

Household food waste to wastewater or to solid waste? That is the question

Decision makers need sound analyses of economic and environmental impacts of options for managing household food waste. Food waste impacts public health (it rots, smells, and attracts rodents) and costs (it drives collection frequency). A life cycle inventory is used to quantify total materials, energy, costs and environmental flows for three municipal solid waste systems (collection followed by compost, waste-to-energy or landfill) and two wastewater systems (kitchen food waste disposer followed by rural on-site or municipal wastewater treatment) for food waste management. Inventory parameters are expressed per 100 kg of food waste (wet weight) to place data on a normalised basis for comparison. System boundaries include acquisition, use and decommissioning. Parameters include inputs (land, materials, water) and output emissions to air, water and land. Parameters are ranked simply from high to low. Ranking highest overall was the rural wastewater system, which has a high amount of food waste and carrier water relative to the total throughput over its design life. Waste-to-energy was second; burning food waste yields little exportable energy and is costly. Next, municipal wastewater tied with landfill. Municipal wastewater is low for land, material, energy and cost, but is highest for food waste by-product (sludge). Landfill ranks low for air emissions and cost. Compost ranks lowest; it has the lowest material and water inputs and generates the least wastewater and waterborne waste.

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Introduction

To evaluate the impacts of food waste management systems, it is necessary to consider both municipal solid waste (MSW) and wastewater systems. It cannot be assumed that all food waste goes to MSW. The use of the household food waste disposer (FWD), installed in a kitchen sink, grinds food waste and diverts it from MSW to wastewater systems. This research project applied life cycle inventory and calculation methods to quantify total system materials, energy, costs and flows to the environment from acquiring, using and decommissioning typical facilities for five

systems currently used to manage food waste.

The five systems include two wastewater systems, a rural conventional on-site system (OSS) or a publicly owned treatment works (POTW). The three municipal solid waste systems are municipal collection of MSW followed by a landfill, compost facility or waste-to-energy (WTE) facility. The five systems, abbreviations and specific facilities used are:

- Municipal solid waste collection followed by landfill (MSW Collection/Landfill); the City of Madison WI

- MSW collection/Dane County WI Landfill.
- Municipal solid waste collection followed by a compost facility (MSW Collection/Compost); the City of Madison WI MSW collection/Columbia County WI Compost Facility.
 - Municipal solid waste collection followed by a waste-to-energy facility (MSW Collection/WTE) the City of Madison WI MSW collection/Hennepin Energy Resources Corp. (HERC) WTE Facility.
 - Food waste disposer followed by a publicly owned treatment works (FWD/POTW); Madison Metropolitan Sewerage District (MMSD) wastewater treatment facilities.
 - Food waste disposer followed by a rural on-site system (FWD/OSS); difference in two on-site systems. The tank and drain field size is increased by 25% to accommodate a FWD.

The specific facilities inventoried are given above. These facilities were chosen because they are representative of current state-of-the-art practices; they are neither unusually large nor small, have stable operating histories and are meeting present laws and regulations. Furthermore, there were locally and/or publicly available data on materials, energy and costs required for this project. For the OSS, the difference between two conventional systems (one designed for and one without a FWD) was inventoried.

The life cycle inventory for each system includes land, total system materials, total system energy, total system costs and total flows to the environment (air emissions, water and waterborne wastes, solid wastes and system food waste residues). Inventory parameters are expressed per 100 kg of wet food waste to place data on a normalised basis for comparison. System boundaries include acquisition, use and decommissioning. Parameters which were ranked included land, input resources and emissions to air, water and land. Parameters are ranked simply from high to low. Specific facts and assumptions for each system are detailed in the results section.

Methods

This research project developed a database from publicly available sources for comparing systems used to manage household food waste. Because the FWD is a household wastewater collection system device that diverts food waste to wastewater systems, FWD parameters are added to the OSS and POTW systems to assess the total impact of the FWD on these systems. Similarly, MSW collection system parameters are added to facility parameters for the three MSW systems.

Based on studies from the literature (Bennett &

Linstedt 1975, Ligman *et al.* 1974, Hutzler & Boyle, Siegrist *et al.* 1976) an average U.S. family of 2.63 persons generates 100 kg of wet food waste in somewhat over a year, assuming 0.13 kg food waste/person/day, and 75% of this can be processed in a FWD (Strutz 1995). For the two wastewater systems, 1031 kg of carrier water, is required to flush 100 kg of food waste through a FWD and is added to the food waste (based on measurements of actual water usage, attributable to FWDs, in multiple households (Ketzenberger 1995).

System acquisition inputs include land, construction materials, capital energy and capital costs necessary to produce a functioning system. Materials include aggregate, concrete, aluminium, asphalt, copper, glass, paint, steel and wood. Fuels include natural gas, coal, refined petroleum, uranium and food. Outputs to the environment include air emissions, water and waterborne wastes, and solid wastes from materials and fuels.

Operation involves quantifying impacts of using a system over its design life. This begins with the input of food into a wastewater or MSW collection system and ends with the export of air emissions, water and waterborne wastes to the environment, the application of system food waste by-products (sludge, septage or compost) to an end use and the disposal of ash, treatment plant residues or MSW in a landfill. Transformations of food waste as it passes through a system are defined and quantified. Other inputs during system use include maintenance materials and operating energy.

System decommissioning includes inputs of materials and energy required to remove a system and outputs to the environment of air emissions, water and waterborne wastes and solid wastes.

The information required for this analysis is voluminous and complex, Diggelman (1998) provides this information in detail. The POTW, compost, landfill and MSW collection systems are public facilities; design, bid, contract and invoice documents and operational and regulatory reports were used to get the desired information. The WTE facility is private, but documents submitted to public agencies proved adequate. FWD data was made available by a manufacturer. The overall differences in OSSs to incorporate a FWD were determined by discussions with experts and consultants, supplemented by state regulatory requirements and discussions with contractors for details. In each case individuals associated with each facility were willing to work with project personnel to provide direction, documents and review to assure accuracy. Data on energy and material flows and emissions associated with materials and energy inputs are from the literature or direct communication (Franklin Associates 1996).

Food waste composition and flow, used throughout this work, is based on national data as follows:

- The composition of food waste is assumed to be C21.53H34.21O12.66N1.00 (Tchobanoglous *et al.* 1993), food waste is 30% solids and 70% water (Morgan 1995), food waste solids are 95% decomposable (Baldwin *et al.* 1998) and 5% ash (Tchobanoglous *et al.* 1993).
- The calorific energy value is 4650 kJ/kg wet food waste (Tchobanoglous *et al.* 1993).
- The 1990 value of 8% food waste in U.S. MSW, as discarded, was used to determine the food waste in MSW (Tchobanoglous *et al.* 1993 and USEPA 1992).

It is assumed that food waste is aerobically decomposed by microbial biomass as it passes through the aeration basin of a POTW or through the compost system; end products are new biomass, carbon dioxide and water. Food waste is anaerobically decomposed as it is processed through an OSS, landfill or POTW digesters to new biomass, methane, carbon dioxide and water. Electrons generated in the hydrolysis of food waste go one-third to new biomass and two-thirds to electron acceptor reactions for both anaerobic and aerobic systems. For the WTE system it is assumed that food waste is oxidised to carbon dioxide, water, NO and N₂ (Ragland 1996). Overall chemical reactions are determined for each system.

For the four municipal systems, it is assumed that the use of the FWD has no impact on system size. The current design of MMSD facilities is set by Wisconsin Administrative Code NR 110(4), which increases POTW design requirements when there are FWDs in a service area. Based on national data, an average of 40% of urban households currently have FWD (Carney 1995), and 20% of rural households have FWD (Strutz 1995). Therefore it is assumed that the current MMSD design incorporates the impact of FWD in their service area. Whether or not households have a FWD it is assumed to have negligible

impact on the average daily per capita weight of MSW discarded and on MSW system design capacities. As indicated above, for the OSS, it was assumed that the use of a FWD requires a redesign of the system.

The five systems are compared, assuming the impacts of the choice at the household to send 100 kg of wet food waste to a system. For the POTW, the ratio of 100 kg wet food waste plus carrier water to the total food waste and carrier water through the POTW over its design life is used to determine the fraction of each parameter attributable to 100 kg of food waste. For the OSS, it is assumed that a 25% larger septic tank and filtration field are required if a FWD is to be used. In this case, the difference between the two systems is all attributable to food waste and the fraction used is 100 kg wet food waste plus carrier water divided by the sum of the total wet food waste and carrier water passing through the OSS over its design life. It is assumed that MSW systems would not change if food waste were diverted to wastewater systems. The fraction used to prorate parameters for MSW systems is 100 kg of food waste divided by the total mass of MSW passing through a system over its design life. Table 1 gives the design life and fractions used to prorate inventory parameters. Financial calculations used for this project assume an interest rate of 10% and an inflation rate of 3%.

Parameters are totalled over system acquisition, operation and decommissioning. Systems are then ranked simply from high to low. Parameters included in the ranking table are land, materials (minus food waste and carrier water), energy (minus exportable food waste energy), water, cost, air emissions, acid gases (NO_x and SO₂), greenhouse gases (CO₂ and CH₄ times 21 to account for its higher potency), wastewater, waterborne wastes, solid and construction wastes and food waste by-products. The rankings for each system are then averaged to give an overall rank.

Table 1: System design life and fractions used to prorate inventory parameters to 100 kg wet food waste.

	System design life, years	System fraction
FWD	12	8.9e-02
Difference in two OSSs	20	5.4e-02
POTW	30	7.4e-10
MSW Collection System	15	5.8e-08
Compost System	15	2.9e-07
WTE System	20	1.8e-08
Landfill system	15	6.2e-08

Results

Table 2 gives a direct comparison of materials, energy and costs for each technology. Table 3 gives total flows to the environment and by-products (sludge, septage, compost, ash and landfill residues) for each of the five food waste management systems. Detailed information leading to Tables 2 and 3 is provided by Diggelman (1998); general facts and assumptions for each technology are presented in the remainder of this section.

Food Waste Disposer (FWD)

Impacts of a FWD over its total life cycle are quantified, including those from acquisition (manufacturing, transporting and installing), use (FWD operation) and decommissioning of a FWD. Flows to the environment from food waste passing through the FWD are added to flows to the environment generated from energy sources to construct, operate and decommission the FWD (burning fossil fuels, etc.) and to those embodied in system materials.

The life-cycle inventory for the FWD is based on the following facts and assumptions:

- The ISE model 333 household-size FWD has a 12 year design life (Strutz 1995);
- The household has 2.63 persons (US Dept. of Commerce 1993);
- Carrier water to use the FWD is 1 litre per person per day (Ketzenberger 1995);
- Dry total solids loadings through the FWD are 0.0291 kg/person/day (Ketzenberger 1995).
- The FWD is used on average 0.6 minutes per day (Ketzenberger 1995);
- The FWD weighs 7.8 kg with packaging; 95% of FWDs are eventually landfilled in the US. (Strutz 1995);
- The area in FWD manufacturing buildings is 36,000 m²; the building design life is 25 years and 3,225,000 FWDs are produced each year (Strutz 1995). The average round-trip distance to a distribution centre is 3150 km in a fully loaded tractor-trailer carrying 2200 units; the fuel consumption is 2.2 km/L (Strutz 1995);
- Installation of a FWD involves a 32 km round trip in a single unit truck which gets 8.5 km/L;
- It is assumed that no materials are consumed during decommissioning of the system; energy required for decommissioning is 25% of the energy for installation and the cost of decommissioning is 25% of the capital cost of the system.

A FWD processes 1120 kg of food waste with 11,520 kg of carrier water over its design life or 1031 kg carrier water is required per 100 kg food waste. Table 2 indicates that the average cost of the FWD is \$17.45 per 100 kg food waste. Table 2 indicates that 120 kg of materials, 9.4×10^4 kJ of

energy and 6.0×10^{-5} m² of land are attributable to 100 kg food waste over the life of a FWD. Not shown here but noted from Diggelman (1998) is that most of the materials (90%) and energy (84%) are attributable to use of the FWD. Water makes up most of the materials (92%) and food waste most of the energy (80%) attributable to the FWD. 87% of the cost is attributable to acquisition; 8% to system use.

Table 3 shows that water makes up most of the 130 kg of flows to the environment. Most of this water is produced during system use (Diggelman 1998). The materials, energy and flows to the environment from the FWD (minus food waste and carrier water) are the trade off for materials, energy and flows from a MSW collection system.

Difference in Two On-site Wastewater Management Systems (OSS)/ FWD

One OSS is designed for, and one without a FWD based on recommendations from various sources (Boyle 1995, Converse 1995, various contractors and Wisconsin Department of Natural Resources personnel); the difference between the two OSSs is attributable to the use of the FWD. Materials, energy, costs and flows to the environment from the acquisition, use and decommissioning of the difference in OSSs are prorated to 100 kg of food waste (plus carrier water). The life cycle inventory includes the following facts and assumptions.

- The system designed for the FWD has a 4750 L, two-compartment septic tank and a 92.9 m² absorption bed; the system designed without the FWD has a 3800 L, two-compartment tank and a 69.7 m² absorption bed.
- The septic system has a 20 year design life.
- The land requirements are assumed to be the area of the bed plus 50%.
- A conservative 3 year pumping interval is assumed (Wisconsin Section 145.24 (3) Stats).
- Effluent concentrations are from Ketzenberger (1995); septage concentrations are from ASCE, Table 2.11, (1992).
- Costs for septage removal and haul are from a local hauler; costs to pump a two-compartment tank every three years- \$120 (Speedway Sewer Service 1994).
- Food waste volatile solids in effluent are assumed to be anaerobically decomposed, half in the tank and half in the absorption bed.
- It is assumed that there is an 80 km round trip required for system materials and a 64 km round haul for septage disposal.
- It is assumed that upon decommissioning, the tank is land filled and absorption bed materials (primarily aggregate) remain on site.

Table 2: Materials, energy and costs of five systems used to manage food waste (per 100 kg wet food waste).

	FWD	OSS	FWD+OSS	POTW	POTW+FWD	MSW Collection	Compost	Compost+Collection	W-T-E	WTE+Collection	Landfill	Landfill+Collection
Land, m ²	6.0e-05	1.9e+00	1.9e+00	2.4e-04	3.0e-04	1.1e-03	7.5e-02	7.6e-02	8.3e-04	1.9e-03	1.8e-02	1.9e-02
Materials												
Construction and landfill materials	5.2e-02	1.4e+03	1.4e+03	3.6e+00	3.6e+00	1.2e+00	2.7e+00	3.9e+00	2.2e+00	3.5e+00	1.1e+02	1.1e+02
Process equipment, vehicles	3.5e-02	-	3.5e-02	2.4e-02	5.9e-02	7.7e-02	1.6e-01	2.4e-01	5.3e-02	1.3e-01	3.9e-02	1.2e-01
Electricity*	6.5e-01	-	6.5e-01	6.3e-01	1.3e+00	2.4e+00	4.3e+00	6.8e+00	1.0e+01	1.2e+01	-	2.4e+00
Natural gas	2.3e-01	-	2.3e-01	7.3e-03	2.4e-01	-	-	-	1.1e+00	1.1e+00	2.7e-01	2.7e-01
Diesel fuel	6.2e-02	5.8e+00	5.9e+00	2.9e-02	9.1e-02	6.5e-01	7.0e-02	7.2e-01	8.5e-01	1.5e+00	6.1e-01	1.3e+00
Gasoline	3.1e-01	-	3.1e-01	9.8e-04	3.1e-01	-	-	-	-	-	-	-
FWD materials	7.0e-01	0.0e+00	7.0e-01	0.0e+00	7.0e-01	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00
Water (including carrier water)	1.2e+02	1.7e+03	1.8e+03	1.0e+03	1.2e+03	1.7e+01	1.2e+01	2.9e+01	1.7e+01	3.4e+01	2.0e+01	3.8e+01
Food waste	0.0e+00	1.0e+02	1.0e+02	1.0e+02	1.0e+02	0.0e+00	1.0e+02	1.0e+02	1.0e+02	1.0e+02	1.0e+02	1.0e+02
Total Materials	1.2e+02	3.2e+03	3.3e+03	1.1e+03	1.3e+03	2.2e+01	1.2e+02	1.4e+02	1.3e+02	1.5e+02	2.3e+02	2.5e+02
Total minus FW and carrier water	1.2e+02	2.1e+03	2.2e+03	1.0e+01	1.3e+02	2.2e+01	1.9e+01	4.1e+01	3.1e+01	5.3e+01	1.3e+02	1.5e+02
Energy, kJ												
Embodied-materials	3.2e+02	5.6e+05	5.6e+05	6.0e+03	6.3e+03	2.0e+04	1.4e+04	3.4e+04	2.4e+03	2.2e+04	7.0e+03	2.7e+04
Embodied-process equip./veh.	1.6e+03	-	1.6e+03	1.1e+03	2.6e+03	2.1e+03	7.4e+03	9.5e+03	2.2e+03	4.3e+03	1.7e+03	3.9e+03
Electricity	6.5e+03	-	6.5e+03	6.4e+03	1.3e+04	2.5e+04	4.3e+04	6.8e+04	1.0e+05	1.3e+05	-	2.5e+04
Natural gas	1.4e+04	-	1.4e+04	4.4e+02	1.4e+04	-	-	-	6.5e+04	6.5e+04	1.6e+04	1.6e+04
Diesel	3.9e+03	3.2e+05	3.2e+05	1.7e+03	5.7e+03	3.6e+04	3.7e+03	3.9e+04	4.5e+04	8.1e+04	3.4e+04	6.9e+04
Gasoline	1.8e+04	-	1.8e+04	5.5e+01	1.8e+04	-	-	-	-	-	-	-
FWD material	5.0e+04	0.0e+00	5.0e+04	0.0e+00	5.0e+04	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00	0.0e+00
Water (including carrier water)	5.8e+02	8.3e+03	8.8e+03	5.1e+03	5.6e+03	8.5e+01	4.6e+01	1.3e+02	8.1e+01	1.7e+02	9.8e+01	1.8e+02
Total Energy	9.4e+04	8.8e+05	9.8e+05	2.1e+04	1.2e+05	8.3e+04	6.9e+04	1.5e+05	2.2e+05	3.0e+05	5.9e+04	1.4e+05
Total minus exportable FW energy**	9.4e+04	8.8e+05	9.8e+05	-4.6e+04	4.8e+04	8.3e+04	6.9e+04	1.5e+05	2.2e+05	3.0e+05	1.9e+03	8.5e+04
Costs (U.S.\$)	17.45	49.75	67.20	0.49	17.94	9.90	6.70	16.60	10.39	20.30	3.75	13.65

*Total mass of fuels required to generate system electricity.

**Exportable electricity based on methane combustion.

Exportable energy for POTW = 6.7 E04 kJ/100 kg FW or 16 kWh of electricity; for landfill 5.7 E04 kJ/100 kg FW or 16 kWh of electricity.

Not included is the energy in food waste of 4.7E+05kJ/100 kg. All values rounded to two significant digits except costs. -Not applicable or no information.

Table 3: Summary of life cycle emissions from acquisition, use and decommissioning of five engineered systems for the management of food waste (kg per 100 kg wet food waste).

	FWD	OSS	FWD+OSS	POTW	POTW+FWD	MSW Collection	Compost System	Collection +Compost	WTE System	Collection +WTE	Landfill System	Collection +Landfill
Air emissions												
Particulates	1.3e-02	1.1e-01	1.2e-01	8.4e-04	1.3e-02	7.3e-03	6.2e-03	1.3e-02	4.2e-03	1.2e-02	4.0e-03	1.1e-02
NO _x	2.0e-02	2.8e-01	3.0e-01	2.3e-03	2.3e-02	3.0e-02	1.6e-02	4.7e-02	1.3e+00	1.3e+00	2.1e-02	5.1e-02
HC not methane	2.1e-02	9.3e-02	1.1e-01	1.2e-03	2.2e-02	1.2e-02	6.9e-02	1.9e-02	4.9e-02	6.1e-02	1.8e-02	3.1e-02
SO _x	2.9e-02	1.3e-01	1.6e-01	2.6e-03	3.2e-02	2.7e-02	2.8e-02	5.5e-02	8.6e-03	3.6e-02	7.2e-03	3.4e-02
Carbon monoxide	5.9e-02	2.2e-01	2.8e-01	2.6e-03	6.2e-02	2.5e-02	1.4e-02	3.9e-02	2.9e-02	5.5e-02	2.0e-02	4.5e-02
CO ₂	6.2e+00	5.1e+01	5.8e+01	3.8e+01	4.4e+01	4.4e+00	4.3e+01	4.7e+01	6.0e+01	6.4e+01	3.1e+01	3.6e+01
Aldehydes	7.1e-05	4.8e-03	4.8e-03	2.4e-05	9.6e-05	5.4e-04	6.1e-05	6.0e-04	7.0e-04	1.2e-03	5.0e-04	1.0e-03
Other organics	9.7e-03	9.4e-02	1.0e-01	5.0e-04	1.0e-02	1.1e-02	1.1e-03	1.2e-02	1.4e-02	2.4e-02	9.9e-03	2.0e-02
Ammonia	2.1e-06	3.1e-05	3.4e-05	1.8e-07	2.3e-06	3.6e-06	5.7e-07	4.2e-06	4.6e-06	8.2e-06	3.3e-06	6.9e-06
Lead	1.6e-06	8.9e-09	1.6e-06	5.1e-09	1.6e-06	1.0e-09	1.6e-10	1.2e-09	1.3e-09	2.3e-09	9.3e-10	2.0e-09
CH ₄	1.1e-04	6.9e+00	6.9e+00	1.3e-05	1.3e-04	6.8e-05	5.8e-05	1.3e-04	9.9e-05	1.7e-04	2.3e+00	2.3e+00
Kerosene	4.7e-07	1.1e-07	5.8e-07	5.9e-08	5.3e-07	5.1e-07	8.8e-07	1.4e-06	3.4e-08	5.4e-07	1.5e-08	5.2e-07
HCl	6.3e-08	9.7e-07	1.0e-06	5.4e-09	6.9e-08	1.1e-07	1.7e-08	1.3e-07	1.4e-07	2.5e-07	1.0e-07	2.1e-07
Water vapour from food waste	0.0e+00	0.0e+00	0.0e+00	1.1e+01	1.1e+01	0.0e+00	7.4e+01	7.4e+01	9.1e+01	9.1e+01	1.0e+01	1.0e+01
Total air emissions	6.4e+00	5.9e+01	6.6e+01	4.9e+01	5.5e+01	4.5e+00	1.2e+02	1.2e+02	1.5e+02	1.6e+02	4.4e+01	4.8e+01
Solid+ Const. Waste	7.3e-01	2.2e+02	2.2e+02	1.3e+00	2.0e+00	4.4e-01	7.6e-01	1.2e+00	1.5e-01	5.9e-01	3.0e+00	3.4e+00
*Other	0.0e+00	1.4e+02	1.4e+02	1.6e+02	1.6e+02	0.0e+00	1.8e+01	1.8e+01	1.5e+00	1.5e+00	1.1e+01	1.1e+01
Water and waterborne wastes												
Water	1.2e+02	1.6e+03	1.7e+03	9.4e+02	1.1e+03	1.7e+01	9.4e+00	2.7e+01	1.3e+01	3.0e+01	8.6e+01	1.0e+02
Acid	4.6e-10	3.0e-02	3.0e-02	3.0e-02	3.0e-02	7.9e-10	1.2e-10	9.2e-10	1.0e-09	1.8e-09	7.2e-10	1.5e-09
Metal ion	9.6e-06	1.5e-04	1.5e-04	8.1e-07	1.0e-05	1.7e-05	2.6e-06	1.9e-05	2.1e-05	3.8e-05	1.5e-05	3.2e-05
DS	6.1e-03	8.2e-02	8.8e-02	1.1e+00	1.1e+00	9.5e-03	1.5e-03	1.1e-02	1.2e-02	2.2e-02	8.7e-03	1.8e-02
SS	3.2e-03	5.6e+00	5.6e+00	9.2e-02	9.5e-02	5.2e-04	5.8e-04	1.1e-03	1.7e-04	6.9e-04	1.1e-02	1.2e-02
BOD	4.8e-04	1.6e-03	2.1e-03	5.8e-05	5.4e-04	2.0e-03	1.8e-04	2.2e-03	1.5e-05	2.0e-03	6.0e-03	8.0e-03
COD	1.8e-03	3.9e-04	2.2e-03	6.0e-06	1.8e-03	5.9e-05	5.0e-05	1.1e-04	5.9e-05	1.2e-04	1.1e-02	1.1e-02
Phenol	3.2e-08	4.7e-07	5.0e-07	2.6e-09	3.5e-08	5.4e-08	8.5e-09	6.2e-08	6.9e-08	1.2e-07	4.9e-08	1.0e-07
Oil	6.6e-04	1.1e-03	1.8e-03	1.5e-05	6.7e-04	1.4e-04	8.0e-05	2.2e-04	2.1e-04	3.5e-04	1.2e-04	2.6e-04
Sulphuric acid	1.1e-03	2.5e-04	1.4e-03	1.4e-04	1.2e-03	1.2e-03	2.1e-03	3.3e-03	7.5e-05	1.3e-03	3.3e-05	1.2e-03
Iron	2.7e-04	6.5e-05	3.4e-04	3.4e-05	3.1e-04	3.0e-04	5.1e-04	8.1e-04	1.9e-05	3.2e-04	5.7e-03	6.0e-03
Ammonia+NO ₃	7.7e-07	1.1e-05	1.2e-05	6.3e-08	8.3e-07	1.3e-06	2.0e-07	1.5e-06	1.7e-06	3.0e-06	1.1e-03	1.1e-03
Chromium	1.9e-09	2.7e-08	2.9e-08	1.5e-10	2.0e-09	3.2e-09	4.9e-10	3.7e-09	4.0e-09	7.2e-09	2.9e-09	6.1e-09
Lead	8.3e-10	1.2e-08	1.3e-08	6.8e-11	9.0e-10	1.4e-09	2.2e-10	1.6e-09	1.8e-09	3.2e-09	1.3e-09	2.7e-09
Zinc	1.2e-08	1.8e-07	1.9e-07	1.0e-09	1.3e-08	2.0e-08	3.2e-09	2.4e-08	2.6e-08	4.7e-08	1.9e-08	3.9e-08
Total water and waterborne wastes	1.2e+02	1.6e+03	1.7e+03	9.4e+02	1.1e+03	1.7e+01	9.4e+00	2.7e+01	1.3e+01	3.0e+01	8.6e+01	1.0e+02
Total	1.3e+02	2.0e+03	2.2e+03	1.1e+03	1.3e+03	2.2e+01	1.4e+02	1.7e+02	1.7e+02	1.9e+02	1.4e+02	1.7e+02
*Septage(OSS)/sludge(POTW)/compost(compost)/ash(WTE)/food residues(landfill).												
Waterborne wastes	1.4e-02	5.7e+00	5.7e+00	1.3e+00	1.3e+00	1.4e-02	5.0e-03	1.9e-02	1.3e-02	2.7e-02	4.5e-02	5.8e-02
acid gases (NO _x and SO _x)	4.9e-02	4.1e-01	4.6e-01	4.9e-03	5.4e-02	5.7e-02	4.4e-02	1.0e-01	1.3e+00	1.3e+00	2.9e-02	8.6e-02
Greenhouse gases+ (CO ₂ & CH ₄ +)	6.2e+00	2.0e+02	2.0e+02	3.8e+01	4.4e+01	4.4e+00	4.3e+01	4.7e+01	6.0e+01	6.4e+01	7.9e+01	8.3e+01

++Methane values multiplied by 21 because on a kg for kg basis methane is 21 times more potent a greenhouse gas than carbon dioxide over a 100 year time period USEPA 2000 (<http://www.epa.gov/ghginfo/qa/index.htm#11>).

- The fraction used to prorate parameters to 100 kg of food waste (0.0537) is 100 kg of food waste plus carrier water to the total food waste and carrier water through the system over the 20-year design life.
- Seven kg of methane are generated as 100 kg of food waste is processed through this system; none are recovered for energy production.

During the 1980s, an eight-year audit of septic tanks in Glide, OR agreed with US Public Health Service studies published in the 1950s that an average twelve-year pumping interval is not unreasonably long. For the approximately 20% of households with FWDs, scum accumulation rates increased by 34%, but sludge accumulation only increased by about 2% over those with no FWD (Bounds 1994).

Table 2 gives a summary of life cycle materials, energy and costs of the difference in OSSs alone and of the FWD/OSS combination. Thirty three hundred kilograms of materials, 9.8×10^5 kJ of energy and 1.9 m² of land are attributable to 100 kg of food waste over the design life of the FWD/OSS; this does not include food waste energy of 4.7×10^5 kJ/100 kg of food waste. Life cycle materials are construction materials (42%), water (54%) and food waste (3%). Of the total energy, including that of food waste, 39% is embodied in construction materials, 22% in diesel fuel and 32% in food waste. The average cost of the FWD/OSS is \$67.20 per 100 kg food waste. Not shown here is the result that most of the materials (97%) and energy (90%) is attributable to system acquisition (Diggelman 1998).

Table 3 gives a summary of flows to the environment from the OSS/FWD; the total attributable to 100 kg of food waste is 2.2×10^3 kg (aggregate remaining in the bed not included). Most of the total system flows are water (77%), but 10% are solid waste and 6% septage.

Municipal Wastewater Collection and Treatment System (POTW)/ FWD

The City of Madison, WI. municipal wastewater collection system and the Madison Metropolitan Sewerage District (MMSD) wastewater treatment plant were used for these calculations. Following are the major facts and assumptions.

- The wastewater collection system assumes a population of approximately 260,000 persons and 120,000 housing units, 40% of which have FWDs.
- MMSD provides tertiary treatment of wastewater. Treatment consists of preliminary, primary and biological secondary treatment with denitrification and phosphorus removal and UV disinfection. Solids treatment consists of sludge thickening, stabilisation and dewatering, followed by storage and land application.
- The design life of the system is assumed to be 30 years.
- Laterals, collector and interceptor sewers are assumed to be placed in trenches with perpendicular sides and bedded in aggregate. Pre-1970 laterals and collectors were made of vitrified clay; post 1970 of PVC (Dailey 1995). A manhole spacing of 76 m is assumed (Dailey 1995). There are 94 pumping stations assumed to be identical to a recently completed station. Total collection system building area is 1239 m² (Dailey 1995); for the wastewater system it is 20,300 m² (MMSD facility drawings).
- The portion of influent TSS that is biodegradable is 80%; the portion of food waste that is biodegradable is 95%. 95% of organic N is converted to ammonia, 97% of which is oxidised. 95% of influent organic P is solubilised to ortho-P. 96% of the BOD₅ is removed overall and 92% of the TSS is removed in the aeration basin. For determining sludge yield due to BOD₅ removal, it was assumed that the yield coefficient is 0.90 kg VSS produced per kg of BOD₅ removed, the decay coefficient is 0.04 per day and the mean cell residence time is 10.5 days. The sludge production due to nitrification assumes a yield coefficient of 0.25 kg NVSS produced per kg ammonia oxidized and a decay coefficient of 0.05 per day. The percent solids of sludge wasted is 0.24%. In the dissolved air flotation process, there is a 98% solids capture rate; the total N and total P are removed in the same ratio as the solids and float has 3.6% solids. The solids capture in the gravity belt thickener is 98%; solids are 5.8%. (MMSD Tech. Memo 1994).
- It is assumed that the weight of process equipment in the system is 10% of the weight of pump stations, manholes, MMSD tanks and MMSD buildings;
- Installation energies are calculated based on the volume of excavated material and an average round trip of 32 km;
- The 1997 Madison Sewer Utility (\$25.30/100 m³) and Madison Water Utility (\$22.25/100 m³) residential service charges were assumed to have embedded all capital and operating costs of the collection and wastewater treatment systems and are used to calculate costs.
- It is assumed that system decommissioning includes no significant use of materials, requires 25% of the energy to install the system and that the cost is included in the services charges;
- The portion of total flows (139×10^3 m³/day) and loadings (26,100 kg TSS/day) over the 30 year design life attributable to 100 kg of food waste and 1031 kg of carrier water is 7.4×10^{-10} . This ratio was used to determine the fraction of each parameter attributable to food waste;

- The mass of food waste in primary and attributable to food waste in secondary sludge sent to digesters is used to determine that 4.8 kg of methane is produced from 100 kg of food waste. It is assumed that 3.86 kWh of electricity can be generated from a kilogram of methane, all of the methane is captured in the anaerobic digester and 90% of the electricity generated is exportable (Taylor 1992 as reported in Franklin Associates Ltd 1994). Therefore, approximately 16 kWh of electricity is available from 100 kg food waste.

Calculations incorporating food waste parameters, FWD use and POTW facts and assumptions indicated that for 40% of households using a FWD, the percentages of wastewater loadings to the MMSD facility attributable to FWD usage increase by less than 10% over no FWD usage, flow increases by 0.1%; BOD₅, TSS and VSS by 7.5, 7.9 and 9.0% respectively; and TKN and total P by 1.4 and 1.2% respectively (Diggelman 1998).

Table 2 summarises life cycle materials, energy and cost of the FWD/POTW system. Thirteen hundred kilograms of materials, 1.2×10^5 kJ of energy and 3.0×10^{-4} m² of land are attributable to 100 kg of food waste passing through this system; this does not include food waste energy of 4.7×10^5 kJ/100 kg of food waste. Materials are predominantly water (92%) and food waste (8%), attributable to both system acquisition (46%) and system use (54%) (Diggelman 1998). Most of the total energy, including that of food waste, is attributable to food waste (80%) and embodied in FWD materials (9%). Most of the system energy is attributable to system use (64%) and system acquisition (34%) (Diggelman 1998). The 100 kg of food waste can theoretically produce 16 kWh of exportable electricity. It is noted that the efficiency of methane generation and conversion to exportable electricity results in an overall energy production of 4.6×10^4 kJ/100 kg food waste for the POTW alone and an overall energy usage of 4.8×10^4 kJ/100 kg food waste when the FWD is included. From Table 2, it is noted that production of 6.7×10^4 kJ exportable electricity represents a conversion efficiency of 14% of the energy in the food waste.

Table 3 shows that there are 1300 kg of flows to the environment from the FWD/POTW system. Flows to the environment include 85% water, 4% air emissions and 12% sludge. Most of these emissions are generated during use of the system (Diggelman 1998).

MSW Collection

All MSW food waste management systems considered here involve collection using a truck; hence the materials, energy and dollars to acquire, operate and decommission a MSW collection system and flows to the environment

from materials, energy and food waste passing through the system are considered separately. The City of Madison (WI) is the collection system used for this project; tonnages, construction materials and costs are specific to this system. National data, based on research at Research Triangle Institute, is used for collection parameters for vehicles, mileage and water requirements. National MSW generation, recovery and discard rates are used. The following are assumptions and facts used for the inventory of the MSW Collection system:

- Weekly collection is assumed for a city of 191,000 population, 72,535 houses and 3815 commercial sites;
- An overall design life of 15 years is assumed for the collection system; buildings are assumed to be 30 years, vehicles 8 years and carts 7.5 years;
- MSW (and food waste) is stored in the kitchen in a HDPE container and transferred to a 340 L HDPE wheeled cart for collection;
- The building area requirement is 9300 m² (Burse 1996);
- It is assumed that the land requirements are double the building requirements and the land is fenced;
- The diesel fuel required to collect MSW is 7.5 L per 1000 kg of MSW (RTI 1995);
- 22 kWh of electricity are required per 1000 kg of MSW (RTI 1995);
- The water required for collection facilities is 42 L per 1000 kg of MSW (RTI 1995);
- Collection costs are \$98.70 per metric ton of MSW (Dreckmann 1997);
- The amount of MSW collected over the 15 year life of the system is 1.7×10^9 kg, for a ratio for 100 kg food waste of 5.8×10^{-8} .

Table 2 indicates that 22 kg of materials, 8.3×10^4 kJ of energy and 1.1×10^{-3} m² of land are attributable to 100 kg of food waste passing through the MSW collection system. 80% of the materials is water; 11% are the fuels required to generate electricity; 6% is construction materials and 3% diesel fuel. 78% of the materials are attributable to system use and 22% to system acquisition (Diggelman 1998). For energy, 43% is attributable to diesel fuel, 30% to electricity and 24% is embodied in materials. 73% of the energy is attributable to system use, 27% to system acquisition (Diggelman 1998).

Table 3 indicates a total of 22 kg of flows to the environment of which 78% is water and 20% is carbon dioxide. Other emissions are very low. Flows are attributable to energy sources (63%), facility water (19%) and materials (18%) (Diggelman 1998).

MSW Collection/Landfill

The Dane County (WI) Landfill is used as the model for this project, and tonnages of MSW, construction materials, vehicles, process equipment and costs are specific to this landfill. To accommodate design changes over the life of the landfill, it is assumed that the latest landfill addition is representative of the entire landfill. Facts and assumptions used are as follows.

- The design life of the landfill is 15 years; there are 30 years of post-closure care, but no landfill reclamation;
- The landfill will receive an average of 293 metric tons per calendar day over its design life; 100 kg of food waste divided by the total MSW gives a ratio of 6.2×10^{-8} ;
- The landfill land area is 12 ha; the fenced area is 28 ha;
- The liner is 1.2 m of clay with a HDPE flexible membrane liner and a geotextile; the final cover system includes 0.61 m clay and a HDPE geocomposite;
- The landfill has a leachate collection system and discharges leachate to the Madison Metropolitan Sewerage District for treatment;
- The landfill has a gas collection system with power generation equipment; the system parasitic load is 10% of the electricity generated (Mandli 1995);
- It is assumed that carbon dioxide and methane go to the landfill gas collection system. Of the landfill gas generated, it is assumed that 66% is collected and used and 33% is vented to the atmosphere;
- It is assumed that food water goes to the leachate collection system; all leachate is captured in the leachate collection system;
- There are two buildings required for the landfill with a total area of 1300 m² (Mandli 1995);
- It is assumed that 5.9 L of diesel fuel per 1000 kg of MSW is required for construction and operation of the landfill (RTI 1995);
- It was assumed that 95% of food waste solids are decomposable (Baldwin and Ham 1996) of which 84% is decomposed in the landfill during the design life (Eleazer *et al.* 1997);
- Average landfill costs of \$37.49/metric ton are assumed (Mandli 1995);
- Electricity generated is calculated based on 6.8 kg of methane produced anaerobically from 100 kg food waste in the landfill, two-thirds recovered and 3.86 kWh per kg of methane recovered minus 10% parasitic load (Taylor 1992 as reported in Franklin Associates Ltd. 1994).

Table 2 indicates that there are 250 kg of materials, 1.4×10^5 kJ/kg of energy and 1.9×10^{-2} m² of land attribut-

able to 100 kg of food waste passing through the MSW collection/landfill system. 44% of the materials are soil liner materials, 40% is food waste and 15% is water. Of the total 88% is attributable to system acquisition (daily cover is included in system acquisition) (Diggelman 1998). Of the total energy, including food waste, 77% is attributable to food waste and 11% is attributable to diesel fuel. Most of the energy (70%) is attributable to system use (Diggelman 1998). As indicated in Table 2, 16 kWh of exportable electricity is generated from the methane recovered from 100 kg of food waste. Consideration of energy exported by conversion of methane to electricity results in an overall energy requirement of 1900 kJ for the landfill alone or 8.5×10^4 kJ including the MSW collection system per 100 kg of food waste. The generation of 5.7×10^4 kJ exportable electricity/100 kg food waste represents a conversion efficiency of 12% of the energy contained in the food waste.

Table 3 indicates that there are 170 kg of flows to the environment attributable to 100 kg of food waste passing through the MSW collection/landfill system. From Table 2 there are 110 kg of soil remaining in the system not included in Table 3; 59% of the flows to the environment are water and waterborne wastes, 29% are air emissions, and 6% food residues.

MSW Collection/Compost

The facility chosen for this project is the Columbia County, WI Composting Facility. Its design capacity of 63 metric tons per day is 62% of the U.S. average design capacity of 118 ton/day; its capital cost of \$2,500,000 is 36% of the U.S. average capital cost of \$6.9 million and its tip fee of \$36/ton is 75% of the U.S. average of \$48/ton (based on Steuteville 1994). All materials, energy and cost data are specific to the Columbia County Composting Facility. Facts and assumptions used are as follows:

- The facility operates at a capacity of 63 tons/day over a design life of 15 years. The resulting ratio of 100 kg of food waste to the total weight of food MSW through the system over its design life is 2.9×10^{-7} ;
- Composting operations are housed in 5900 m² of buildings with an additional 45% for concrete pads for windrows of about 2700 m². The site is 26 ha, entirely fenced (Casey 1996);
- In-vessel composting process equipment includes two process trains, each of which includes a steel digestion drum, trommel screen and a conveyor;
- MSW is 20% moisture; cheese factory wastewater is added to reach 50% (Casey 1996);
- Ninety-five percent of the degradable solids in food waste ultimately degrade. It is assumed that 83% of the decomposition occurs in the in-vessel composter and

- 17% occurs during the windrow curing which follows;
- Compost is 50% dry solids and 50% moisture;
- It is assumed that there is no leachate from the process;
- Capital costs were \$2,500,000; operating costs over the 15 year design life of the facility \$20,167,496 and decommissioning costs at 25% of capital costs were \$625,000 for a total of \$23,292,496. This is \$6.70 per 100 kg of food waste.

Table 2 indicates that there are 140 kg of materials attributable to 100 kg of food waste passing through the MSW collection/compost system; most of the materials (71%) are food waste and water (21%) attributable to the use of the system. There is 1.5×10^5 kJ of energy attributable to 100 kg of food waste of which food waste energy is 76% and electricity fuels is 11%. Most of the energy is attributable to system use (Diggelman 1998). Land requirements are 7.6×10^{-2} m².

Table 3 shows that there are 170 kg of flows to the environment attributable to 100 kg of food waste passing through the MSW collection/compost system; 71% are air emissions, 11% compost and 16% is water.

MSW Collection/Waste-To-Energy (WTE)

The facility chosen for this project is the Hennepin County, MN, Energy Resources Corp. (HERC) mass burn unit. It utilises waterwall technology for heat recovery and dry scrubber/fabric filter systems for air pollution control. Because some of the information requested of the HERC was considered proprietary and unavailable to this project, information gaps were filled from other sources, primarily the Minnesota Pollution Control Agency's files, as well as private sources. Facts and assumptions used are as follows.

- The HERC has a design capacity of 1088 metric tons of MSW per day, but handles 907 tons per day; it has a design life of 20 years. The ratio of 100 kg to the total MSW processed through this facility over its design life is 1.8×10^{-8} ;
- The facility is on a 4.6 ha site with about 1400 m² of auxiliary buildings (MPCA files);
- There are two process trains of furnaces, boilers, turbines, etc;
- The gross power output is 38 MW and 770 kWh/ton processed; the net power output is 33 MW and 595 kWh/ton (NREL 1992 and HERC brochures). Based on a higher heating value of Hennepin County's reference refuse of 1.047×10^4 kJ/kg MSW (MPCA files), 595 kWh/ton represents an exportable energy conversion efficiency of 20%;
- The energy value of food waste is 0.47×10^4 kJ/kg. Based

on Diaz *et al.* (1982) values for facility energy requirements of 0.035×10^4 kJ/kg and system energy losses of 0.43×10^4 kJ/kg, net energy from burning food waste is very low. It is assumed that there is no net system energy output from burning food waste;

- Air pollution control includes lime injection, thermal DeNO_x and activated carbon for mercury control;
- When MSW is combusted, 25% becomes ash; 88% of the ash is bottom ash and 12% is fly ash;
- Food waste dry solids are 95% combustible; 5% becomes ash;
- Cost information is inexact because of an artificially low tipping fee and various other factors and reporting methods specific to HERC. From HERC brochures supplemented by information compiled in NREL (1992), final expenses are estimated to be \$104 per ton of which 47% is capital, 41% operating and 12% decommissioning expenses.

From Table 2, the land attributable to 100 kg of food waste passing through the MSW collection/WTE system is 1.9×10^{-3} m². One hundred fifty kilograms of material are attributable to 100 kg food waste; most of the materials (67%) are attributable to food waste, water (23%) and electricity fuels (8%). Most material usage is attributable to the use of the system (Diggelman 1998). There are 3.0×10^5 kJ/kg of energy attributable to 100 kg of food waste passing through the MSW collection/WTE system; nearly all of which (98%) is attributable to system use (Diggelman 1998). As indicated above, no exportable energy is attributable to food waste.

Table 3 shows that there are 190 kg of flows to the environment attributable to 100 kg of food waste passing through this system; 84% are air emissions, 1% ash and 16% is water.

Results

There is much information in Tables 2 and 3, with considerable detailed work and calculations behind each entry. The inclusion of 100 kg of food waste (and carrier water as appropriate) swamps the totals for several entries for material flows and energy requirements; hence, some totals are shown with and without food waste and carrier water. Values excluding food waste and carrier water highlight requirements and flows of the process itself; values including food waste and carrier water are more accurate in showing total impacts of using a particular technology to treat or dispose of food waste.

Carrier water usage is of overriding importance in several ranking categories to follow. The amount used here for modelling is based on household studies by Ketzenberger

(1995), as mentioned previously, but is subject to change depending on household practices. For example, if the FWD is used only while rinsing dishes, no additional water would be required for FWD usage. Conversely, if the FWD is always used separately, more carrier water may be used.

System Summaries

Table 4 gives a simple ranking of the five systems for 11 parameters, including land, total system materials (minus food waste and carrier water), total system energy (minus food waste and carrier water), cost, water use, wastewater

produced, waterborne wastes, air emissions, acid gases, greenhouse gases, solid and construction wastes, and system food waste by-products. The authors recognise that there are inherent difficulties in comparing incommensurable quantities, particularly for air emissions, where water vapour, particulate, acid gases and lead impacts are in no way equivalent.

The rankings for each system are averaged and given an average ranking. It is noted that local factors will determine the relative importance of each parameter; for example, cost may be critical in some situations and land

Table 4: Food waste management system ranked by issue (1-low; 5-high).

	FWD/ OSS	FWD/ POTW	MSW Collection/ Compost	MSW Collection/ WTE	MSW Collection/ Landfill
Land, m ² /100 kg	1.9E+00	3.0E-04	7.6E-02	1.9E-03	1.9E-02
Rank	5	1	4	2	3
Materials (minus FW and CW), kg/ 100kg	2214	130	41	53	153
Rank	5	3	1	2	4
Energy (minus exportable food waste energy), J/100kg	9.8E+08	4.8E+07	1.5E+08	3.0E+08	8.5E+07
Rank	5	1	3	4	2
Water, kg/100kg	1744	1058	27	30	104
Rank	5	4	1	2	3
Cost, \$/100kg	67.20	17.94	16.60	20.30	13.65
Rank	5	3	2	4	1
Air emissions, kg/100kg	66	55	121	157	48
Rank	3	2	4	5	1
Acid gases (NO _x and SO ₂), kg/ 100kg***	0.46	0.05	0.10	1.33	0.09
Rank	4	1	3	5	2
Greenhouse gases (21*CH ₄ +CO ₂), kg/100kg*	202	44	47	64	83
Rank	5	1	2	3	4
Wastewater, kg/100kg	1744	1058	27	30	104
Rank	5	4	1	2	3
Waterborne wastes, kg/100kg	5.73	1.27	0.02	0.03	0.06
Rank	5	4	1	2	3
SW+CW, kg/100 kg	216	2	1	1	3
Rank	5	3	2	1	4
FW byproduct, kg/100 kg**	140	155	18	2	11
Rank	4	5	3	1	2
Average Rank	4.67	2.50	2.42	2.92	2.50
Rank	5	2/3	1	4	2/3

*Methane values are multiplied by 21; on a kg for kg basis, methane is 21 times more potent than CO₂ over a 100 year time period USEPA 2000 (<http://www.epa.gov/ghginfo/qa/index.htm#11>).

**Septage (OSS), sludge (POTW), compost (compost), ash (WTE), food residues (landfill).

***HCl negligible; all methane generated is combusted in energy recovery or emitted (no soil oxidation or sorption).

area in others. Further, other factors not considered here may be of overriding importance, such as health and aesthetic benefits of immediate removal of food waste from the household using a FWD as opposed to on-site storage and collection as MSW. The overall ranking and discussion is given here only as an example of use of the results of this study.

FWD/OSS

The FWD/OSS ranks highest for inputs (land, total system materials, total system energy, and total system cost) and for total flows to the environment attributable to 100 kg of food waste. The difference in two OSSs, designed with and without the FWD is all attributable to the use of the FWD; therefore the 100 kg of food waste represents a much larger fraction of the total food waste and carrier water passing through this difference in systems over its design life than for any other system. FWD carrier water is an important contribution overall to materials and to flows to the environment, contributing about three quarters of the flows to the environment.

FWD/POTW

The FWD/POTW system ranks lowest for land required, net energy required and acid and greenhouse gases per 100 kg food waste. It also ranks low for air emissions and solid and construction waste. It ranks in the middle of the five systems for cost at \$17.94/100 kg food waste, but it is notable that the cost of the FWD makes up most (97%) of the total system cost and that this cost is borne by the homeowner. The cost to process food waste through the POTW is less than \$0.50 per 100 kg of food waste. The FWD/POTW system ranks highest for food waste residues requiring management (sludge), which may or may not be considered a useful product depending on the system at hand. The Madison Metropolitan Sewerage District estimates an average fertilizer value of \$15/dry ton; at MMSD the demand for sludge by farmers exceeds the supply (Taylor & Northouse 1992 as reported in National Research Council 1997). The POTW/FWD has the second highest water requirements and wastewater and waterborne waste flows to the environment, primarily due to FWD carrier water. Water makes up about 85% of the total flows to the environment (Table 3). The 100 kg of food waste and carrier water is a small fraction of the total flows and solids passing through the FWD/POTW over its 30-year design life.

While not an objective of this study, it is noted that wastewater systems are carbon limited systems. Adding food waste carbon to a carbon limited wastewater system contributes to a net removal of nutrients (nitrogen and

phosphorus) from effluent, if nutrients are assimilated with carbon into biomass and removed from the system as sludge.

MSW Collection/Compost

The MSW collection/compost system overall ranks lowest. It has the least requirements for materials and water and produces the least amounts of wastewater and waterborne wastes. It has the highest land requirements of the three MSW systems and ranks second highest overall for land. Total system costs are second lowest and similar to the other municipal systems, but as indicated earlier, capital costs for the modelled facility are low by national standards. This system ranks second highest for air emissions.

MSW Collection/WTE

The MSW Collection/WTE system ranks second highest overall. It produces the most air emissions and acid gases, but the least food waste by-products (ash) and solid waste. Costs are the highest of the MSW systems. Approximately 80% of the flows to the environment are air emissions (Table 3). It ranks highest of the municipal systems for energy requirements.

The assumption of no recoverable energy needs discussion. Tchobanoglous *et al.* (1993) gives a heating value of 4650 kJ/kg of wet food waste, which must be reduced by boiler, heat exchange and electrical generation losses to determine exportable energy from food waste. Because of the high water content of food waste and facility energy requirements and losses associated with producing exportable energy, net energy recovered from food waste is low and assumed to be zero as indicated before (Diaz *et al.* 1982). One can add a value for this according to other facts and assumptions, but it would probably not change the ranking of total energy requirements. For example, if the 4650 kJ/kg heating value were to result in 30% conversion, a high but possible value for modern facilities maximizing heat recovery (Nilsson 2000), this would be 1.4×10^5 kJ/100 kg wet food waste, which would not change the total energy ranking of WTE among the five systems. (Note that the exportable energy production efficiency for the HERC modelled here was previously given as 20%.)

MSW Collection/Landfill

The MSW collection/landfill system ranks low overall. It has one of the lowest energy requirements and the lowest cost of the five waste management systems. It produces low flows to the environment, including air emissions and total food waste residues requiring management. About 60% of the total flows to the environment are water and 30% are air emissions (Table 3). Assuming that 3.86 kWh

of electricity can be generated per kilogram of methane, that 66% of the landfill methane is recovered and that 90% of the electricity is exportable, 100 kg of food waste can theoretically produce 16 kWh of exportable electricity, close to that from the FWD/POTW system.

Conclusions

The following conclusions are based on four operating systems chosen for modelling and the difference in two on-site systems; complex data from many public sources, some of which may be outdated and/or unverifiable; plus opinions and calculations. Accordingly, these results need interpretation and possibly recalculation before application to other situations. Results of this study are summarised in the following conclusions.

- Total flows to the environment from wastewater systems are about 10 times those from municipal solid waste systems, primarily because of food waste disposer carrier water.
- The food waste disposer/on-site system, the only rural system, ranked either first or second for most parameters. Because a larger fraction of the difference in on-site systems was attributable to the 100 kg of wet food waste, land materials, energy and flows to the environment were higher for the rural system than for the four municipal systems.
- The municipal solid waste collection/waste-to-energy system ranks second highest overall, and for total system cost. Burning food waste yields little exportable energy in these systems.
- The food waste disposer/municipal wastewater system has the lowest requirements for land and energy and produces the least acid and greenhouse gases. It is second highest in water usage, wastewater and waterborne wastes, because of food waste disposer carrier water. Over the life cycle, most of the cost is for the food waste disposer and is borne by the homeowner; the cost to a community to process food waste through a municipal wastewater system is less than \$0.50 per 100 kg of food waste. It produces the most food waste by-product in the form of sludge. Food waste going to wastewater systems captures residual value in food waste as it produces sludge during treatment, assimilating nitrogen and phosphorus, and is used as a soil amendment. Sludge converted in digesters to methane, if burned to generate electricity, replaces electricity generated from fossil fuels.

It is clear from this study that the food waste disposer, when evaluated objectively, can be viewed as a component of a municipality's overall waste management

system; it impacts both wastewater and municipal solid waste systems. As concluded above, when food waste goes through a food waste disposer to a wastewater system and it contributes to the uptake of nitrogen and phosphorus during treatment, is used as a soil amendment with or without digestion to methane which is burned as a substitute for fossil fuels, it is beneficially reused. When food waste goes to municipal solid waste systems, it drives collection frequency, making food waste an expensive component of municipal solid waste. For communities (and countries) with state-of-the-art waste management systems, in which food waste disposers have been banned for potentially negative impacts on wastewater treatment facilities, the results of this study may seem counterintuitive.

- The municipal solid waste collection/compost system ranks lowest overall; it has the lowest total system materials and water requirements and generates the least wastewater, waterborne waste and solid wastes. Food waste nutrients are returned to soil from compost systems.
- The municipal solid waste collection/landfill system ranks next to lowest overall and lowest for cost. It also ranks low for system energy requirements, total air emissions and food waste by-products.
- For the three municipal solid waste systems, the collection system contributes from half to three-quarters of the total system cost. Systematic diversion of wet, putrescible food waste from municipal solid waste to food waste disposers has the potential to produce drier, more storable municipal solid waste and reduce the need for weekly collection, the cost of weekly collection, and urban air emissions and noise associated with municipal solid waste collection.

Historically, the FWD has been sold (or banned from sales) as a consumer convenience appliance. Even in countries like the United States where the FWD is common, that has not changed substantially. Hopefully, this study will contribute to a more holistic and realistic understanding of the role of the FWD in a community's overall (wastewater and MSW) waste management system. FWDs can be effective tools for both wastewater and MSW managers. If a community considers reducing their MSW collection frequency to reduce costs, requiring citizens to use FWDs can contribute to reducing public health issues (odour, rodents and insects) related to rotting food waste. Reducing MSW collection frequency also reduces fossil fuel consumption and related urban air emissions. Sending food waste to state-of-the-art wastewater facilities effectively captures food waste energy as methane, a renewable energy source. Sending food waste through FWDs is an effective way to manage food waste.

Acronyms

FWD	Food waste disposer
HERC	Hennepin Energy Resources Corporation
MMSD	Madison Metropolitan Sewerage District
MSW	Municipal solid waste
NREL	National Renewable Energy Laboratory
OSS	On-site system
POTW	Publicly operated treatment works
USEPA	United States Environmental Protection Agency

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