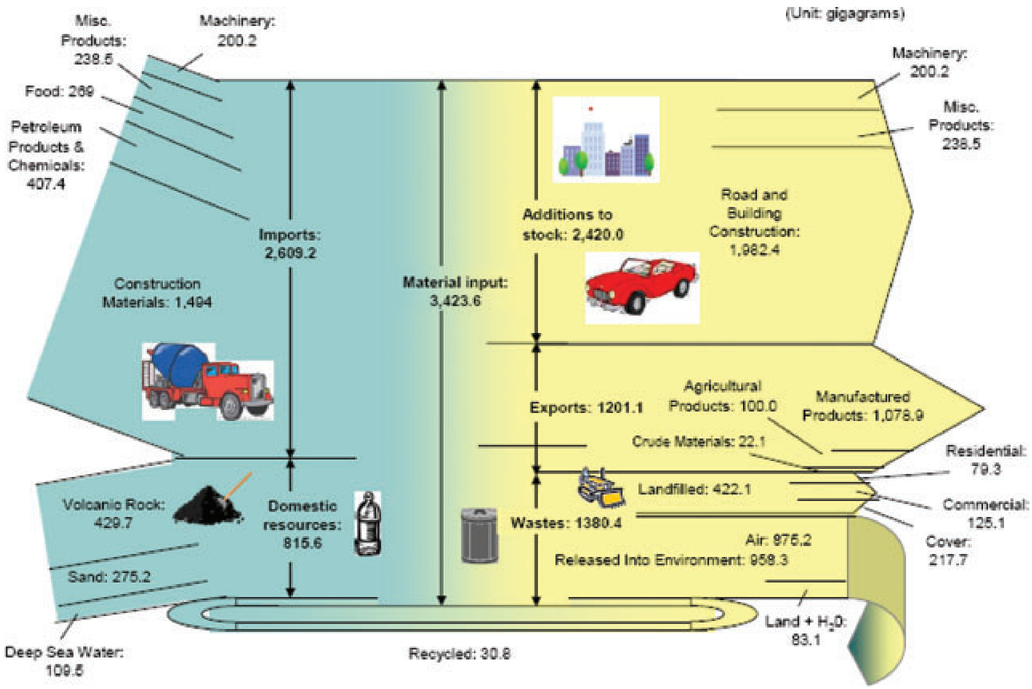

Figure 1 Overview of material flows on the Island of Hawaii (in gigagrams). One gigagram (Gg) = 10^3 metric tons ≈ 1.102×10^3 short tons. *Source:* Houseknecht and colleagues, Yale Center for Industrial Ecology.

4. The waste management system (Oden et al. 2008).

Their findings were integrated and amended with further research to form the present article. Its purpose is to provide a multilevel, quantitative picture of material flows on the island of Oahu as a means of highlighting the sustainability issues and opportunities that the island faces. The present study offers options for import substitution, resource reutilization, and accompanying legislative change as a means of addressing the complementary issues of dependence and waste management. The study does not address existing government program goals, types of economic instruments, or deeper consumption issues related to human social behavior.

Oahu Material Flows

Thinking of Oahu as a generic system (figure 2), material flows on the island logically fall into the following categories: (1) imports from international and mainland U.S. ports, (2) products from the other Hawaiian islands, and (3) domestic production, all of which provide raw materials to Oahu's markets. These materials then enter use in Oahu's economy as products. After use, remaining materials are discarded into waste management. Most of this waste is burned for electricity production, while the resulting ash and the rest of the waste are landfilled. A large amount of material is reused or recycled on the island; some also is sent for export, along with commercial products from the island's industry. Oahu's exports are adjusted for re-exports to and from other islands that do not enter the system of Oahu.

The material flow results presented here are the product of data gathering and interviews conducted by graduate student researchers in the spring of 2008. Significant follow-up research to fill in data gaps and conduct the analysis occurred over the summer of 2008. The major source of statistical information about Oahu is the *Hawaii State Data Book* (2006), published annually by

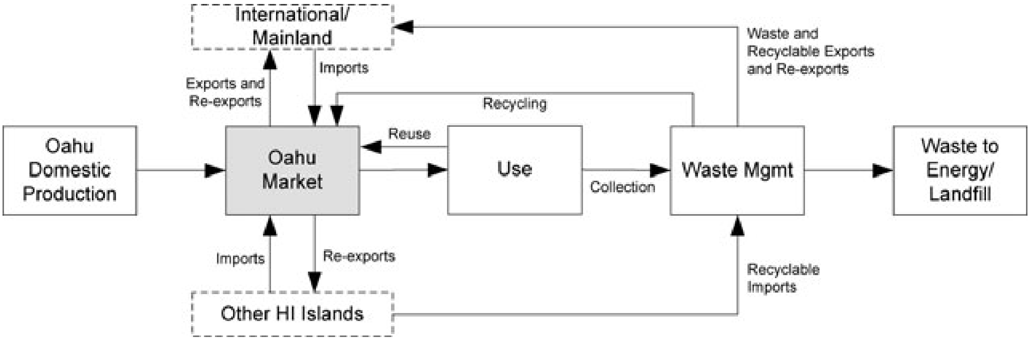

Figure 2 Schematic diagram of material flows on Oahu.

the Department of Business, Economic Development, and Tourism (DBEDT), which follows the format of the *Statistical Abstract of the United States*. Material flows are summarized in each section and quantified in table 1.

Imports

Nearly 98% of goods imported into Oahu arrive by ship. The port of Honolulu, an improved natural harbor, is the largest in the state and is the only port in the state that is capable of handling container traffic. As a result, containers destined for other islands in the state must be off-loaded in Honolulu, reloaded onto smaller vessels, and re-exported. This greatly inflates the raw import and export data, which must be adjusted. Indeed, various regulations ensure that out-of-state and interisland traffic are handled by separate companies.[3] In addition to containers, Honolulu's port handles liquids (mostly petroleum), dry bulk (mostly aggregate), neo-bulk (such as lumber), and other miscellaneous shipments, totaling 13.4 million tons annually. Barber's Point, an industrial port located in the southwest of the island, services the two oil refineries and many of the

Table 1 Island-wide material flows for Oahu, Hawaii, 2005 (in 1,000 tons, excluding water)

Mass balances	1 +	2 −	3 =	4	5 =	6 +	7 +	8
Products (waste materials)	*Imports*	*Domestic production*	*Exports*	*Apparent consum.*[a]	*Waste generation*[a]	*On-island recycling*	*Disposal*	*Waste exports*
Lumber (C&D, wood)	350	9	270	89	58	8	50	0
Paper (paper)	110	0	40	70	360[b]	0	290	70
Minerals (C&D, glass)	540	3,400	215	3,725	460	210	250	0
Metals (scrap)	2,450	0	1,600	850	176[b]	0	21	155
Chemicals (hazardous)	145	0	69	76	30[b]	15	2	13
Food and agriculture (scraps, sludge)	857	104	239	722	203	43	160	0
Biomass/green waste	0	200	0	200	160	80	80	0
Fossil fuels/ash	9,500	0	2,700	6,800	70	70	0	0
Final products/ discarded products	2,659	5	1,534	1,130	274	15	255	4
Total	16,611	3,718	6,667	13,662	1,791	441	1,108	242

Note: 1,000 tons (short tons) = 2,000,000 pounds (lb) ≈ 907,000 kilograms (kg, SI) = 907 metric tons. Consum. = consumption. C&D = construction and demolition.
[a]Calculated by mass balance
[b]Incorporates waste from final products

200 industries located in the nearby Campbell Industrial Park. Annual imports to Barber's Point amount to 3.8 million tons, most of which is petroleum. Kewalo Basin is a much smaller commercial fishing port, handling 9,000 tons of seafood annually (IWR 2005).

Domestic Production

For most of the 20th century, Oahu was an agricultural powerhouse, producing large quantities of pineapples, sugar, and livestock. These industries have nearly collapsed, meaning that the island produces very little of what it finally consumes, resulting in a large trade deficit in goods. The most significant domestic extractive industries are rock quarrying, small-scale agriculture (including flowers), fishing, and water provisioning. The island's three commercial quarries produce nearly 3.4 million tons of basalt, almost all of which goes to satisfy the island's construction industry. No sand deposits exist on Oahu, so approximately 70,000 tons of sand are imported from Canada for concrete production every year (as well as more than 400,000 tons of foreign cement). The island's farms and fisheries produce more than 100,000 tons of food annually; the most significant products in 2005 were pineapples (48,000 tons) and milk (26,000 tons), though production of both has since dropped off considerably owing to the closure of several large agricultural operations (DBEDT 2006). Most of this food is consumed on the island. An estimated 200,000 tons of nonproduct biomass (such as grass clippings) are generated every year. Because of Oahu's peculiar volcanic history and geography, the island contains several large aquifers that support all of the water demand, totaling 790 million cubic meters (or 870 million tons) of water per day.[4] As is usually the case, material flows of water dominate the overall material flow picture by mass.

Conversion and Use

Considered here are the largest subsectors of Oahu's economy: power generation, construction, the public sector (dominated by the U.S. military), tourism, and transportation. These sectors have significant linkages among them. Retail goods were excluded as materials are largely unaltered as they pass through commercial stores; the only significant flow included is waste packaging material.

Power Generation

The AES cogeneration plant[5] is the only coal-fired power plant on the island and produces about 14% of the island's electricity (180 MW). Although the state has set aggressive renewable portfolio standards, very little renewable energy generation takes place on Oahu. Five to seven percent of the island's power comes from the H-POWER waste to energy facility, with the remaining 80% coming from six large-scale oil-fired sources. All of the plants take in fuel, oxygen, and water, and emit carbon dioxide, water vapor, and ash. The AES plant uses 25,000 tons of limestone from Oahu quarries, 7,000 tons of shredded waste tires, 5,400 tons of waste oil, and a small amount of activated carbon from a nearby wastewater treatment plant. Of the 50,000 tons of fly ash produced by AES in 2005, 7,000 tons is used by Hawaiian Cement, and the remainder is mixed with 20,000 tons of bottom ash and water and used to cap the PVT landfill[6] (Parthasarathy et al. 2008; Chertow and Miyata 2009).

Construction

In 2006, more than 16,500 building permits were issued on Oahu, approximately 60% of which were for residential projects. Based on the square footages of each project and calibrated by in-depth studies of ten projects for which detailed data were available, the private construction sector accounted for more than 360,000 tons of material added to the existing building stock (excluding water and fuel). The U.S. military also engages in a significant amount of construction and the Department of Defense (DoD) has a federal mandate to contract out as much work as possible (above a certain size) to private enterprise (OMB 2003). Most of the new construction is for housing, served by two large contractors: Actus Lend Lease for the Army and Air Force, and Forest City for the Navy and Marine Corps. Both are reporting high rates of concrete reuse as they demolish some homes and build others. In total, construction for the military in 2005–2006 amounted to 153,000 metric tons of material addition to stock (Espinoza et al. 2008).[7]

Military

In addition to using materials for construction, the military consumes 880,000 tons of liquid fuels, particularly for refueling large ships and aircraft; this fuel is centrally stored at the Pearl Harbor naval base. Fuel is the military's largest material use by far, excluding water. As many military personnel live on-base and dine in central locations, there are significant flows of food to the military sector: an estimated 2,200 tons is consumed annually. Another small but interesting military material flow is the 275 tons of ammunition used in target ranges. After use, the brass casings are recycled and some portion of the lead bullets is recovered (Twilligear 2008).

Tourism

Quantifying the material flows of the tourism sector is complicated, as it is difficult to determine how much of the island's goods and services are consumed by tourists as opposed to residents. Tourists also are constantly importing and exporting materials in luggage. The Hawaii Data Book estimated that each visitor spent nearly $180 per day, of which $40 was to shopping and $30 was to food (DBEDT 2006). Most of what tourists spend goes toward lodging, and hotels dominate the landscape of the large tourist centers.

Transportation

The tourism sector heavily influences transportation, as rental cars make up a large portion of the total fleet. There are nearly 600,000 cars on Oahu, all of which are imported, a large number for a small island of only 1,500 square kilometers (km^2).[8] Despite large influxes of new cars, in 2006 the mass of the Oahu vehicle fleet actually decreased through the export of used and end-of-life vehicles. The transport sector consumes some 990,000 tons of liquid fuels, which, along with military fuel use and power generation, accounts for the vast majority of petroleum use on the island (DBEDT 2006).

Waste Management

As they are tracked by both the City and County of Honolulu as well as the state of Hawaii, municipal waste generation and disposal statistics are well-quantified and characterized. For other types of waste, such as construction and demolition (C&D) or recyclable materials, statistics are not as robust. The best estimate, counting all municipal, commercial, and industrial activities, is that 1.8 million tons of solid waste material were generated for fiscal year 2006, with about a third of this total being recovered by various private businesses and waste brokers on the island (R.W. Beck 2007a). Traditional recyclables such as paper, metal scrap, and household bottles and cans are largely exported, mostly to Asia, though the volumes and exact destinations change frequently with the volatility in worldwide scrap markets. Some large retailers backhaul packaging waste to the west coast of the United States in containers that they own, but this constitutes a small percentage of the total. More than 400,000 tons of materials are recycled or reused on-island, including 210,000 tons of inorganic minerals used as landfill cap, structural fill, and road base by one large construction company (Grace Pacific Corp.) and several smaller operations; 70,000 tons of power plant ash from AES; and 80,000 tons of green waste recycled by a single company, Hawaiian Earth Products, in two large operations in the south of the island.

Outside of the public system, approximately 200,000 tons of C&D waste is disposed annually at the private PVT landfill. This constitutes approximately 80% of all C&D waste on the island; the remainder is inadvertently sent for disposal to the public system. This C&D waste is largely inorganic material such as concrete, sand, and old paving. The U.S. military operates its own waste management system that intersects with the public system at many points. Most nonhazardous military waste is collected by private contractors, though the Marine Corps operates a small landfill at its Kaneohe base that takes in 2,000 tons of MSW and 750 tons of other assorted wastes (Lotti 2008).

Of the approximately 900,000 tons of waste that are not recovered earlier or disposed of at private facilities, two-thirds are treated at

H-POWER, the waste-to-energy facility. In the process of preparing the MSW, some 21,000 tons of metal are recovered and sent for recycling, and 79,000 tons of noncombustible residue are screened out that currently have no end use. The remaining 300,000 tons of MSW, as well as the ash and noncombustible residue from H-POWER, are disposed at the Waimanalo Gulch landfill, on the western side of the island. Green waste is completely banned from landfill disposal but can be sent to H-POWER in amounts less than 10% per load. Despite this restriction, an estimated 80,000 tons is disposed of in this way.

As of 2006, there was no municipal curbside recycling program, though pilot programs have been conducted in several neighborhoods of Honolulu as a precursor to an island-wide effort now being implemented (Honolulu ENV 2008a). MSW and green waste are collected regularly from residences; commercial establishments use private haulers to haul municipal waste to one of three transfer stations or directly to H-POWER or the Waimanalo Gulch landfill. For general household waste, large appliances, propane tanks, auto batteries, green waste, and tires, residents can make use of the six drop-off "convenience centers."

All wastewater is treated by the City and County of Honolulu. The eight wastewater treatment plants (WWTPs) have a combined outflow of more than 150 million cubic meters annually into both freshwater and ocean outlets (Honolulu ENV 2008b). Honouliuli Water Recycling Facility generates 16.5 million cubic meters of recycled water every year for nondrinking uses. Most of this reclaimed water is used for golf course irrigation; the rest is treated to a higher standard and is used in industrial applications. Biosolids are generated during the wastewater treatment process and comprise about 5% of Oahu's total solid waste. Honolulu currently landfills the biosolids but is considering reuse options. It has developed a partnership with Synagro, a company that will digest, dewater, and heat-dry approximately 20,000 tons of biosolids generated from the Sand Island WWTP (half of the total) to be used as fertilizer pellets. Since 1998, the Navy facility in Kalaeloa had composted green waste with biosolids from the Honouliuli WWTP to produce soil additives and compost (approximately 10,000 tons in 2005). Because of changes in Navy policies, however, this facility stopped accepting material from the city but still processes biosolids generated by the Navy (Oden et al. 2008).

Exports

The majority of exports are petroleum products shipped from the Chevron and Tesoro refineries at Barber's point (IWR 2005). Much of this is shipped to the outer islands for direct consumption, mostly for transportation and power generation. This is not considered re-export as the crude oil is refined into various fractions on Oahu before being shipped out. The remaining export shipments are largely food and farm products and waste materials. Although the material throughput of Honolulu's airport is small compared with the ports, it is still an important gateway for products that are time-sensitive, such as cut flowers or mail. Taking into account both overseas and intrastate traffic, Oahu is a net exporter of both air freight (45,000 tons) and mail (1 ton) (HDoT 2008).

Material Flow Summary

One of the primary benefits of applying MFA to what is largely a waste management problem is the ability to see the entire system of material flows upstream and downstream of waste management, broken up by category. This allows readers to follow materials as they enter the Oahu system through import or domestic production; circulate or become additions to existing building stock (such as when building materials are placed into houses where they stay for long periods of time); are recycled on the island; or leave the system through disposal or export, thus providing a clear view of material requirements and import substitution opportunities.

Table 1 is a summary of material flows for Oahu for 2005. Imports and Oahu's domestic production (columns 1 and 2) constitute the inputs to the system. Products that are exported from the island (column 3) constitute the non-waste outputs. The difference between inputs and non-waste outputs is known as apparent consumption (column 4) and represents the net mass of products that enters Oahu's economy for use.

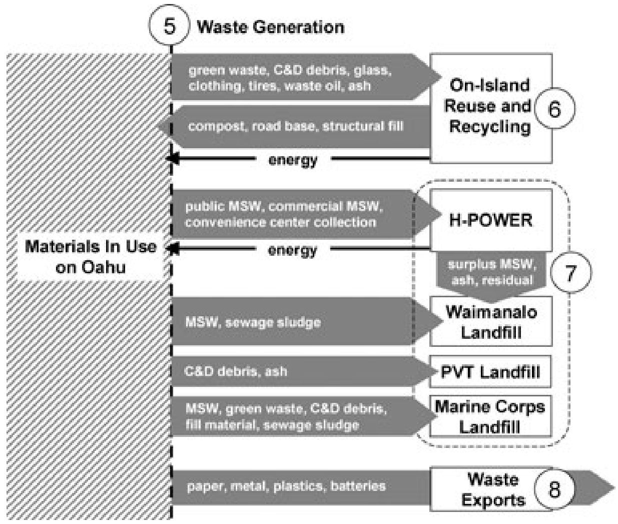

Figure 3 Waste management and recovery material flows on Oahu. The processes are numbered according to table 1. C&D = construction and demolition; MSW = municipal solid waste.

Some of these products are used and discarded within the same year and enter waste management. To these are added products that entered the economy in the past and have reached the end of their useful lives and are thus discarded. These together constitute waste generation (column 5), which is balanced by the three waste management options: on-island reuse and recycling, disposal (including waste to energy and landfilling), and export of materials off-island (columns 6 through 8). Although it is not shown in table 1, the difference between apparent consumption (column 4) and waste generation (column 5) represents material that is added to in-use stock, such as buildings and durable goods. Both apparent consumption and waste generation are calculated by mass balance, as shown in table 1.

Each material category shows both the type of product input (such as fuel) and the corresponding waste material shown in italics (such as ash). Although an effort has been made to separate material flows by category, there is some crossing of material categories that complicates the overall picture. This is most apparent in the case of paper. Some 70,000 tons of paper enter the economy as paper products (apparent consumption), but 360,000 tons of waste paper are generated. This large mismatch occurs because much of this waste paper existed previously as packaging on final products or as the final products themselves (as catalogs, for example). It was not possible to ascertain what portion of the paper in waste generation entered the economy as basic unprocessed paper, highlighting the difficulties in tracking single substances through a complex economy.

The differences between apparent consumption and waste management clearly show that (1) fossil fuels and food and agricultural products are consumed rather than entering the waste management regime and that (2) most construction minerals, metals, and durable final products are added to stock through the process of economic growth and will enter the waste stream at a later date. Water and wastewater are the largest flows by mass through the island system, some three orders of magnitude larger than total solid material flows.

To visualize the waste management system in more detail, a material flow diagram was created (figure 3) that describes the types of waste and shows the relationship between H-POWER and the landfill. The processes in figure 3 are numbered according to table 1.

Implications and Applications of Oahu MFA Results

The MFA results suggest significant opportunities for improving the island's long-term sustainability in three general areas: (1) import substitution; (2) waste utilization; and (3) enabling changes at the legislative level.

Import Substitution

As shown clearly in table 1, Oahu's dependence on foreign goods is variable but in general quite high, ranging from 10% for construction minerals, to 100% for fossil fuels. In many cases, however, there are unused or underutilized resources on the island that could serve to displace at least some portion of these imports. The opportunities are particularly attractive in the cases of construction minerals, energy, and food.

Construction Minerals

Excluding water, inorganic minerals such as sand and gravel for construction are among the largest material flows by mass for large systems. This also was found to be the case both for Hawaii Island (as seen in figure 1) and Oahu. Though Oahu has three domestic quarries, these do not fulfill the demand of the island's construction industry, and the concrete industry is forced to import some aggregate and a large quantity of sand. One company currently recycles nearly 100,000 tons of C&D waste into concrete and fill but is limited in the applications to which it can put this recycled material. City highway regulations have placed a cap of 30% recycled aggregate for road base construction and 10% glass for limited road construction projects (R.W. Beck 2007a).

A large supply of waste inorganic minerals still exists that could be safely utilized: the PVT landfill on the island took in 250,000 tons of C&D material in 2005, and of this, managers estimate that approximately 8% is asphalt, 20% to 25% is concrete, and 10% to 20% is sand, rock, and dirt. Both the Island Demo transfer station that handles C&D waste and the PVT landfill could potentially process or separate and use/sell valuable construction material, though the mixed state of most incoming waste currently present challenges. Revisiting construction specifications and permit rules could increase C&D waste recovery and lead the island toward self-sufficiency while reducing pressure on domestic sources for this important material category.

In part as a result of Hawaii's container deposit law that charges a five cent deposit at purchase to be collected when beverage containers are returned,[9] Oahu businesses recover 20,000 tons of glass annually. An additional 16,000 tons (mostly noncontainer glass) is sent for waste treatment and disposal. Though limited amounts of glass are ground into fine particles and used in construction projects, there are virtually no economically viable disposal or recycling options for glass handlers on Oahu. The consultancy R.W. Beck (2007a) recommended to the City and County of Honolulu an expansion in the permitted uses of glass in construction to create a local market for this material.

Energy

Hawaii has no fossil fuel resources of any type. The only natural available energy is renewable, and Hawaii as a state has been early in meeting required renewable energy portfolio standards. Generating electricity from renewable sources avoids fossil fuel imports that would otherwise be necessary and so has significant material implications for the island. Oahu imports 880,000 tons of coal for electricity generation each year; 94% remains on Oahu, and 6% is shipped to Hawaii Island. H-POWER provides the largest source of indigenous energy to Oahu, with a capacity of ~50 MW generated from local waste. The island is heavily dependent on imported petroleum for power generation and transportation fuel; the interruption of fuel imports currently poses one of the most critical dangers to the island's economy. Efficiency measures and conservation must be considered as short-term (and often low-cost) solutions to curtail growing demand and long-term strategies for energy sustainability. Such measures also would have significant material flow implications, though they are not traditionally considered in MFA.[10]

A new state collaboration with the Department of Energy and the local electric utility called the Hawaii Clean Energy Initiative sets a target of 40% renewable electricity generation and 60% to 70% renewable energy for the entire state. This would likely require tying together the islands in a statewide microgrid and would result in a large decrease in petroleum use for power generation and transportation.

Waste oil and recovered tires are high-heat content materials currently burned for electricity in the AES plant that could be used to a greater degree to displace coal imports. An estimated 10,500 tons of tires are shipped off-island for processing on the U.S. mainland, depriving Oahu of a valuable energy and material resource (R.W. Beck 2007a). Approximately 5,400 tons of waste fuel oil is collected and burned at AES. Another 3,900 tons of waste cooking oil also is converted into biodiesel by the Pacific Biodiesel operation in Honolulu, which is then sold to island residents and businesses.

Great attention has been awarded to the prospect of growing biofuels on Oahu. The Rocky Mountain Institute has identified 150 km^2 of Oahu as prime biofuel cropland and additional 67 km^2 as restricted use or nonprime. Approximately 7,000 km^2 of cropland would be required to replace Oahu's gasoline demand with ethanol (RMI 2006). This area is almost 50 times greater than the prime agricultural land available and almost five times greater than the total land area of Oahu. So there is a large discrepancy between the energy demand and the energy that could be made available using current biofuel technology. Any significant effort to produce biofuels on Oahu also would place greater demand on freshwater resources, but some of the irrigation infrastructure needed for sugarcane production is still intact (RMI 2006).

Considering solar power, there is a small (and growing) use of photovoltaic panels for electricity generation, but most of the solar energy that is harnessed is for hot water heating. There are 24,000 solar water heating systems on Oahu covering approximately 10% of structures. Their installation is being promoted by local government and the electric utility, and a large expansion in their use could contribute significantly to reduced energy demand (DBEDT 2006).

Food

More than 90% of Oahu's food demand is being met by imports. As with fuel, consistent supplies of food are essential for sustaining the daily lives of island residents in the case of a large-scale disruption to trade. Oahu has a total of 521 km^2 of agricultural land, 283 of which are currently in use. An estimated 55% of the fallow land in use is considered to be "prime agricultural lands" once used in monoculture operations (HDoA, 2004). A great deal of potential for agricultural expansion exists, particularly with renewed interest in achieving food and energy self-sufficiency (Sustainability Task Force 2008), but the competitive opportunities for both food and biofuel crop cultivation present serious issues for such a densely populated island.

Barriers to the expansion of agriculture include providing consistent water supply through improved irrigation systems and committing to sufficient growing quantities so that food wholesalers and retailers can transition toward reliance on consistent local supplies. A white paper released by Hawaii's Department of Agriculture indicated that many imported crops have the potential to be replaced by locally grown varieties and proposed that Hawaii could realistically become self-sufficient in producing much of its current food supply with the appropriate assistance. It must be noted, however, that this would require serious changes in dietary preferences and agricultural infrastructure. In addition, thought must be given ahead of time to the reuse of agricultural by-products so they could be cycled rather than disposed.

A key barrier to the development of the aquaculture (fish farming) industry in Hawaii is the competitive disadvantage caused by the cost of importing fishmeal. Many instances exist worldwide of fish farming using vegetable feed, and according to the Marine Finfish Department at Hawaii's Oceanic Institute, everything from papaya waste to macadamia nut shells to discarded fly agar is being investigated to identify alternative sources of imported fishmeal for aquaculture (Laidley 2008).

Waste Management

In many ways, Oahu's waste management system works very well. Nearly 34% of the total waste stream is diverted through recycling, composting, and reuse. H-POWER supplies 5% to 7% of the island's electricity and treats roughly two thirds of the MSW, thus prolonging the life of the landfill. Progressive organic waste regulations require much of the food waste to be composted along with the island's green waste. This comprehensive composting system provides a source of low-cost fertilizer for farmers and in turn results in less methane generation at the landfill and better burn rates at H-POWER. Several opportunities to enhance the waste management system are given below, as elucidated by the MFA results, some of which are currently being undertaken by the City and County of Honolulu, and some which have yet to be enacted in any significant way.

Residential Recycling

In 2007, the City and County of Honolulu began a pilot program for residential curbside pickup of recyclables. Prior to this, the only recycling option for residents was to bring material to community drop-off bins: 40 cubic yard containers scattered at about 100 locations around the island. In terms of collection and waste diversion rates, the pilot was largely successful, and curbside recycling is gradually being expanded to the entire island. A comprehensive program is projected to divert an additional 48,000 tons of green waste and 27,000 tons of recyclables from the municipal landfill (Honolulu ENV 2008a).

Processing and Sorting at Treatment and Disposal Sites

Currently, no entity is extracting metals from the waste that is directed to the municipal landfill. One critical issue is whether it is possible for the City and County, or another entity, to sort out metals before they enter the landfill. A small pilot study that was performed by Schnitzer Steel at the City and County of Honolulu determined that at least ten tons of metal per day is ending up in the landfill that is easily recoverable using demonstrated technologies (Oden et al. 2008). Island Demo transfer station does extract some metal from its waste stream, generating some $0.5 to 1 million in revenues annually.

Materials Recycling versus Energy Recovery

One of the most debated issues surrounding material flows on Oahu is to what extent materials should be shipped off of the island for recycling versus finding new uses for used materials on the island. A study commissioned by the Department of Environmental Services, for example, found that in the case of wastepaper, the global life cycle energy and greenhouse gas benefits of off-island recycling were greater than those for on-island use for electricity (R.W. Beck 2007b). The global benefits of wastepaper recycling accrued off-island, however, and do not contribute to local sustainability. Still, the H-POWER plant, which generates the electricity, has had to divert 150,000 tons of MSW in 2006 to the landfill as it was too much to process, so the City is considering a major expansion of H-POWER to add a third boiler, to process up to an additional 300,000 tons of MSW.

Reuse Opportunities

According to the R.W. Beck solid waste report (2007a), nearly 19,000 tons of material were reused on the island in 2005. The majority of this was clothes, furniture, and housewares donated to the island's numerous thrift stores.

The conversion and use section of the MFA revealed additional opportunities for materials reuse. Most of the hotels on the island undergo a complete renovation every ten years, during which they discard all furniture and fixtures. In addition, all linens and towels are replaced annually. Considering the largest 25 hotels on the island, these renovations produce solid waste equivalent to 4,700 tons per year. The discarded materials are collected by a third-party hotel liquidator that resells some furniture but also landfills a substantial amount, particularly items that are difficult to resell such as mattresses (Parthasarathy et al. 2008).

For usable furniture and appliances, there are several businesses on Oahu that accept used items (and refurbish them if needed) for resale or donation to the island community and nonprofit groups, thus avoiding disposal fees. Other businesses serve as material exchanges for used or surplus building materials. The Hawaii Department of Health has long encouraged contractors to make use of these services to conserve landfill space and improve material efficiency (HDoH 2008). If remanufacture or reuse of furniture and other wood products is not possible due to quality concerns, the next best option would be to send these to H-POWER for conversion to electricity, given the high energy content of wood. H-POWER currently charges $91 per ton flat rate tipping fee for private haulers, which is identical to the landfill's tipping fee. Introducing a favorable fee scale for materials with high-heat content may improve the economics of this option.

Mattresses can be another valuable resource, being nearly 60% by weight of steel coils with the remainder readily burnable materials such as wood and synthetic textiles. Shredding and separation by a private business or transfer station may be economical assuming moderate scrap prices and contribute to waste reduction at the landfill. The stream of used linens and towels would be appropriate for rag recycling or waste-to-energy, rather than landfilling.

Organic Materials

Expanding partnerships between WWTPs and fertilizer manufacturers could divert an additional 41,000 tons of biosolids from the municipal landfill, though transport of such a quantity of biosolids to the Synagro facility on Sand Island in Honolulu may be problematic for traffic and public health reasons. This fertilizer could be used on the other islands or exported.

The R.W. Beck solid waste report (2007a) also suggested increasing the use of untreated wood waste and gypsum wallboard from construction projects in composting operations. The MFA reveals that there are about 18,000 tons of untreated wood entering the waste management system that could be reused after minimal treatment in various applications. Some of this wood waste is in the form of used pallets, which can also be refurbished by companies such as Island Recycling.

Military Reuse and Recycling

In 2006, the military recycled more than 4,000 tons of material, out of 25,000 tons of waste generated, for a recycling rate of 16%. One of the most significant barriers to increased recycling in the military is the lack of communication and coordination among waste management officers in the different branches, with each handling its waste in a slightly different way. The Air Force has direct contacts with companies abroad and bales and ships all of its own material; the other three branches contract with on-island waste brokers. The Air Force also processes some waste on-site: glass cullet is incorporated into cement and may be used as pipe bed material, and plant waste is mulched. The various branches have many common material and service requirements but have not created joint management strategies because of control and security concerns. The Navy operates a recycling facility at Pearl Harbor that occasionally takes in material from the other branches, but these deliveries are sporadic. Particularly around waste management, coordination among the military branches would help to develop scale for suppliers and potential users of secondary material. Given the large amount of land that the military controls on Oahu, programs such as the Navy's conversion of sewage sludge and green waste to soil additives could be quite beneficial if revived on a larger scale.

Backhauling Opportunities

Of great importance to material flows on the island is the fact that all of the containers arriving at Oahu are full but more than two thirds of containers generally leave empty. The commercial sector currently backhauls an estimated 12,000 tons of old corrugated cardboard (OCC) to the mainland United States and discards an additional 29,400 tons. Through cooperative programs among the large retailers, a significant portion of the discarded OCC may be diverted from incineration and disposal. R.W. Beck also suggests commercial backhauling of plastic film, which currently amounts to 31,700 tons of commercial discards (R.W. Beck 2007a).

Legislative Drivers

Many of the constraints to the current system of waste management on Oahu are economic, resulting from the island's remote location, high land and energy prices, and intermediate-sized market. There are, however, some legislative drivers that greatly influence the current system and that may be examined for potential changes that could effect waste reutilization and minimization. Title 11, Chapter 58.1 of the Hawaii Administrative Rules governs solid waste management in the state, primarily outlining permit and reporting requirements. The City Department of Transportation Services writes the design and construction specifications for road construction projects on Oahu, which have restrictions on the amounts and uses of recycled aggregate and glass, as discussed above. Careful consideration could be given to altering these restrictions within safety limits, which may help to foster an important end-market for these secondary materials.

Table 2 Potential opportunities for Oahu material flows

	Qty. displaced (in 1,000 tons)
Reduce imports through...	
Increased recovery of useful construction materials by the Island Demo transfer station and the PVT landfill, which is currently restricted by operating permits	65–125
Increased recovery of glass by private and municipal recyclers, and increased use of glass in public and private construction projects	20–35[a]
On-island production of a significant quantity of ethanol or biodiesel for motor fuel to replace imported gasoline	10–20[b]
Expansion of renewable electricity generation to 10%, from its current negligible level to replace imported crude oil, in accordance with the Hawaii Clean Energy Initiative	140–170[b]
Greatly expanding and diversifying the domestic supply of food on the island to replace 5–20% of imported food, using fallow but productive agricultural lands abandoned by plantations and old farms	35–140
Utilize wastes more fully by...	
Expanding the pilot curbside recycling program to cover the entire island, with regular pickup of paper, glass, bottles and cans, and green waste	70–80
Enacting a system to screen incoming waste at the Waimanalo Gulch and PVT landfills and extract useful metals	10–20
Encouraging a system of reuse of furniture, textiles, fixtures, and usable construction pieces from hotel renovations	3–5
Expanding existing military programs for reuse and recycling, spreading best practices from each base to all of the other bases and cooperating on collection programs	3–5[c]
Organizing large commercial entities to collect, aggregate, and backhaul corrugated cardboard and plastic film in otherwise empty containers to the mainland	30–50
Expanding on existing partnerships, increase the use of wastewater treatment sludge as a potential fertilizer	30–40
Collecting, screening, and shredding wood waste for reuse	15–25[a]
Enabling the expansion of capacity to process tires that are now being treated as waste into tire-derived fuel for use at the AES power plant or other applications	10–12
Consider legislation that would...	
Allow road beds to be constructed with up to 50% recycled construction materials	50–150
Allow up to 30% ash content in concrete	30–60
Ban landfilling construction and demolition waste, as has been enacted in several other states to reduce the overall strain on local landfills	85–105[d]

Note: 1,000 tons (short tons) = 2,000,000 pounds (lb) ≈ 907,000 kilograms (kg, SI) = 907 metric tons. Qty. = quantity.
[a]Sum of import substitution and waste diversion.
[b]Assuming current levels of consumption and no additional imports are required for alternative production.
[c]Assuming that the military increases its recycling rate to the average of ∼35%.
[d]Assuming that this does not result in increased illegal dumping.

Oahu's waste management issues, although unusual in many respects, are certainly not unique, and many other cities and states in the United States have passed innovative legislation to reduce waste generation. One such regulation that has stimulated local recyclers and secondary materials markets is a Massachusetts ban on certain C&D wastes including asphalt, concrete, brick, metals, and wood (Chertow 2008). Such a regulation would divert a combined 94,000 tons of materials from Oahu's landfills, assuming an 80% efficient ban. Precedent also exists: The City has banned materials with alternative uses from landfills in the past, including green waste, corrugated cardboard, metals, auto batteries, and tires.

Table 2 presents a summary of the opportunities for materials management discussed above, with mass estimates for potential increases in import substitution or waste diversion. Ranges are based on material availability and feasible recovery rates. These opportunities are not all mutually exclusive, but taken in combination, they could comprise an aggressive strategy to reduce imports and waste disposal by several hundred thousand tons.

Conclusions

The major conclusions of this article are straightforward. Many opportunities exist for Oahu to increase material self-sufficiency. This can be done through a combination of increasing the amount of local materials available, decreasing the demand for materials, and enhancing the cycling of all materials, both imported and local. Understanding what these materials are and how they flow through the system underlies coordinated decision-making for the people of Oahu. This article shows how MFA can illuminate the connections among imports, exports, and waste management and how it is broadly applicable to islands and other well-bounded areas around the world.

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Notes

1. The Island of Hawaii is the largest in area of the islands that make up the state of Hawaii, anchoring the archipelago to the southeast.
2. One short ton = 2,000 pounds (lb) ≈ 907 kilograms (kg, SI) = 0.907 metric tons. In keeping with local Oahu records and statistics, this article uses short tons throughout, unless otherwise noted.
3. In the United States, the Jones Act requires that any vessel transporting goods between two U.S. ports be an American-flagged ship.
4. One cubic meter (m^3, SI) = 10^3 liters (L) ≈ 264.2 gallons (gal).
5. AES is a global power generation and distribution company, operating in 29 countries.
6. The PVT landfill is owned and operated by the PVT Land Company, Ltd.
7. One metric ton (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.
8. One square kilometer (km^2, SI) = 100 hectares (ha) ≈ 0.386 square miles ≈ 247 acres.
9. For more information, see www.hi5deposit.com.
10. Although the focus of this study was on material flows rather than energy, the Yale Center for Industrial Ecology has done extensive analysis on how Hawaii Island could reduce its level of fossil fuel dependency (which is comparable with that of Oahu) to 31% of primary energy demand (Johnson et al. 2007).

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