Assessment of Materials Management Options for the Massachusetts Solid Waste Master Plan Review

Final Report

Submitted to:

Massachusetts Department of Environmental Protection

Contract EQEH193

Submitted by:

Tellus Institute

Boston, MA

In Partnership with:

Cascadia Consulting Group

&

Sound Resource Management

December 2008

Disclaimer

This report was prepared by the Tellus Institute, a not-for-profit research and policy organization under a contract with the Massachusetts Department of Environmental Protection. The report (including its summary and analysis of information) is entirely the work of the Tellus Institute and its subcontractors on this project. The opinions expressed in this report are those of the Tellus Institute and do not necessarily reflect MassDEP policies.

Assessment of Materials Management Options for the Massachusetts Solid Waste Master Plan Review

Table of Contents

Appendix 1: Waste Reduction Experience in Other Jurisdictions: Detailed Review

Appendix 2: Documentation for the Morris Environmental Benefits Calculator Model

Appendix 3: Morris Environmental Benefits Calculator – Detailed Modeling Results

Appendix 4: References

Executive Summary of Key Findings

Our literature review and modeling of environmental impacts of waste management focused on the lifecycle impacts of various approaches for materials and solid waste management, including recycling, composting, landfilling, and waste-to-energy incineration, plus the emerging technologies of gasification, pyrolysis, and anaerobic digestion. The scope of this review and the selection of these technologies were identified by MA DEP. Other technologies, such as MSW co-composting, are beyond the purview of the current report. Our review has several overarching conclusions:

1) **From a lifecycle environmental emissions and energy perspective, source reduction, recycling and composting are the most advantageous management options for all (recyclable/compostable) materials in the waste stream.** (See Tables ES-1 and ES-2, below.) This finding confirms the traditional solid waste management hierarchy that has guided MA DEP's Solid Waste Master Plan to date.

2) **After maximizing diversion through source reduction, recycling and composting, it is appropriate for DEP to continue to monitor developments regarding alternative waste management technologies that produce energy – gasification, pyrolysis, and anaerobic digestion.** In evaluating conventional and alternative management options for the remaining waste stream, the competing needs of energy generation and prevention of climate change come into play, given that materials with high fossil fuel energy content, such as plastics and rubber, also emit high levels of greenhouse gases when they are combusted or processed for energy. Expected federal regulation of carbon emissions, or market mechanisms such as cap-and-trade systems, may place additional focus on solid waste management facilities as emission sources, making greenhouse gases an increasingly important consideration in future waste management decision-making.

3) Several factors lead us to conclude that **gasification and pyrolysis facilities are unlikely to play a major role in MSW management in Massachusetts by 2020**. Key issues informing this conclusion include: the lack of experience in the U.S. with large-scale alternative technology facilities successfully processing mixed MSW and generating energy; the long lead times to plan, site, construct, and permit such facilities; the significant capital costs required and the loss of solid waste management flexibility that is associated with the long-term contractual arrangements that such capital-intensive facilities require; and the relatively small benefit with respect to greenhouse gas emissions compared to diversion or landfilling.

4) **The prospects for anaerobic digestion facilities appear to be more favorable** given the extensive experience with such facilities in the U.S. for the processing of sewage sludge and farm waste and the fact that no significant human health or

environmental impacts have been cited in the literature. Moreover, since anaerobic digestion is more similar to composting than high-temperate combustion, its risks are expected to be akin to composting, which is considered low-risk. Anaerobic digestion may be most suitable for source-separated organic material as an alternative to conventional composting. Ultimately, the degree to which anaerobic digestion makes sense will depend largely on the economics of such facilities, including the energy they produce, versus directly composting such material in aerobic composting facilities.

5) As summarized in Table ES-1, below, among the other technology options – landfilling, waste-to-energy incineration, and gasification/pyrolysis – from a life-cycle perspective **no technology performs better than the others across *all* the seven emissions categories reviewed. However, reported per ton emission factors for gasification/pyrolysis facilities are lower than for WTE incineration facilities for all pollutants, and lower than landfill emissions for all except carbon dioxide (eCO_2).** (Key assumptions and a discussion of the modeling results are presented in section III.)

Table ES-1: Summary of Per Ton Emissions by Management Method

Management Method *	Pounds of Emissions (Reduction)/Increase Per Ton – Summary						
	Climate Change	Human Health - Particulates	Human Health - Toxics	Human Health- Carcinogens	Eutrophi-cation	Acidifi-cation	Ecosystem Toxicity
	(eCO_2)	(ePM2.5)	(eToluene)	(eBenzene)	(eN)	(eSO2)	(e2,4-D)
Recycle/ Compost	(3620)	(4.78)	(1587)	(0.7603)	(1.51)	(15.86)	(3.48)
Landfill	(504)	2.82	275	0.0001	0.10	2.38	0.21
WTE Incineration	(143)	(0.30)	68	0.0019	(0.01)	0.04	0.29
Gasification/ Pyrolysis	(204)	(0.36)	(1)	(0.0000)	(0.05)	(0.93)	0.09

* Quantitative performance data from anaerobic digestion facilities comparable to that for the other facility types is not readily available for the modeled emissions categories and therefore not included in the table.

6) For modern landfills, waste-to energy incinerators, as well as the gasification and pyrolysis plants, the emission factors used to compare environmental performance are based largely on modeling and/or vendor claims for modern, state-of-the art facilities, as opposed to actual operational data from real world experience. For example, actual operating performance for Massachusetts WTE facilities has been shown to produce far higher emissions than the modeled figures. Similarly, there remains significant uncertainty as to whether commercial scale gasification/ pyrolysis facilities

processing MSW and generating energy can perform as well as the vendor claims or modeled emissions.

7) **Preference among the alternative technology options based on environmental performance is dependent on the relative importance placed on eCO_2 emissions versus the other pollutants**. For example, on a per ton MSW basis, modern landfills with efficient gas capture systems reduce two and a half times as much eCO_2 as gasification and pyrolysis facilities, and three and a half times as much as waste-to-energy incinerators.

8) **From a life-cycle net energy perspective, waste diversion through recycling provides the most benefit, saving an estimated 2,250 kWh per ton of solid waste. Of the other waste management technologies, gasification and pyrolysis facilities have the most potential for energy production at about 660 kWh per ton, followed by modern waste to energy incinerators at 585 kWh per ton, and then anaerobic digestion, and landfilling**. The estimated energy potential of the various management methods is summarized in Table ES-2, below.

Table ES-2: Net Energy Generation Potential Per Ton MSW

Management Method	**Energy Potential*** (kWh per ton MSW)
Recycling	2,250
Landfilling	105
WTE Incineration	585
Gasification	660
Pyrolysis	660
Anaerobic Digestion	250

* Per-ton energy generation potential estimates are dependent on a number of factors including: the composition of the MSW stream, the specific technologies considered (e.g., fluid bed versus fixed bed for gasification), and the source of the data. Source references are provided in section III.

9) In considering potential sources of energy to meet the Commonwealth's electricity needs, **if 100% of MSW currently landfilled or exported (about 3.5 million tons) were processed by pyrolysis facilities, the maximum potential electricity production would be 2.3 million MWh per year or about 4% of the state's 2005 electricity consumption**.

10) The Morris Environmental Benefits Calculator (MEBCalc) model was used to analyze the relative environmental and energy impacts of three alternative solid waste management systems for the Commonwealth in 2020 – Scenario 1: Business As Usual; Scenario 2: Enhanced Diversion, No Alternative Technologies; and Scenario 3: Enhanced Diversion with Alternative Technologies (gasification and pyrolysis). As summarized in Table ES-3, results of the modeling indicate that **Scenario 1, without an enhanced diversion program (or the introduction of new thermal treatment technologies), produces significantly lower environmental benefits than the other scenarios across all emissions categories considered.** Without an enhanced recycling program, Scenario 1 has a disposal stream that is about 3 million tons more than the other scenarios.

Table ES-3: Scenario Emission Impacts

	Total Tons of Emissions (Reductions)/Increases						
	Climate Change	Human Health - Particulates	Human Health - Toxics	Human Health Carcinogens	Eutrophica-tion	Acidification	Ecosystems Toxicity
	(eCO2)	(ePM2.5)	(eToluene)	(eBenzene)	(eN)	(eSO2)	(e2,4-D)
Scenario 1	(10,447,814)	(5,158)	(2,323,047)	(1,131)	(2,638)	(28,640)	(9,286)
Scenario 2	(14,541,153)	(15,024)	(5,031,471)	(2,268)	(5,171)	(53,809)	(14,754)
Scenario 3	(14,247,299)	(17,696)	(5,283,074)	(2,268)	(5,315)	(56,837)	(14,891)

11) **The emissions profiles for Scenarios 2 and 3 are very similar for virtually all emissions categories. The shifting of MSW from landfilling to gasification and pyrolysis has a small impact on overall system emissions.** This is because only about 10% of the total waste stream is sent to the new thermal processing facilities and because the emissions associated with the 80% of the waste stream that is either recycled/composted or incinerated in conventional waste to energy facilities in both scenarios has a determinative impact on the overall emissions profile. Though the overall differences are small, the shifting of waste from landfilling to gasification and pyrolysis facilities that occurs in Scenario 3 results in lower overall emissions for all pollutants except eCO_2.

12) **The fraction of waste recycled or composted has a dominant impact on the overall system energy profile for all three scenarios**. This is due to a combination of the size of the recycled/composted waste stream (47% in Scenario 1, 62% in Scenarios 2 and 3), plus the high energy savings per ton of diverted waste. As summarized in Table ES-4, below, Scenario 1 has a net energy potential of almost 22 million MWh. The enhanced recycling/composting activities in Scenarios 2 and 3 boost the overall solid waste management system's net energy potential by about 6.1

million MWh or 28% over Scenario1. Introducing the gasification and pyrolysis facilities in Scenario 3 and shifting MSW from landfills to these new thermal treatment facilities increases overall net system energy potential by 1 million MWh.

Table ES-4: Scenario Energy Impacts

2020 Scenario	Post-Diversion Technology	Tons Managed	kWh/Ton	MWh Potential
Scenario 1 No Max Diversion No Alt Tech	Recycled/Composted	8,537,028	2,250	19,208,313
	Landfilled w/ 75% + Energy	6,690,532	105	702,506
	Modern WTE Incineration	3,100,000	585	1,813,500
	Totals	18,327,560		**21,724,319**
Scenario 2 Maximum Diversion No Alt Tech	Recycled/Composted	11,395,364	2,250	25,639,568
	Landfilled w/ 75% + Energy	3,832,196	105	402,381
	Modern WTE Incineration	3,100,000	585	1,813,500
	Totals	18,327,560		**27,855,449**
Scenario 3 Maximum Diversion Plus Alt Tech	Recycled/Composted	11,395,364	2,250	25,639,568
	Landfilled w/ 75% + Energy	1,955,335	105	205,310
	Modern WTE Incineration	3,100,000	585	1,813,500
	Gasification/Pyrolysis	1,876,861	660	1,238,728
	Totals	18,327,560		**28,897,107**

13) **For both pollutant and energy impacts, the scenario analysis points to the significant benefits of broadening and strengthening the Commonwealth's recycling and composting diversion programs and the modest additional benefits associated with shifting non-C&D MSW from landfills to new thermal processing facilities.**

In addition to our overarching conclusions, the following key findings are organized by method/technology within the traditional solid waste management hierarchy.

Waste Generation and Source Reduction

- DEP anticipates that waste generation in the state will continue to grow, increasing, on average, 2% per year. Thus, overall waste generation (residential, commercial, and C&D) is expected to go from 13.9 million tons in 2006 to 18.3 million tons by 2020.

- Trying to avoid growth in waste generation should be a core element of DEP's efforts to move from a waste management to a materials management approach. This requires an upstream focus on waste reduction through: (1) changes in production processes and packaging (in which extended producer responsibility (EPR) may be an important element); and (2) changes in consumption patterns.

- Waste reduction experience in other jurisdictions suggests that individual waste reduction and reuse programs should be integrated in a coherent overall strategy to maximize effectiveness. Stand-alone elements such as education or technical assistance for home composting, for example, are much more effective when combined with economic or policy incentives such as Pay-As-You-Throw pricing or disposal bans.

- Sustainable consumption initiatives, such as those underway in Europe, offer significant waste prevention potential, well beyond the levels currently deemed achievable in the U.S. The potential is greatest where the focus is not limited to technological improvements and dematerialization, but includes consideration of values and lifestyle changes such as downsizing of living space, increased reliance on public transit and car-sharing rather than private vehicle ownership, and adopting life-cycle and precautionary approaches as a consumer of goods and services.

- Focusing on priority materials and/or sectors based on waste reduction potential, including both prevention and reuse, is a sound strategy. The Commonwealth's programmatic focus on commercial and residential organics and certain C&D wastes is consistent with this approach.

- Economic instruments such as taxes or fees should be part of the mix, but should be linked to long-term waste reduction goals in the context of increasing resource productivity. Getting price signals right for goods and services by including environmental externalities is an important element for achieving the structural changes in the economy that are required to move towards a sustainable materials management system.

- Government partnerships with the private sector, NGOs and other stakeholders are critical for the successful development and implementation of waste reduction and reuse programs. Policies and programs developed by government agencies without meaningful involvement by the citizens, businesses, and other organizations ultimately responsible for changing their production or consumption patterns will not gain the support necessary for effective implementation.

Recycling and Composting

- Our review of the LCA literature and our modeling outputs confirm that, after source reduction, waste diversion through recycling and composting is the most advantageous management option from an environmental and energy perspective.

- MA DEP should recommit to maximizing diversion. In addition to strengthening existing programs to capture higher fractions of divertible material, DEP should emphasize those high-volume materials that are relatively easy to recycle/compost (and for which there are available markets): food waste (residential and commercial), mixed paper, some plastics, as well as wood, wallboard, and roofing from the C&D waste stream. This may require additional source separation on the part of households and businesses.

- If current diversion rates remain unchanged through 2020, the tonnage of recycled and composted material will increase from 6.6 million tons in 2006 to 8.5 million tons in 2020. At the same time, the waste volume requiring processing and/or disposal also increases by about 2.5 million tons in 2020.

- In our alternative scenarios with more robust waste diversion efforts, of the 18.3 million tons projected to be generated in 2020 (assuming 2% annual growth in the waste stream), we estimate the realistic potential for recycling/composting in 2020 will be approximately 11.4 million tons. (In these scenarios, the overall diversion rate would increase from 47% in 2006 to 62% in 2020.)

- The significantly higher diversion rates in the alternative scenarios (which represent considerable success in expanding and deepening recycling and composting programs state-wide) are largely offset by the expected growth in waste generation. In absolute terms, the post-diversion 2020 waste stream requiring management is 6.9 million tons, only slightly less than the 7.3 million tons disposed in 2006.

Waste-to-Energy Incineration and Landfilling

- While MA waste-to-energy incineration capacity is expected to remain at about 3.1 million tons per year through 2020, MA permitted landfill capacity is expected to decline precipitously from 2.5 million tons per year in 2006 to about 630,000 tons per year by 2020.

- The assumed growth in waste generation, combined with the loss of in-state landfill capacity, means that significant additional processing/disposal capacity will be required in Massachusetts and/or significant increases in net waste exports will occur.

- Landfilling waste in modern landfills with efficient gas capture systems actually reduces carbon emissions per ton of MSW, regardless of waste stream composition, because landfills act to store carbon. For state-of-the-art WTE incineration facilities, which unlike landfills release bound carbon to the atmosphere, the impact on greenhouse gases is dependent on the waste stream. For the overall MSW stream, WTE facilities reduce per ton net eCO_2 somewhat, but for the post-diversion waste stream, they increase net carbon emissions slightly. (See section III for details.)

Alternative Technologies

- In considering alternative processing technologies – gasification, pyrolysis, and anaerobic digestion – it is important to note that a significant fraction of the undiverted waste stream (well over one million tons, comprising fines and residuals, other C&D and non-MSW, and glass) is largely inert material and not appropriate for processing in these facilities.

- Carbon reductions per ton of MSW are two and a half times greater from modern landfills with efficient gas capture systems than from gasification and pyrolysis facilities.

- Of the alternative technologies, anaerobic digestion is the most mature, though it is most suitable for source-separated organic material rather than mixed MSW. It may be most appropriate as an alternative to conventional aerobic composting, since anaerobic digestion requires less land area, gases can be captured for energy production, and odors are controlled. Also, anaerobic digestion facilities process a wider range of organics than aerobic composting facilities and can therefore lead to a higher landfill diversion rate than composting.

- Given the size of the organic waste stream (particularly food and yard waste), anaerobic digestion may have considerable near- to medium-term potential for producing biogas for fuel or electricity generation in MA. The degree to which AD makes sense will depend largely on the economics of such facilities, including the energy they produce, versus directly composting such material in aerobic composting facilities. The higher capital and operating costs of anaerobic digestion facilities compared to traditional aerobic composting, means that changes in the regulatory framework, incentives, or both would likely be needed to foster its broad adoption in Massachusetts.

- The alternative thermal technologies are not as mature as AD. Given that our LCA results demonstrate that recycling/composting is preferable to other waste management approaches including gasification/pyrolysis (see literature review and MEBCalc model outputs), consideration of these facilities should be primarily for mixed MSW after diversion. Except for a small number of materials that are relatively easy to source-separate but lack ready markets (carpet, for example), source-separated streams should generally be recycled or composted rather than thermally processed.

- There is not a consensus as to the readiness of alternative thermal facilities for commercial processing of mixed MSW in the U.S. Any such facilities would require inclusion of significant pre-processing, not only to size-reduce the material, but also to remove metals, glass, and other materials that are unsuitable for thermal processing. The most valuable (high BTU) materials remaining in the post-diversion waste stream will be non-recyclable paper (e.g., coated or contaminated), low-value plastics, as well as the relatively small quantities of remaining paper, corrugated and wood that for some reason are difficult to separate/recover.

- Because it releases bound carbon in materials such as plastics, thermal conversion of certain materials to fuels or energy is problematic from a climate change perspective even at the potentially high energy recovery levels of advanced conversion technologies.

- Similar to the situation for WTE incinerators, the capital requirements for building alternative technology facilities and their likely need for long-term contracts to ensure an adequate feedstock waste stream may limit the future flexibility of the state's overall materials management efforts. That is, locking in the use of waste for energy production may forestall potential additional recycling or composting in the future, something the MA Solid Waste Master Plan has heretofore explicitly avoided.

I. Project Background & Context

In the context of mounting environmental challenges – climate change, natural resource depletion, and volatile commodity and energy prices – MA DEP is currently reviewing the *Solid Waste Master Plan: 2006 Revision*, the key document summarizing the Commonwealth's waste reduction and management strategy. This report provides the Department with background information that will inform the development of a new Master Plan, one that lays the groundwork for shifting to a "materials management" framework. Such a framework recognizes the important link between society's demands for goods and services (i.e. our consumption patterns) and waste generation, and places greater emphasis on reducing waste during the production process. Moreover, it encompasses a deeper level of waste reduction efforts through reuse, recycling, and recovery. The new Plan will promote a materials management approach, both as an environmental protection strategy as well as an economic plan and vision.

In the MA *Solid Waste Master Plan: 2006 Revision*, DEP maintained the overall waste reduction goal of 70% by 2010 that it established in the earlier *Beyond 2000 Plan*. Since DEP defines waste reduction to include both source reduction and recycling, this implies a recycling goal of 56 percent. Though significant increases in tonnage diverted from disposal were achieved between 2000 and 2004 (from 6.50 to 7.58 million tons), this was almost totally offset by continued increases in waste generation over this period (from 12.96 to 13.93 million tons). Thus, the actual recycling rate of 48 percent in 2004 remained 8 percent below the 2010 recycling goal.

The *2006 Revision* acknowledged ongoing resource constraints facing the agency, as well as opportunities created by strong recycling markets, and identified a number of innovative waste reduction strategies that build on recent successes. These included: expanding and targeting compliance and waste ban enforcement; building partnerships with businesses and municipalities to reduce waste and leverage additional resources; and enabling businesses and municipalities to take advantage of strong recycling markets by providing technical assistance on a range of waste reduction initiatives.

Based on Tellus Institute's February 2003 report, *Waste Reduction Program Assessment and Analysis for Massachusetts*, the *2006 Revision* also identified target waste streams with the greatest additional diversion potential, including: commercial organics (especially food waste), paper and cardboard; residential organics and paper; and wood, asphalt shingles, and gypsum in the C&D waste stream.

Finally, the *2006 Revision* maintained the goal to "substantially reduce the use and toxicity of hazardous products" from the *Beyond 2000 Plan* as a long-term goal, and identified a specific priority of reducing mercury-containing products. It is within this context that the current project, Materials Management Options for Massachusetts Solid Waste Master Plan Review, has taken place.

A. An Emerging New Framework

The past few years have seen climate change concerns rise to the top of the world's policy agenda. In addition, since 2003 world oil prices have risen from less than $30 a barrel to well over $100 in mid-2008, and the term "peak oil" has become part of the common lexicon. These two "crises" – volatile energy prices and climate change concerns – can be seen as indicators that the world has entered a new and dynamic phase.[1] While much uncertainty remains as to the ultimate magnitude and impacts of these crises, it is clear that there is no single technology or policy solution. To successfully meet these challenges governments at all levels, the business community, and society generally need to respond in ways that dramatically reduce fossil fuel use and greenhouse gas emissions, while maintaining resilience and flexibility.

There is wide agreement that a key part of the solution is the development of alternative energy sources, including biomass. As such, there is increasing pressure to look to the municipal solid waste stream as a potential source of alternative energy. At the same time, it is important to note that the energy and climate crises, combined with environmental considerations, will likely alter solid waste generation and management practices over the coming decades and may greatly limit the potential for a range of energy from waste technologies. For example, the highest BTU materials in MSW (e.g., plastics and rubber) are high in fossil fuel content, so that combusting these items actually releases greenhouse gases that are stored in those materials.

In general, we expect that over the long term the residual waste stream in Massachusetts will become smaller and have a different composition profile. For example, in coming decades as society reacts to the climate and energy crises the waste stream may contain smaller quantities of carbon-based materials with high combustion energy potential. While the magnitude and timing of such changes are uncertain, they have important implications for the mix of management approaches and technologies that will comprise the Commonwealth's future solid waste management system.

In undertaking this Master Plan Review, MA DEP recognizes some of these developments, and calls for a shifting of emphasis from a waste management to a materials management approach, with greater emphasis on upstream waste reduction. DEP's integrated approach combines economic, waste reduction, and environmental considerations, and should contribute to the Commonwealth's sustainability.

In addition to the significant impact of the current financial crisis and economic downturn, the key long-term developments that are likely to drive changes in production processes as well as waste generation and management include:

---

[1] Since this report was drafted a third crisis has emerged, the near collapse of the global financial system and a deepening recession, particularly in the U.S.

- Climate Change
- Energy Crisis
- Natural Resource Depletion and Ecosystem Services Degradation
- Rise of Commodity Prices

Climate Change

As Massachusetts and the U.S. move from rhetoric about the need for climate change mitigation to implementation actions, the Commonwealth's waste reduction efforts should be fully cognizant of, and integrated with GHG reduction initiatives. By definition, this will support an enhanced focus on upstream methods of reducing waste and its associated environmental impacts. As carbon emissions are regulated to reduce the climate impacts associated with our production and consumption system, it is reasonable to anticipate efforts by industry to shift from petroleum-based products to bio-based products, where possible, as well as to alter the composition and reduce the amount of packaging waste associated with product manufacturing and consumption. Plastics may offer an important example of this shift, as the use of bio-based plastics such as PLA (polylactic acid), which are compostable, has grown rapidly in recent years. While there remains considerable debate as to the degree to which PLA and bio-based plastics are environmentally preferable, it is clear that environmental and economic forces will exert increasing pressure for alternatives to petrochemical-based plastics, given their large GHG footprint. Similarly, as a result of efforts to minimize energy use and GHG emissions, there will be substantial efforts to reduce plastic and paper packaging waste, including through light-weighting, and enhance its recyclability, whatever their feedstock makeup. In the case of petroleum/natural gas-based plastics, the desire to eliminate land and marine debris and their associated impacts on wildlife will also support the movement to alternatives to petrochemical-based packaging materials.

Energy Crisis

Over the past five years, the price of oil rose four-fold to well over $100 per barrel in mid-2008, only to fall back to about $60 per barrel recently. While we may have retreated from a triple-digit price for oil, most energy experts agree that the era of cheap oil is behind us. The relative importance of various factors – the timing of "peak oil," the decline in the value of the dollar, competition from China and other rapidly growing economies, speculation by multinational oil companies – is debatable, but the basic fact remains that oil will continue to become both more scarce and more expensive. The rising cost of energy, combined with the likely regulation of carbon emissions due to climate concerns (see above), will provide strong incentives for reducing the embedded energy in our products and services, and for capturing and recycling/reusing those products with high energy content. This in turn has important implications for material and process choices in product manufacturing. A recent report by Progressive Investor concluded that: "The higher energy costs go, the more economically valuable are recycled materials."[2]

Natural Resource Depletion and Ecosystems Degradation

As the economies of China, India, and other countries rapidly expand and a consumer culture emulating that of the U.S. is increasingly embraced globally, the demand and competition for natural resources has intensified. While this is certainly the case for energy resources, as mentioned above, it also applies to a host of metals, other raw materials such as timber, and the environmental cleansing and food production services provided by the planet's ecosystems. A rapid upswing in deals by China and India for copper and agricultural output from African countries is a prime example of this phenomenon. In addition, soil quality for food production in many parts of the U.S. and the world has been significantly degraded,[3] and farmers are increasingly dependent on petrochemical inputs to maintain productivity levels.[4] While the historic practice of small-scale ecological farming in which organic wastes were used to replenish soil health has largely been replaced in the U.S. by large-scale industrial agriculture, soil reclamation may offer an important opportunity for productively using composted organic wastes. In addition, the competition for resources for product manufacturing and the huge impact of resource exploration and extraction on natural ecosystems will both provide further push to replace virgin raw resources with recycled materials in manufacturing products.

Rising Commodity Prices

Closely linked to the pressure on natural resources globally there has been a surge in global commodity prices in recent years, though the current economic crisis has temporarily reversed this trend. While these increases are somewhat linked to the decline in the dollar and other macro economic forces, the underlying growth in demand, particularly from large expanding economies such as China and India, combined with increasing scarcity of certain resources, are the dominant factors. With higher commodity and energy prices, the value of most recycled materials – whether paper, plastics, metals – have generally tracked this trend and increased significantly. For energy-intensive recyclables, including plastics and metals, commodity price increases have been especially dramatic.

---

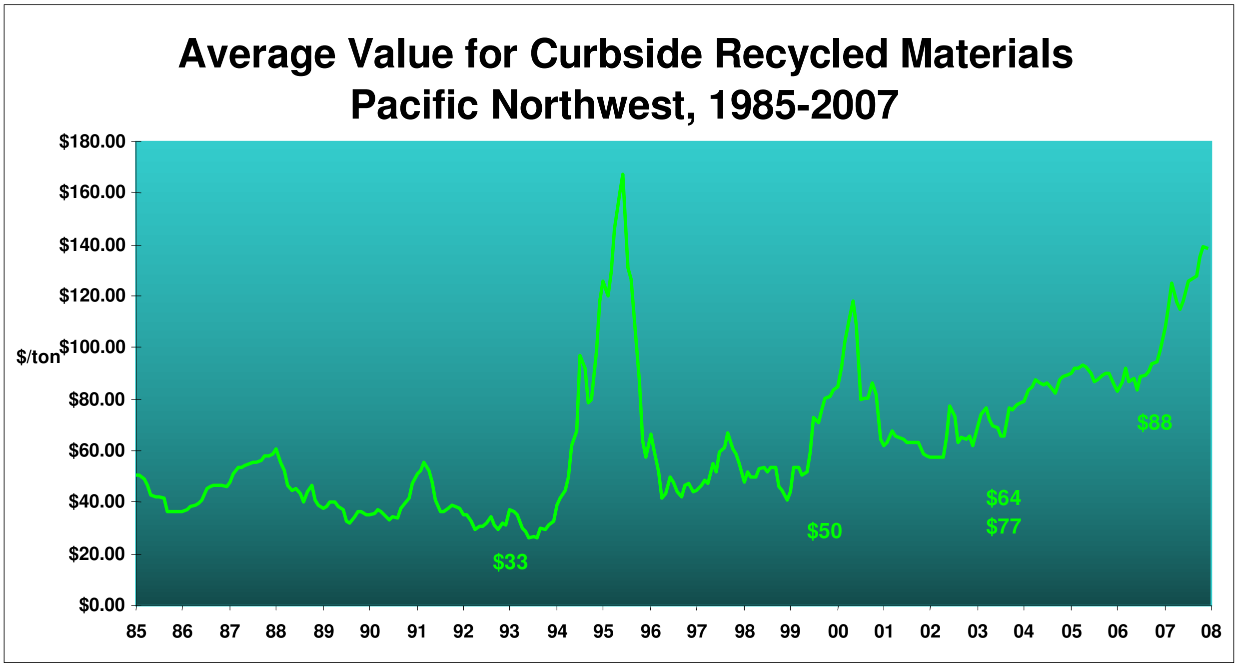
[2] Progressive Investor, "Investing in Recycling," April 2008, as cited at: http://www.sustainablebusiness.com/index.cfm/go/news.display/id/15705

[3] See, for example, Sara J. Scherr, International Food Policy Research Institute, "Soil Degradation: A Threat to Developing-Country Food Security by 2020?" (February 1999). Scherr (p. 17) cites the Global Assessment of Soil Degradation (GLASOD), which reports that 23% (almost 2 billion hectares) of globally used land was degraded between 1945 and 1990.

[4] The importance of this issue is already recognized in much of Europe, but not widely in the U.S.

Figure I-1, below portrays the weighted average market price (large quantities packed for shipment to end-use manufacturers, F.O.B. processing facility) for a basket of materials collected by curbside programs in Washington State's Puget Sound region.[5] These materials include: mixed paper, newspaper, cardboard, glass containers, aluminum cans, tin-plated steel cans, PET bottles, and HDPE bottles. While similar trends have occurred on the East Coast, unfortunately comparable historical data for Massachusetts or the Northeast are not readily available.

Figure I-1: Value of Curbside Recycled Materials, Pacific Northwest



B. Implications for Solid Waste Management

Notwithstanding the current economic crisis, these trends are likely to continue (and possibly strengthen) over the long term. In combination, in decades ahead these factors may fundamentally alter manufacturing practices and consumption patterns as well as solid waste generation and management practices. Some analysts have opined that escalating energy prices, commodity price inflation and scarcity, and global environmental concerns such as climate change have created a "perfect storm" for the recycling industry. While there is considerable uncertainty about the future trajectory of global climate change, energy and commodity prices, and other factors, historical trends

[5] Jeffrey Morris, Sound Resource Management, "Notes about Recycling Markets," accessed at http://www.zerowaste.com/RecyclingMarkets.htm, June 2008.

may no longer be a useful guide to MA DEP solid waste management policy. The Commonwealth's residuals waste management stream in 2015 or 2020 may very well be smaller than it is today, and it may have a lower average energy content per ton.

Whether the deep societal changes in production and consumption patterns that are required to address the above challenges will be undertaken, and if so, the timing of such changes, is also uncertain. There will likely be a period of transition in which markets adjust, investments are reoriented, and infrastructure is reconfigured. It is reasonable to expect that the tradeoffs between material recovery and energy generation may differ by material or product type and may remain unresolved or change over time. It is in this context that DEP should consider future waste management policy, including the potential impacts and the viability of alternative technologies such as pyrolysis, gasification, and anaerobic digestion.

There are several policy implications for managing the future waste stream in Massachusetts. While most of these are not new, the circumstances described above – carbon constraints in combination with volatile energy and commodity prices – combined with the continuation of relatively high waste disposal costs in the Northeast, create strong incentives for achieving much higher levels of waste reduction and diversion.

Furthermore, these changing circumstances suggest crafting a waste management strategy that is quite flexible, being cautious about large facility investments that could portend substantial future stranded costs, and embracing the view that wastes are mostly material resources that need to be returned to the manufacturing system or the farm and soil where they were produced.

C. Report Structure

Following this section on the Background and Context for the project, Section 2 presents the results of our literature review, focusing on life-cycle assessments of the costs and benefits of the various waste management processes and technologies – source reduction, recycling, composting, incineration and landfilling, with a special focus on the emerging technologies of pyrolysis, gasification and anaerobic digestion. Section 3 reports on the results of applying the Morris Environmental Benefits Calculator (MEBCalc) model to the Massachusetts solid waste stream to assess the life-cycle environmental and energy implications for three alternative waste management scenarios, including one that incorporates the new thermal technologies considered in this report. Section 4 reviews the experience of successful waste reduction and materials management efforts from throughout the U.S. and internationally and identifies "best practices" for consideration in Massachusetts.

Finally, Appendix 1 provides a detailed review of the waste reduction practices in other jurisdictions that were summarized in Section 4. Appendix 2 is the documentation for the Morris Environmental Benefits Calculator model, and Appendix 3 provides the detailed modeling results. A list of references is included as Appendix 4.

II. Literature Review

A. Life Cycle Assessments of Alternative Waste Management Approaches

Overview and Context

In the context of the confluence of emerging issues described above – climate change, the energy crisis, natural resource depletion, and rising commodity prices – jurisdictions throughout the U.S. and abroad are reexamining their options for managing their solid waste. Solid waste planners and managers, as well as government policymakers, are increasingly concerned with the long-term costs and benefits of various waste management systems, including environmental impacts as well as net energy impacts. In this light, life-cycle assessment has emerged as a key tool for allowing analysts to compare different approaches and technologies in a fair and comprehensive way.

Life-cycle assessment is the comprehensive examination of a product's or system's environmental and economic aspects and potential impacts throughout its lifetime, including raw material extraction, transportation, manufacturing, use and ultimate disposition or reuse. The International Standards Organization, through ISO 14040, has defined life cycle assessment as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle."

In the current literature review for MA DEP, the lifecycle impacts of the following waste management approaches were included:

1) recycling, and composting;
2) disposal in municipal waste combustors and landfills; and
3) alternative technologies: gasification, pyrolysis, and anaerobic digestion.[6]

More than two dozen reports on LCA studies were reviewed. In identifying key LCAs, the project team built on the previous efforts of DEP staff. There is a particularly rich LCA literature on and a better understanding of the life-cycle impacts of recycling, landfills and municipal waste combustors; while lifecycle analyses for the alternative technologies are not as abundant.

[6] The scope of this review and the selection of these technologies were identified by MA DEP. Other technologies, such as MSW co-composting, are beyond the purview of the current report.

In this section we briefly summarize the LCA literature on conventional solid waste management technologies. In the following section, we focus particular attention on the best current understanding of the feasibility of gasification, pyrolysis, and anaerobic digestion technologies and summarize key technical, environmental, and economic issues.

The literature review prioritized studies and reports that account for full lifecycle impacts of the alternative materials management approaches. Key parameters considered include:

- greenhouse gas emissions;
- air and water pollution, toxic chemicals, and natural resource depletion;
- energy use;
- job creation and economic development; and
- cost savings for waste generators.

Most studies did not include comprehensive life-cycle analyses, either in terms of covering the full life cycle or in terms of all of the identified impacts. For example, few studies analyzed the job and economic development impacts of the systems assessed. Note that an important consideration in reviewing the literature, particularly for the alternative technologies covered in the next section, is whether the technology manages mixed MSW, or only certain materials.

The literature reveals that LCA studies on complex products and waste management systems often use different assumptions and different system boundaries, which leads to results that are difficult to compare and sometimes contradictory. Of particular value were the meta-analyses that documented and summarized the results of numerous LCA studies. The systematic review these reports undertook used criteria that eliminated those LCA studies with less robust methodologies and assumptions.

Two excellent examples are: *Environmental Benefits of Recycling: An International Review of Life Cycle Comparisons for Key Materials in the UK recycling sector*, by the Waste & Resources Action Programme (WRAP, May 2006) and *Paper and cardboard – recovery or disposal? Review of life-cycle assessment and cost-benefit analysis on the recovery and disposal of paper and cardboard*, European Environment Agency (2005). According to the WRAP report, it "is the largest and most comprehensive review of LCA work on key materials that are often collected for recycling – paper/cardboard, plastics, aluminum, steel, glass, wood and aggregates." It screened several hundred studies and identified 55 "state-of-the-art" LCAs for detailed review.

Summary Findings

Key findings from the literature on conventional solid waste management approaches – recycling/ composting, landfills, and waste-to-energy incinerators – are presented below. Many of these are drawn from the meta-analyses mentioned above that summarized the findings from multiple LCAs.

- Recycling offers lower environmental impacts and more environmental benefits than landfilling or incineration.
- Recycling saves energy, reduces raw material extraction, and has beneficial climate impacts by reducing CO_2 and other greenhouse gas emissions. Per ton of waste, the energy saved by recycling exceeds that created by landfill gases or the energy harnessed from thermal conversion technologies.
- For paper and cardboard, recycling is environmentally preferable to landfilling across virtually all environmental parameters – fossil fuel and overall energy consumption, global warming, acidification, eutrophication, toxicity, and others. The relative benefits of recycling paper and cardboard are less pronounced, but still clear, in comparison to incineration.[7]
- For glass, closed loop recycling has lower environmental impacts than landfilling or incineration. A small number of studies that assumed poor recycling rates from low-density areas and/or very long transport distances did not share this finding. The outcome of the LCAs for glass were driven by the type of energy used to produce primary glass and the type of energy used to manufacture secondary glass from recycled cullet.
- For plastics, while there are many differences in terms of assumptions and system boundary definitions that effect the outcome of the individual LCAs (e.g., the weight ratio that recovered material substitutes for virgin material; whether washing/cleaning the recovered plastic was necessary), recycling was generally found to be environmentally preferable to landfilling and incineration for all environmental impact categories, generally performing about 50% better.
- For aluminum as well recycling was found to preferable to landfilling and incineration across all environmental impact categories. In terms of greenhouse

[7] One review of LCAs, *Environmental benefits of recycling: An international review of the life cycle comparisons for key materials in the UK recycling sector* by the Waste & Resources Action Programme (WRAP), reported a minority of studies that found paper incineration preferable to paper recycling in terms of the consumption of fossil fuels and global warming impacts. The WRAP study identified differences in several specific assumptions (e.g., the marginal electricity assumed for virgin production) that had a direct impact on the relative environmental benefits of recycling versus incinerating paper and cardboard.

gases, recycling is reported to save between 5 and 10 tons of CO_2-equivalents per ton of aluminum.

- As for aluminum, recycling was also found to have lower environmental impacts for steel, with energy consumption being a primary factor. One key issue affecting the results of the LCAs for steel and aluminum is the assumed effectiveness of steel reclamation and recycling from incineration slag.

- For wood waste, few LCAs reported on wood recycling. The LCAs comparing landfilling and incineration for wood found incineration to be environmentally preferable, driven by the reduction in fossil fuel use and its associated pollutants including eCO_2.

B. Alternative Solid Waste Management Technologies: Pyrolysis, Gasification, and Anaerobic Digestion

Overview and Context

Population growth, industrial and residential consumption patterns, rising energy costs, and the growing cost of traditional solid waste processing methods are among the drivers for alternative approaches to managing municipal solid waste (MSW) in the United States. In general, alternative MSW processing technologies seek to minimize environmental impacts and divert MSW from landfills at a price that is competitive with other MSW management options. With higher fossil fuel prices worldwide, management technologies that recover energy from MSW are receiving increasing attention. A growing number of potentially viable and commercially marketed alternative MSW technologies exist at varying stages of implementation worldwide. Each technology brings its own set of environmental, economic, and technical advantages and disadvantages, which are summarized below. This section of the report summarizes key findings from a review and comparison of relevant literature on emerging alternative technologies for management of MSW.

The literature review draws upon sources of information from local and national governments currently using alternative MSW technologies and from communities which are considering implementing new technologies. Recently published materials, including reports and websites, from environmental agencies, nongovernmental organizations, and private consulting firms were reviewed. In total, 33 comparative study documents and 31 technical studies were covered in this analysis.

In reviewing alternative waste management technologies, it is important to consider their appropriate role within a waste management hierarchy. These technologies are generally more appropriate after recycling and composting programs as alternatives to landfilling or "traditional" incineration, rather than as approaches for handling the full MSW stream. The results of the literature review underscore that waste reduction and recycling impose fewer environmental burdens and consume less energy than other solid waste management practices.

Many of the comparative studies make similar points regarding the dual benefits of recycling. Essentially, recycling saves energy that would otherwise be needed to extract raw materials, process them, and produce new goods. Furthermore, the literature shows that the energy saved by waste reduction and recycling exceeds the energy that could be created at a waste-to-energy MSW processing facility, even when factoring in the energy needed to collect and process recycled materials. Overall, the "Reduce, Reuse, Recycle" approach—the three R's—provides the most environmental benefits, uses the least amount of energy, has the greatest potential to divert the most waste from landfills, and poses the fewest concerns regarding environmental and human health impacts.

Though high diversion rates are possible utilizing the conventional solid waste hierarchy, diverting all material discards at the present time would be cost-prohibitive, especially given the mixed material composition of some current discards. Accordingly, the literature review considered lifecycle and technical assessments of various alternative MSW technologies that could be used to handle the remaining waste, rather than sending it to landfills or the types of thermal technologies currently in commercial operation in the US

Alternative Technology Overview

Alternative MSW management options are typically identified as either **thermal** or **biological/chemical** technologies. Figure II-1 categorizes various MSW management technologies into these two groups and shows the major outputs of each method.

- **Thermal technologies** typically operate at temperatures between 700 and 10,000 degrees Fahrenheit and can reduce solid waste by up to 80-90% of its original volume.[8] Thermal conversion is a process that converts carbon-based MSW into a synthetic gas that can be used to produce electricity or can be used as fuel.[9] Thermal conversion methods include incineration, as well as pyrolysis, and gasification. Some thermal conversion technologies may require intensive pre-processing to remove non-combustibles and/or to reduce material diversity in the incoming discards stream.

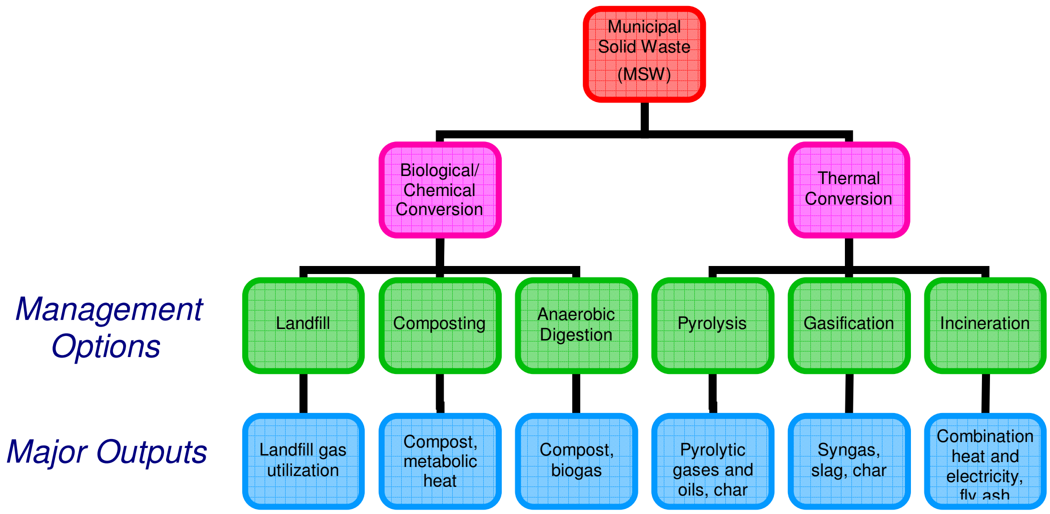
---

[8] URS Corporation, Evaluation of Alternative Solid Waste Processing Technologies, conducted for the City of Los Angeles (September 2005), E-S 1.

[9] Synthetic gas contains about one-fourth the BTU value of natural gas.

- **Biological/chemical technologies** operate at lower temperatures and have slower reaction rates. The feedstocks must be biodegradable, so unless the material is source separated, these methods may require intensive pre-processing. Biological/chemical technologies can also produce electricity, fuels, and high-grade compost. Methods include composting, anaerobic digestion, and capture of landfill gases.

Figure II-1. Alternative MSW Management Options and Their Outputs



While the previous section of this report focuses on the traditional management approaches of recycling/composting, landfilling, and incineration, this review focuses on those alternative technologies that have a track record of commercial operation and could feasibly be "scaled-up" in the near term. Accordingly, two thermal technologies **– pyrolysis** and **gasification** – and one biological/chemical technology **– anaerobic digestion –** were the focus of the literature review. These alternative technologies have a more substantial operational track record, particularly in Europe and Japan, than other emerging technologies.

Conventional thermal treatment of MSW, typically referred to as **incineration**, involves the combustion of MSW in an environment with a sufficient quantity of oxygen available to oxidize the feedstock fully. Incineration plant combustion temperatures are typically in excess of 1500 degrees Fahrenheit. As explained further below, **pyrolysis** is the thermal degradation of MSW and, in contrast to incineration, requires the total absence of oxygen. The pyrolysis process requires an external heat source to maintain temperatures between 650 and 1500 degrees Fahrenheit. **Gasification** can be seen as a treatment in between pyrolysis and incineration, in that it involves the partial oxidation of a substance.

Oxygen is added, but the amounts are not sufficient to allow the fuel to be completely oxidized or full combustion to occur.[10]

Summary Findings

- **Pyrolysis** and **gasification** are potentially viable thermal conversion technologies, though gasification has a stronger track record of facilities with the ability to process MSW. Pyrolysis and gasification both remain unperfected for processing high volumes of MSW to produce energy at the current time.

- Gasification and pyrolysis facilities have more commonly been used for processing uniform feedstocks such as coal, wood, and vegetative biomass.

- No commercial gasification or pyrolysis facilities are currently processing MSW in the United States. Several jurisdictions around the country are researching conversion technologies or considering proposals to develop facilities. Other countries, most notably Japan and several European nations, have more commercial experience with these technologies.

- Like incineration, pyrolysis and gasification can effectively reduce the volume of MSW. However, the energy recovery step, which is championed by technology suppliers, has yet to perform consistently when processing MSW at a commercial scale.

- Pyrolysis and gasification may undermine recycling programs, as the need of the plants for a steady waste stream with high fuel value may compete with recycling. Additionally, these facilities are highly capital-intensive and thus require long-term investments (and often contracts), which may limit flexibility to adopt alternative waste management options or minimization strategies in the future.

- Gasification and pyrolysis have net electric output of about 660 kWh/ton processible MSW.[11] If all of the 3.5 million tons of MSW currently landfilled or exported was processed by these alternative technologies, it would produce about 2.3 million MWh of electricity, or about 4% of the state's 2005 electricity consumption.

---

[10] Department for the Environment, Food, and Rural Affairs. *Advanced Thermal Treatment of Municipal Solid Waste (2007).* http://www.defra.gov.uk/environment/waste/wip/newtech/pdf/att.pdf

[11] Energy output per ton varies with waste feedstock composition and the particular technology. As detailed below, the literature reports wide ranges for the energy potential of thee facilities, based primarily on vendor claims as opposed to actual performance of commercially operating facilities. The 660 kWh per ton figure represents the high end of this range.

- **Anaerobic digestion** received generally positive reviews. It is largely compatible with recycling programs because the technology requires pre-sorting and separation of recyclable materials, and no significant human health or environmental impacts have been cited in the literature. Moreover, since anaerobic digestion is more similar to composting than high-temperate combustion, its risks are expected to be akin to composting, which is considered low-risk.
- Anaerobic digestion facilities produce less than half the energy (per ton of feedstock) of gasification or pyrolysis facilities, about 250 kWh/ton.
- In Europe, about 90 anaerobic digestion plants are processing MSW, and the technology has been introduced in the United States on many dairy farms to process agricultural waste and generate electricity for farms.

The remainder of this summary document provides a basic definition of each technology of interest, presents information on operations at established facilities, and summarizes significant technical, environmental and economic issues associated with each process. A comparison table is included at the end, as are two separate matrices summarizing the literature review.

Technology Definitions and Existing Operations

Pyrolysis

Commercially Operating Facility in the United States: No

Large Facility Example: Hamm-Uentrop, Germany; facility can process 175 TPD of MSW[12]

Net Energy Generated: 400 to 700 kWh per ton of waste processed depending on feedstock composition.[13] Average heating value of feedstock is 3,660 Btu/pound.[14]

Pyrolysis is the decomposition or transformation of a compound caused by heat. Pyrolysis typically occurs at temperatures in the range of 650 to 1,500 degrees

---

[12] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-18.

[13] Ibid.

[14] City of Los Angeles, Bureau of Sanitation, *Technical Study Documents from URS: Gasification.* http://www.lacity-alternativetechnology.org/PDF/GasificationFacility.pdf

Fahrenheit. Most pyrolysis systems use a drum, kiln-shaped structure, or a pyrolysis tube, which is externally heated, either using recycled syngas or another fuel or heat source. Organic materials are essentially "cooked" in an oven with no air or oxygen present; no burning takes place. Temperature is the main control over the products created during the pyrolytic reaction. Higher temperatures produce mainly gaseous byproducts, and lower temperatures produce more liquid pyrolysis oils. In addition to energy production, ferrous metals contained in the solid residue (i.e. char) can be captured for reuse.

Pyrolysis reactions are endothermic, so they require externally supplied heat. Syngas produced by pyrolysis can be used as a source of external heat; therefore if the feedstock has a large heating value, the pyrolytic process becomes more self-sufficient and will use a smaller amount of fossil fuels. Theoretically, the volume of MSW feedstock entering the pyrolysis reactor can be reduced by as much as 90%, but this figure can change if the pyrolysis facility is not operating under optimal conditions, which appears to be common based on real-world experience. MSW feedstock typically requires shredding to a 12-inch maximum size prior to feeding the pyrolysis reactors, and some pyrolysis facilities require even more of a size reduction.[15]

---

[15] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-5.

Gasification

Commercially Operating Facility in the United States: No

Large Facility Example: Tokyo, Japan; facility can process 180 TPD of MSW

Net Energy Generated: <400 to 500 kWh per ton MSW (one-stage, fluid bed technologies); 700 to <900 kWh per ton two-stage/gasification-pyrolysis, fixed bed facilities. Average heating value of feedstock is 3,870 Btu/lb.[16]

Gasification involves the thermal conversion of organic carbon-based materials in the presence of internally produced heat, typically at temperatures of 1,400 to 2,500 degrees Fahrenheit, and in a limited supply of oxygen. Gasification of carbon-based materials generates synthetic gases ("syngas"), composed primarily of hydrogen and carbon monoxide. Syngas contains about one-fourth the BTU value of natural gas on a per cubic foot basis. Inorganic materials are converted to either bottom ash (low-temperature gasification) or to a solid, vitreous (glass-like) slag (high-temperature gasification). After cooling and cleaning, syngas can produce methanol, ethanol, and other liquid fuels, which can be used in boilers or internal combustion engines to generate electricity, though the cooling and cleaning process reduces its energy value.

Bottom ash is frequently landfilled, but it can be used for construction purposes and as an amendment in bricks or paving stones. Bottom ash must be treated before it is landfilled or used because fresh bottom ash is not a chemically inert material. Treatment of bottom ash includes aging (typically for 6-20 weeks), metals separation, and size reduction.[17] Slag can be used to make roofing tiles or can be used as asphalt filler. If the gasification system uses oxygen injections, which result in extremely high temperatures, then metals can be recovered in ingot form. Like pyrolysis, gasification technologies require pre-processing to reduce the size of MSW feedstock, generally to a size between 2 and 12 inches. The MSW volume reduction rate of gasification technology can be between 80-90% depending on which specific processing method is used (e.g., one-stage fluid bed or two-stage fixed bed technology).[18]

---

[16] City of Los Angeles, Bureau of Sanitation, *Technical Study Documents from URS: Pyrolysis (Belgium)*, http://www.lacity-alternativetechnology.org/PDF/PyrolysisFacility.pdf, accessed May-June 2008.

[17] European Commission, Integrated Pollution Prevention & Control, *Reference Document on the Best Available Techniques for Waste Incineration – Executive Summary* (2006), 403-405.

[18] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-7.

Anaerobic Digestion

Commercially Operating Facility in the United States: Not for MSW. U.S. facilities process only agricultural feedstocks, and the energy produced is generally used on farms.

Large Facility Example: Barcelona, Spain; facility can process 1,000 TPD of MSW[19]

Net Energy Generated: Biogas yield averages 4,300 standard cubic feet (scf) or 250 kWh per ton of feedstock

In anaerobic digestion (AD), biodegradable materials are converted through a series of biological and chemical reactions into methane and carbon dioxide (CO_2). (Unlike traditional composting, AD takes place in an oxygen-free environment.) A first type of bacteria breaks down large organic molecules into small units like sugar; this step is referred to as hydrolysis. Another type of bacteria then converts the resulting smaller molecules into volatile fatty acids, mainly acetate, but also hydrogen and CO_2; this process is called acidification. The last type of bacteria produces biogas (methane and CO_2) from the acetate, hydrogen, and carbon dioxide. The biogas produced can be used on-site to generate electricity and heat using a generator. If a nearby industrial user exists, the biogas can be conveyed over short distances for such uses as boiler fuel. The biogas can also be purified extensively to pipeline quality and pressurized for use, for example, as compressed natural gas, a safe and clean vehicle fuel. The solids remaining following the digestion process can be used as compost.[20]

Technical, Environmental, and Economic Factors

Pyrolysis

Technical

- Pyrolysis is an appealing technology because, if a facility is operating optimally, it can reduce the volume of MSW by as much as 90%. Though this result is technically achievable, commercial plants have not been able to sustain this reduction level in practice. For example, a pyrolysis plant outside of Burgau, Germany, which processes approximately 38,000 TPY of MSW, has only been able to achieve a 70% reduction level. About 600 pounds of inert material (char)

---

[19] City of Los Angeles, Bureau of Sanitation, *Technical Study Documents: Anaerobic Digestion (Spain), http://www.lacity-alternativetechnology.org/PDF/AnaerobicDigestionFacility_Spain.pdf, accessed May-June 2008.*

[20] URS Corporation, *Evaluation of Alternative Solid Waste Processing Technologies*, conducted for the City of Los Angeles (September 2005), Section 2-10.

are produced for every ton of MSW the plant receives, and this material must be landfilled.[21]

- Pyrolysis has not been perfected, particularly for handling MSW. Only a handful of operating facilities (about 10) worldwide are commercially processing MSW.[22] Though the chemical process of pyrolysis has been used to process coal since the early 20th century, it has only recently been applied to MSW.[23]

- Brightstar Environmental constructed a 30,000 TPY pyrolysis facility in New South Wales, Australia. The plant ran for four years in a test phase, and in 2004 was closed due to technical problems with the solid residue component of the process and because the facility repeatedly exceeded the allowable limit for emissions. This shutdown represented a $134 million loss to the company.[24]

- Pre-processing of feedstock materials is required for pyrolysis (and gasification) both to remove materials that cannot be broken down by these processes, and to size-reduce materials for the handling/feed systems.

Environmental

- Pyrolysis produces low levels of air emissions containing particulate matter, volatile organic compounds, heavy metals, dioxins, sulfur dioxide, hydrochloric acid, mercury, and furans. (The types of emissions produced are similar to those from conventional incinerators.) However, the California Integrated Waste Management Board (CIWMB) *Conversion Technology Report to the Legislature* in March 2005 found that the current pyrolysis plants in Europe are capable of meeting the strict air emission standards that a plant in Los Angeles would be required to meet.[25] In light of their contributions to climate change, carbon dioxide emissions are also of concern.

- Unlike traditional incineration or "waste-to-energy" combustion, pyrolysis occurs in a "reduced" environment with a limited amount of air or oxygen. This

---

[21] City of Los Angeles, Bureau of Sanitation, *Technical Study Documents from URS: Pyrolysis (Belgium)*, http://www.lacity-alternativetechnology.org/PDF/PyrolysisFacility.pdf, accessed May-June 2008.

[22] Dvirka and Bartilucci Consulting Engineers, Waste Conversion Technologies: Emergence of a New Option or the Same Old Story? May 9, 2007.

[23] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-5.

[24] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-5.

[25] California Integrated Waste Management Board, *Draft Conversion Technologies Report to the Legislature* (2005), http://www.ciwmb.ca.gov/organics/Conversion/Events/CTWorkshop/DraftReport.pdf, accessed May-June 2008.

distinction is intended to minimize the formation of unwanted organic compounds. However, environmental and citizens groups opposed to incineration typically extend their health and environmental concerns to pyrolysis as well.[26]

- Pre-processing systems, such as recycling programs, provide the opportunity to remove chlorine-containing plastics, which could otherwise contribute to the formation of organic compounds, such as dioxins.

Economic

- Because of the small number of facilities operating with MSW worldwide, data on capital, operating, and maintenance costs are largely unavailable.

- Pyrolysis systems are managed in a control room and can be operated by a relatively small number of staff. The significant pre-processing required for pyrolysis (and gasification) involves shredding the MSW down to a specified maximum size prior to going into the feeder chute. In the case studies reviewed, that processing is done in very large (>30 ton/hour) mechanical shredders and does not involve significant manual labor. Thus, job creation potential as a result of the processing step is expected to be relatively low.[27]

Gasification

Technical

- Gasification, like pyrolysis, can reduce the volume of MSW by 80-90%, if a facility is at optimal operational conditions,[28] though this can vary between plants.

- Approximately 90 gasification plants exist worldwide, though a precise figure for the number processing MSW (as opposed to a more uniform source separated stream) is difficult to ascertain. Some facilities are in a pilot stage, testing MSW as feedstock but may not regularly handle MSW. Also, some facilities do not process MSW exclusively. For example, the Kurashiki facility in Japan operated

---

[26] McKinnon-Rutherford, Kristen. *Debunking the Myths of Incineration* (2007), 51.

[27] City of Los Angeles, Bureau of Sanitation, *Technical Study Documents from URS: Pyrolysis (Belgium)*, http://www.lacity-alternativetechnology.org/PDF/PyrolysisFacility.pdf, accessed May-June 2008.

[28] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-8.

by Interstate Waste Technologies uses industrial waste, plastic auto shredder residue, and MSW in its feedstock.[29]

- Gasification has been used commercially to convert solid, uniform biomass feedstocks (e.g., coal, wood, vegetative biomass) into liquid and gaseous fuels. Technology suppliers, however, have had difficulty converting MSW to liquid or gaseous fuels on a reliable commercial scale. MSW is not a uniform feedstock, and therefore the resulting synthetic gas may have varying ratios of carbon monoxide and hydrogen, making it difficult to market commercially.[30]

- Multiple gasification technology suppliers exist in the U.S. and overseas. The readiness and reliability of the technologies offered varies significantly. A 2006 review of thermal processing technologies performed for New York City's Department of Sanitation identified two suppliers – the Ebara Corporation and Interstate Waste Technologies – as being qualified to develop a commercial gasification facility in New York to process MSW.[31]

- Some gasification facilities have experienced significant operational problems. For example, a plant in Karlsruhe, Germany, which was operated by the Thermoselect Corporation, had serious difficulties during its "scale-up" to process 792 TPD. There were considerable delays in commissioning, which led to a reduced processing capacity. In 2002 the facility large quantities of natural gas to heat the waste, and did not deliver any electricity or heat back to the grid.[32] The plant was shut down in 2004 due to environmental, litigation, and economic issues.[33]

---

[29] Alternative Resources, Inc., *Focused Verification and Validation of Advanced Solid Waste Management Conversion Technologies* (Concord, Mass.: March 2006), Section 6.0.

[30] Alternative Resources, Inc., *Issues and Economics of Fuels Versus Electricity Produced for Conversion Technologies* (January 2008).

[31] Alternative Resources, Inc., *Focused Verification and Validation of Advanced Solid Waste Management Conversion Technologies, Phase 2 Study*, Prepared for New York Economic Development Corporation and New York Department of Sanitation (March 2006), Section 6.0.

[32]Franconian County Newspaper [Fränkische Landeszeitung], "Natural Gas Use Should Be Halved This Year [Erdgas-Verbrauch soll dieses Jahr halbiertwerden]," January 29, 2003, as cited in Greenaction for Environmental Health and Global Alliance for Incinerator Alternatives, Incinerators in Disguise: Case Studies of Gasification, Pyrolysis, and Plasma in Europe, Asia and the United States (2006).

[33] Ibid.

Environmental

- Air emissions are the paramount environmental concern with regard to gasification, and the emissions are very similar to those from pyrolysis. In 2005, the City of Los Angeles conducted an evaluation of solid waste processing techniques in Europe and Japan and concluded that a gasification plant could meet California's stringent air emission requirements. The study determined that commercially available control equipment could reduce air emissions to levels well below federal and state regulatory limits.[34]

- Emissions from gasification plants may be lower than from conventional combustion technologies. Nine air pollutants from existing waste-to-energy facilities in Massachusetts were measured and compared with the average emissions from gasification facilities. Emission levels from the Massachusetts WTE facilities were higher for all nine pollutants.[35] The Massachusetts combustors all began operations prior to 1990 and, from an emissions standpoint, perform far worse than state-of-the-art WTE facilities.

- Gasification and pyrolysis have significant wastewater impacts: quenching water and water used in cleaning steps is contaminated and generally cannot be released into sewer systems and wastewater treatment plants without additional treatment.

Economic

- The unit capital cost of a commercially operating gasification plant is estimated at $81,000-$146,000 per ton per day of installed capacity. For example, capital costs for a plant that can process 150 TPD would fall between $12 and $22 million.[36]

- Typical operating and maintenance costs are $57 to $67 per ton of waste processed.[37]

- Similar to pyrolysis facilities, waste preprocessing involves mechanical shredding for size reduction and is not a significant job producer.

---

[34] URS Corporation, *Evaluation of Alternative Solid Waste Processing Technologies*, conducted for the City of Los Angeles (September 2005), Section 2-15.

[35] Alternative Resources, Inc., *Memorandum: Air Emissions from Existing Massachusetts Waste-to-Energy Facilitates Compared to Air Emissions from Advanced Thermal Conversion Technologies* (January 14, 2008).

[36] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-18.

[37] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-18.

Anaerobic Digestion

Technical

Anaerobic digestion is a reliable technology that has been used for over a century to process sewage biosolids, but it is less commonly used for MSW. Currently, nearly 90 anaerobic digestion plants in Europe are processing MSW, handling a total of 2.75 million TPY of MSW. Most of these plants process source-separated organic materials, though some new facilities in Europe are designed to process mixed MSW, using a method that involves mechanical separation following the anaerobic digestion. The ability of these mixed MSW digestion facilities to produce marketable compost products, however, remains an open question.[38]

- Non-degradable materials found in MSW feedstock, which have not been source-separated, are highly problematic for anaerobic digestion. If those contaminants are not removed from the feedstock in a pre-processing stage, it will significantly reduce the value of the compost and in some cases damage the equipment. Also, if the pre-processing step is not done properly, much of the material would potentially need to be landfilled.

Environmental

- Excess liquid from digestion may produce some wastewater, which would require treatment or disposal. Proper process design and moisture management can minimize this waste stream to negligible levels or eliminate it all together.

- Though these facilities are designed with leak-free process vents to produce no odor or air emissions, some anaerobic digestion facilities have experienced problems with odor and community opposition. Most organic emissions and odors occur in material handling areas.[39]

Economic

- The intensive pre-processing step to remove non-degradable material makes this technology costly, but it can provide a boost in job opportunities for a local economy. Although some of this processing can be done mechanically, it usually relies on a more systematic waste collection system to separate recyclables, organics, and non-organics at the source. This separation is the main area for job

---

[38] City of Los Angeles, Bureau of Sanitation, *Technical Study Documents from URS: Anaerobic Digestion*, http://www.lacity-alternativetechnology.org/PDF/AnaerobicDigestionFacility.pdf, accessed June 2008.

[39] City of Los Angeles, Bureau of Sanitation, *Technical Study Documents from URS: Anaerobic Digestion*, http://www.lacity-alternativetechnology.org/PDF/AnaerobicDigestionFacility.pdf, accessed June 2008

creation. Operating the plant after the processing has been done would likely require a similar number of workers as pyrolysis or gasification facilities.[40]

- Anaerobic digestion facilities simply cannot process a certain portion of the waste stream that is non-degradable. That portion of the waste stream can vary. For example, in King County (Seattle), Washington, it is estimated to be roughly 32% of the county's waste stream.[41] This material must be processed in some other fashion, requiring either another type of waste conversion facility or landfill capacity.

- The cost of an anaerobic digestion system depends on the size of the facility and varies among technology providers. As an indication of possible costs, a large 1 MWe (~10,000 ton) facility is estimated to cost £3 to 4 M ($4.7 to $6.2 million) in capital costs and £100,000 ($155,000 USD) per year for operational costs.[42]

Areas for Further Review

Human Health

The influence of air emissions from thermal conversion technologies, including pyrolysis and gasification, on human health remains a key question. Particularly when considering long-term human health impacts, even small quantities of pollutants such as dioxins, furans, and mercury can be detrimental to human health. Many of these substances (dioxins in particular) can be carried long distances from their emission sources; persist for decades in the environment without breaking down into less harmful compounds; and accumulate in soil, water, and food sources.[43]

Technologies are available, however, that can substantially reduce air emissions from gasification and pyrolysis facilities. Wet and dry scrubbers can be used to decrease chlorides, hydrochloric acid, and sulfur dioxide. Other forms of air pollution control equipment can help capture fine particulate matter and trace metals. A recent California study of conversion technologies in use elsewhere concluded that existing pollution

---

[40]Karena Ostrem, *Greening Waste: Anaerobic Digestion for Treating the Organic Fraction of Municipal Solid Wastes*, http://www.seas.columbia.edu/earth/wtert/sofos/Ostrem_Thesis_final.pdf.

[41] R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options*, Draft Report (May 2007), Section 3-19.

[42] Department for the Environment, Food, and Rural Affairs, Advanced Biological Treatment of Municipal Solid Waste (2007). 27. http://www.defra.gov.uk/environment/waste/wip/newtech/pubs.htm. Accessed June 2008.

[43] National Research Council, *Waste Incineration and Public Health* (Washington, D.C.: National Academy Press, 2000).

control methods could enable such facilities to meet U.S. air quality standards.[44] Even with these air pollution control technologies, however, little information and no consensus in the scientific community exists on the long-term impacts of pyrolysis and gasification on human health. Thus, citizen and environmental groups opposed to incineration typically extend their concerns to cover other thermal conversion methods.

In considering the potential air emissions and health impacts of those conversion technologies that produce a synthetic gas (syngas), note that the syngas production phase is distinct from the combustion phase. It is important to consider the degree of scrubbing of metals and others pollutants and what kinds of pollution controls will be used on the combustion facilities that burn the synthetic gas. That is, in assessing the life cycle impacts of syngas from MSW, the emissions from the facility combusting the syngas to produce electricity (or for some other direct energy use) should be included.

Compatibility with Recycling Programs

Pyrolysis & Gasification

Pyrolysis and gasification can significantly reduce the volume of MSW and divert that material from landfills. However, it should not be understated that minimizing waste generation and reusing materials should be the primary goal of waste management, as opposed to simply reducing the volume of MSW. Thermal waste-to-energy technologies are not renewable energy sources. Rather, these technologies depend on a steady stream of natural resources, like paper from virgin forests and plastics derived from fossil fuels. Communities should therefore understand and capture the value of recycling, reusing, and reducing materials before they are discarded as waste.

Conclusions from the literature review of comparative studies on solid waste management showed overwhelmingly that recycling imposes fewer environmental burdens and consumes less energy than landfilling or thermal conversion technologies. A study from San Luis Obispo County, California, comparing recycling, disposal with energy recovery from landfill gas, and thermal waste-to-energy technologies found that "Energy grid offsets and associated reductions in environmental burdens yielded by generation of energy from landfill gas or from mixed solid waste combustion are substantially smaller than the upstream energy and pollution offsets attained by manufacturing products with recycled materials."[45] In other words, energy saved by recycling exceeds energy created by landfill gases or energy harnessed from thermal conversion technologies like pyrolysis and gasification.

---

[44] Alternative Resources, Inc., conducted for Los Angeles County, *Conversion Technology Evaluation Report* (Concord, Mass.: October 2007), Section 1:0, 1-6.

[45] San Luis Obispo County, *Comparison of Environmental Burdens: Recycling, Disposal with Energy Recovery from Landfill Gases, and Disposal via Hypothetical Waste-to-Energy Incineration* (2002).

Furthermore, some studies have concluded that waste-to-energy conversion technologies undermine recycling programs. A study by the Zero Waste New Zealand Trust reported that thermal conversion technologies need a constant supply of materials, often with a high fuel value (like paper and plastics), which can shift the focus away from recycling programs. The study stated that developing thermal conversion technologies can "result in the creation of long-term contractual agreements with local authorities guaranteeing a certain tonnage of waste per year. This situation effectively destroys incentives for local decision-makers to minimize waste or lead resource recovery programs."[46]

Some countries that employ thermal waste-to-energy technologies have banned waste that could otherwise be recycled from going to landfills or incineration plants. For example, Denmark was the first country in Europe to introduce a ban on landfilling waste suitable for reuse or recycling. Demark also uses fiscal incentives to support recycling programs. Tipping fees for landfill waste are 51 Euros (US $79) per metric ton; incineration tip fees are 44 Euros ($68) per metric ton; and recycling is free.[47] This system may be hard to replicate in some parts of the United States (e.g., the Midwest or Southwest), where many waste facilities are privately owned and landfill tip fees have generally been lower. (Note that the Northeast has the nation's highest landfill tip fees, estimated at $70 per ton on average in 2004.[48])

Anaerobic Digestion

The intensive pre-processing needed before feedstocks can begin anaerobic digestion not only complements a highly functioning recycling program, but it depends upon a waste collection system in which materials are sorted properly. A report on waste management options and climate change prepared for the European Commission concluded that implementing recycling programs in conjunction with the use of anaerobic digestion would most effectively reduce greenhouse gases: "The study has shown that overall, source segregation of MSW followed by recycling (for paper, metals, textiles, and plastics) and composting/anaerobic digestion (for biodegradable waste) gives the lowest net flux of greenhouse gases, compared with other options for the treatment of bulk MSW."[49] Though source segregation of MSW can be labor-intensive and costly, a well-organized recycling program, complemented with anaerobic digestion, generally offers more environmental benefits and energy savings than other waste management options.

---

[46] Zero Waste New Zealand Trust, *Wasted Opportunities – A Closer Look at Landfilling & Incineration*, http://www.zerowaste.co.nz/default,33.sm, accessed May-June 2008.

[47] RenoSam and Rambell, *The Most Efficient Waste Management System in Europe*: *Waste to Energy in Denmark* (2006), 13.

[48] Edward W. Repa, Ph.D., National Solids Waste Management Association, *NSWMA's 2005 Tip Fee Survey* (NSWMA Research Bulletin 05-3, March 2005), http://wastec.isproductions.net/webmodules/webarticles/articlefiles/463-Tipping%20Fee%20Bulletin%202005.pdf, accessed May-June 2008.

[49] AEA Technology. *Waste Management Options and Climate Change: Final Report to the European Commission* (2000), http://ec.europa.eu/environment/waste/studies/climate_change.pdf.

Water & Wastewater

The quantity of water required in gasification and pyrolysis facilities (for quenching and cleaning) needs to be considered in assessing facility impacts and feasibility. Similarly, the volume and quality of wastewater generated, and whether pre-treatment is required before release into a sewer system or wastewater treatment plant, should be considered.

Conclusions

- Waste reduction and recycling impose fewer environmental burdens and consume less net energy than other solid waste management techniques. Overall, the "Reduce, Reuse, Recycle" approach offers the most environmental benefits, uses the least amount of energy, could potentially divert the most waste from landfills, and poses the fewest concerns regarding human health. Maximizing waste reduction and diversion should generally be higher-level management goals than reducing the volume of waste after it is generated or producing energy.

- Pyrolysis and gasification are potentially viable, but unperfected conversion technologies for processing MSW to produce energy at the current time. Numerous technology suppliers exist, particularly for gasification, as do examples of facilities that can successfully reduce the volume of MSW. Examples are limited, however, of commercial gasification or pyrolysis facilities that have consistently produced marketable energy from MSW processing in the same way that it has been possible with more uniform feedstocks such as coal or wood.

- Anaerobic digestion received generally positive reviews. Though it requires significant pre-processing of MSW, it is a technology that complements recycling programs and poses few risks to the environment or human health. Many commercially operating facilities in Europe are currently processing MSW.

- The scientific community lacks consensus regarding the long-term effects of pyrolysis and gasification on human health.

- Capital intensive thermal conversion technologies need a constant supply of materials, often with a high fuel value (like paper, plastics, and organics), which can compete with recycling programs.

Table II-1: Alternative Technology Comparison Summary

Summary Factors	Anaerobic Digestion	Gasification	Pyrolysis
Overall advantages	Proven, effective technology if there is a local compost market to make use of the byproducts. AD uses biological and chemical technologies to break down organics and produces valuable gases that can be captured using this process. (In contrast, conventional aerobic composting can break down biodegradable materials but does not typically produce valuable gases that are captured.) AD also produces fewer air emissions than thermal technologies. Because the AD system is enclosed, odors are controlled more than with composting facilities, which are typically open to the outside air	The MSW reduction rate of gasification technology can be between 80-90% by weight – traditional thermal conversion technologies can only reduce volume by about 75%.	Pyrolysis can reduce the volume of MSW by as much as 90%.
Overall disadvantages	Intensive pre-processing step makes this technology costly and difficult to use for large amounts of MSW.	To date, "scale-up" projects have not been consistently reliable for energy production from MSW on a commercial scale. Large, commercial facilities for MSW are limited. Advanced thermal technologies require pre-sorted, size-reduced, homogenous materials.	Few large-scale facilities have been implemented. Advanced thermal technologies require pre-sorted, size-reduced, homogenous materials.
Large operating unit example	Barcelona, Spain (largest AD plant for MSW) can process 1,000 TPD of MSW. In operation since 2003.	Tokyo, Japan. Can process 180 TPD and has three years of experience processing MSW.	Hamm-Uentrop, Germany. Can process 175 TPD of MSW. In operation since 1985.

Summary Factors	Anaerobic Digestion	Gasification	Pyrolysis
Facilities commercially operating in U.S.	None for MSW. AD facilities in the U.S. are used in the dairy industry to process manure and produce electricity. One AD facility in Canada is processing MSW.	None.	None.
Technology readiness/reliability	AD has been used for over a century to process sewage biosolids. Currently nearly 90 AD plants in Europe are processing approximately 2.75 million tons of MSW per year.	There are many established and emerging gasification technology suppliers (including Global Energy Solutions, Ebara, Entech Renewable Energy System, and Thermoselect). There are approximately 90 facilities operating worldwide, but precise numbers for MSW-only facilities are uncertain as many accept industrial waste such as plastic auto shredder residue.	There are several technology suppliers. One supplier, WasteGen UK Ltd., has the longest operational facility in Germany for 22 years.
Known technical constraints	Non-degradable materials in MSW that have not been source-separated are highly problematic. If these contaminants are not removed from the feedstock, they can damage the equipment, significantly reduce the value of the resulting compost, and potentially result in landfilling of the material.	MSW feedstock requires pre-processing to reduce the size of the MSW to between 2 and 12 inches.	MSW feedstock requires shredding to a 12-inch maximum size prior to charging the pyrolysis reactors – some technologies require more of a size reduction.
Feedstocks	MSW, biowaste, waste paper, industrial waste, and sewage sludge.	MSW, biomass	Residual domestic waste, commercial waste, and sewage sludge.

Summary Factors	Anaerobic Digestion	Gasification	Pyrolysis
Energy outputs	Biogas (methane and CO_2) which can be burned to generate steam and electricity. Biogas can also be purified extensively to pipeline quality and pressurized to be used, for example, as compressed natural gas, a safe and clean vehicular fuel.	Organic materials are converted to synthetic gases (“syngas”), composed mostly of hydrogen and carbon monoxide. Syngas can be used in boilers, gas turbines, internal combustion engines or can be used to produce chemicals. Syngas can also produce methanol and ethanol.	Pyrolytic oils and fuel gases, which can be used as boiler fuel, or refined for higher quality uses, such as engine fuels. Also, thermal energy released during the pyrolytic reaction can produce steam for electricity generation. The heating value (268-376 Btu/$ft^{3)}$ depends on the quality of the feedstock.
Net energy generation	Depends on the feedstock; organic fraction of post-recycling MSW produces biogas yield averaging 4,300 scf per ton, or around 250 kWh per ton.	Fluid bed technologies (one-stage) vary from 400 to 500 kWh per ton of waste processed. Fixed bed (two-stage/gasification-pyrolysis) facilities vary between 700 to more than 900 kWh per ton of waste processed. Fluid bed technologies are considered to be more mature than fixed bed.	Varies based on feedstock composition; ranges from 400-700kWh per ton of waste processed.
Material outputs	Compost product following digestion process.	Inorganic materials are converted to either bottom ash (low-temperature gasification) or vitreous slag (with high-temperature gasification). Bottom ash is frequently landfilled, but can be used in bricks or paving stones. Slag can be used to make roofing tiles or as asphalt filler. If system uses oxygen injection (creating extremely hot temperatures), then metals can be recovered in ingot form.	Ferrous metals contained in the solid residue can be recovered for reuse.

Summary Factors	Anaerobic Digestion	Gasification	Pyrolysis
Pollution outputs	Wastewater from excess liquid from digestion. Some odors. Air from compost piles must be treated in a biofilter.	Similar emissions to pyrolysis. Syngas can be cleaned to remove most unwanted particulates and compounds.	Greenhouse gases (CO_2, CH_4). Most of the particulate matter is removed from the syngas when it passes through a cyclone, but some particulate matter is released in flue gas along with hydrochloric acid, sulfur dioxide, cadmium/thallium, mercury, dioxins/furans. For every ton of MSW, 600 lbs of char/ash are produced, which generally is landfilled as inert waste.
Capital costs	1 MWe (~10,000 ton per year or about 33 TPD) capacity facility estimated to cost £3 to £4 million ($4.7 to $6.2 million USD) or $142,000 to $188,000 per TPD of installed capacity.	$146,000 to $181,000 per TPD of installed capacity.	Not available.
Operating/maintenance costs	1 MWe (~10,000 ton) capacity estimated to cost £100,000 ($155,000 USD) per year.	Approximately $57-65 per ton of waste processed.	Not available.
Job creation	Significant processing of the MSW is needed before it can be digested; it is uncertain how many jobs this step would create, though employment is expected to be higher than for thermal technologies.	Similar to pyrolysis; relatively low job creation.	Pyrolysis system itself is managed from a control room. Labor would be needed to manage feedstock. No exact numbers for jobs created, but relatively few.

Summary Factors	Anaerobic Digestion	Gasification	Pyrolysis
Financial risks	More extensive global operational experience than thermal technologies, but no U.S. facilities for MSW to date. AD cannot process waste stream that is not biodegradable; therefore municipalities will have additional costs to implement other processing technologies or landfill a portion of waste stream.	Thermoselect had serious problems doing a "scale-up" to a 792 TPD facility in Karlsruhe, Germany. There were considerable delays in commissioning, which led to a reduced processing capacity and the plant was shut down in 2004 due to environmental, litigation, and economic issues.	Brightstar Environmental constructed two gasification units in Australia, estimated at 50 TPD, which ran for four years and then were shut down due to problems with the char gasification component of the process. This shut-down represented a $134 M loss to Brightstar.
Human health risks	The health risks from the solid and liquid residue from the AD plant should be low, as long as source-separated waste is being used (i.e., no chemical contaminants are entering the system from other waste).	Generally similar air emissions to pyrolysis. CIWMB *Conversion Technology Report to the Legislature* (March 2005) showed that the current gasification and pyrolysis plants in Japan and Europe are fully capable of meeting the strict air emission standards that a plant in Los Angeles would be required to meet, but the long-term human health implications of these emissions are unknown.	Generates low levels of PM, SO_X, mercury, dioxins, but the long-term human health implications of these emissions are unknown. Due to the limited number of commercial-scale operating pyrolysis facilities, some questions about its safety remain unresolved. However, CIWMB's *Conversion Technology Report to the Legislature* (March 2005) showed that the current gasification or pyrolysis plants in Japan and Europe are capable of meeting the strict air emission standards that a plant in Los Angeles would be required to meet..

Summary Factors	Anaerobic Digestion	Gasification	Pyrolysis
Public acceptance	Potential odors from plants remain a reason communities are concerned about this technology. Many U.S. communities have a strong track record of opposition (NIMBY) to any type of waste facility, including composting and recycling operations. Transportation impacts are also of concern to local citizens.	Varies depending on location and public outreach efforts – has been more accepted in countries where the governments communicated to citizens that the highest pollution protection measures are taken and monitored continuously. Considering waste facility siting experience, environmental laws, and citizen activism, gaining public acceptance for these facilities is expected to be challenging in the United States (see anaerobic digestion).	Varies depending on location and public outreach efforts – has been more accepted in countries where the governments communicated to citizens that the highest pollution protection measures are taken and monitored continuously. Likely to be difficult in the U.S. (see anaerobic digestion and gasification).
Compatibility with recycling programs	Yes. Would not be possible without a highly functioning recycling program so that MSW is processed as much as possible before reaching facility.	Same issues as pyrolysis/thermal conversion. Gasification is “easier” (though less energy efficient and environmentally friendly) than three R’s, so there needs to be an incentive program to continue recycling.	Pyrolysis facilities need a steady stream of energy-rich MSW to produce energy, which generally is not compatible with a comprehensive recycling program. The proper fiscal/policy tools (e.g., those in place in Denmark), however, could provide sufficient incentives for recycling.

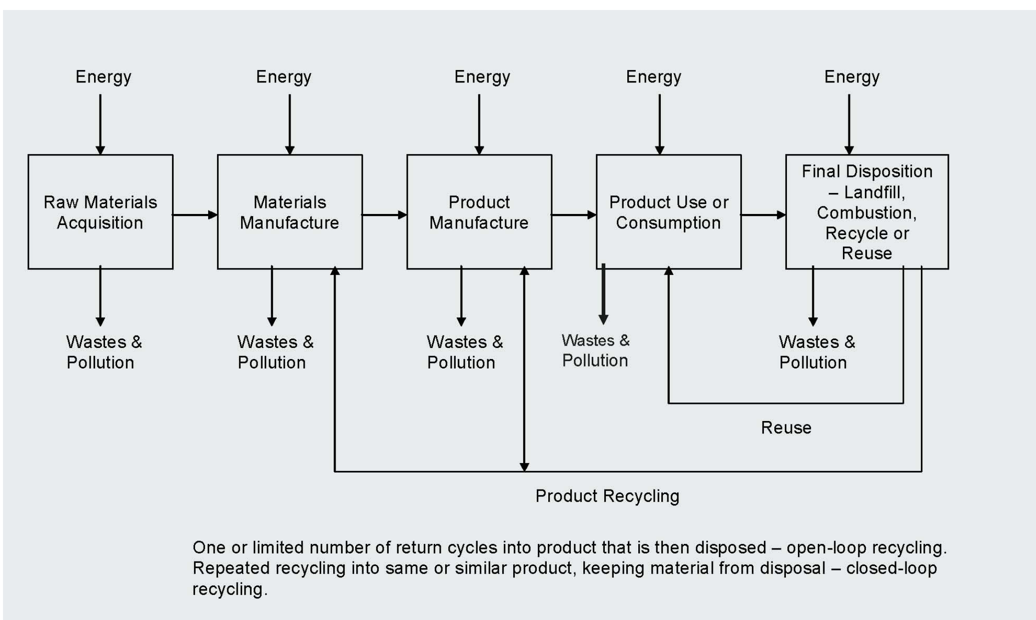
III. Results of the Morris Environmental Benefits Calculator (MEBCalc) Model

A. Model Overview

The project team utilized the Morris Environmental Benefits Calculator (MEBCalc) model, a life-cycle assessment (LCA) tool developed by team member Jeffrey Morris, to assess the relative impacts of different waste management systems for Massachusetts. The model employs a life-cycle approach to capture the input of energy and the output of wastes and pollution that occur over the three phases of a material's or product's life cycle:

- Upstream phase – resource extraction, materials refining, and product manufacturing,
- Use phase – product use, and
- End-of-life phase – management of product discards.

Figure III-1: Schematic of a Life-Cycle Assessment



The LCA approach employed in MEBCalc is shown above in Figure III-1. It depicts how reuse and recycling short circuit the upstream phase, thereby conserving energy and reducing releases of waste and pollutants in the production of goods and services. Most of this environmental value comes from pollution reductions in the manufacture of new products made possible by the replacement of virgin raw materials with recycled materials and the replacement of synthetic petroleum-based fertilizers with compost.

The model utilizes the best data sources available, relying on the following:

- US EPA WAste Reduction Model (WARM)
- US EPA MSW Decision Support Tool (DST)
- Carnegie Mellon University Economic Input-Output Life Cycle Assessment (EIO-LCA) model
- Washington State Department of Ecology Consumer Environmental Index (CEI) model
- Peer-reviewed journal articles authored by team member Jeffrey Morris.

The environmental benefits estimates are based on pollution reductions that decrease the potential for seven categories of damage to public health and ecosystems:[50]

- Climate change
- Human disease and death from particulates
- Human disease and death from toxics
- Human disease and death from carcinogens
- Eutrophication
- Acidification
- Ecosystems toxicity.

---

[50] For a detailed description and discussion of these environmental impact categories see Bare, Jane C., Gregory A. Norris, David W. Pennington and Thomas McKone (2003), TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology* 6(3-4): 49-78, and Lippiatt, Barbara C. (2007), *BEES 4.0 Building for Environmental and Economic Sustainability, Technical Manual and User Guide*, US Department of Commerce Technology Administration, National Institute of Standards and Technology, Publication NISTIR 7423, May 2007.

Life cycle analysis and environmental risk assessments provide the methodologies for connecting pollution of various kinds to these seven categories of environmental damage. For example, releases of various greenhouse gases – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and others – cause global warming which leads to climate change. The United Nations Intergovernmental Panel on Climate Change (IPCC) has thoroughly reviewed the scientific data to determine the strength of each pollutant relative to carbon dioxide in causing global warming. Based on these global warming potential factors the emissions of all greenhouse gas pollutants are aggregated into CO_2 equivalents (eCO_2).

Similar scientific efforts enable the quantity of pollutant releases to be expressed in terms of a single indicator for the other six categories of environmental damage. This greatly simplifies reporting and analysis of different levels of pollution. By grouping pollution impacts into a handful of categories, environmental costs and benefits modeling is able to reduce the complexity of tracking hundreds of pollutants. This makes the data far more accessible to policy makers. For this process the Morris Environmental Benefits Calculator relies on the methodologies used in US EPA's TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) model and the Lawrence Berkeley National Laboratory's CalTOX model.[51, 52]

For key materials in the MSW stream the methodology aggregates pollutants for each environmental impact category in terms of the following indicator pollutants:

- Climate change – carbon dioxide equivalents (eCO_2)
- Human health-particulates – particulate matter less than 2.5 microns equivalents ($ePM_{2.5}$)
- Human health-toxics – toluene equivalents (eToluene)
- Human health-carcinogens – benzene equivalents (eBenzene)
- Eutrophication – nitrogen equivalents (eN)
- Acidification – sulfur dioxide equivalents (eSO_2)
- Ecosystems toxicity – herbicide 2,4-D equivalents (e2,4-D)

---

[51] Bare, Jane C. (2002), *Developing a Consistent Decision-Making Framework by Using the U.S. EPA's TRACI,* U.S. Environmental Protection Agency, Cincinnati, OH; and Bare, Jane C., Gregory A. Norris, David W. Pennington and Thomas McKone (2003), TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology* 6(3-4): 49-78.

[52] See a description of the CalTOX model, references, and downloadable manual and software at http://www.dtsc.ca.gov/AssessingRisk/caltox.cfm.

Full documentation of the model is provided in Appendix 2, Documentation for the Morris Environmental Benefits Calculator Model, which references the supporting documentation for the other tools and sources mentioned above.

B. Key Modeling Assumptions

The model was applied to the Massachusetts-specific waste stream in terms of the tonnage and material composition reported in MA DEP's *Solid Waste Master Plan: 2006 Revision* (section 4), the 2006 Solid Waste Data Update on the *Beyond 2000 Solid Waste Master Plan*, as well as Tellus Institute's 2003 report prepared for DEP, *Waste Reduction Program Assessment and Analysis for Massachusetts*. The 2006 MA total waste stream (residential, commercial, and construction and demolition) is summarized in Table III-1.

Table III-1

2006 Total Massachusetts Waste Stream: Generation, Diversion and Disposal (tons)

Material Type	Actual Generation	Recycling & Composting Diversion	Other Diversion	Disposal Tonnages
Corrugated	828,492	490,945		337,548
Mixed Paper	2,238,890	953,505		1,285,385
Newspaper	456,587	180,266		276,321
Glass	516,288	312,762		203,526
Plastics	697,444	37,857		659,587
Aluminum	42,234	25,042		17,192
Steel/Tin Cans	121,226	58,237		62,989
Scrap Metal	569,765	295,701		274,063
White Goods	25,552	22,332		3,220
Food	1,173,020	29,268		1,143,752
Yard Waste	1,139,053	724,000		415,053
HHP	26,454	5,958		20,496
Other Materials	1,465,394	374,128		1,091,266
ABC	2,966,500	2,800,000		64,800
Wood	573,500	120,000		223,200
Wood for Non-Fuel	-	70,000		-
Wood Waste	-	50,000		-
Wood for Fuel	-	0	80,000	-
Gypsum Wallboard	185,000	10,000		72,000
Roofing	203,500	30,000		79,200
Other C&D*	571,100	0		230,400
Fines/Residuals	-		790,000	
Other Non-MSW	90,000			90,000
Totals (tons)	13,890,000	6,470,000	870,000	6,550,000

Note that the following definitions are used throughout the MEBCalc model:

- Recycling: closed loop material recycling
- Composting: aerobic composting
- WTE Incineration: mass burn thermal conversion/advanced thermal recycling (offset to natural gas powered electricity generation)
- Gasification/Pyrolysis: averages for advanced thermal conversion technologies (offset to natural gas electricity)
- Landfill + Energy: 75% methane capture & conversion to electricity in an internal combustion engine (offset to natural gas electricity)
- Recycled: closed loop discarded-materials-content products
- Virgin: newly extracted raw-materials-content products

Key assumptions used in the MEBCalc model for calculating the life-cycle emissions are drawn from the sources mentioned above in section III.A and include the following:

- All emissions resulting from landfilling a particular waste material that will occur over time as a result of burying that material are modeled as if they occur at the time of landfilling.
- Material decomposition rates are taken from the WARM model and are based on national dry-tomb standard landfills.
- Similarly, carbon storage rates for each waste material are based on the WARM model.
- Net GHG emissions are based on (1) gross GHG emissions per ton MSW, including transport related emissions; (2) any increases in carbon stocks due to waste management practices (e.g., landfilling results in increased carbon storage as a portion of the organics disposed in a landfill do not decompose); and (3) energy generation from waste that displaces fossil fuel consumption and related emissions. This approach is the same as that used by EPA and can be summarized as follows:

  Net GHG emissions = Gross GHG emissions – (Increase in carbon stocks + Avoided utility GHG emissions).

- CO_2 emissions from biogenic waste (e.g., paper, yard trimmings, food discards) are accounted for according to IPCC Guidelines and consistent with EPA's approach in WARM and DST. That is, carbon emissions from biogenic sources is considered as part of the natural carbon cycle – returning CO_2 to the atmosphere that was removed by photosynthesis – and its release does not count as adding to atmospheric concentrations of carbon dioxide. Conversely, CO_2 emitted by burning fossil fuel, is counted because they enter the cycle due to human activity. Similarly, methane emissions from landfills are counted (even though the carbon source is largely biogenic) because the methane is generated only as a result of the anaerobic conditions that human landfilling of waste creates.[53]

- A landfill gas (LFG) capture rate of 75% is assumed. This is consistent with the default capture rate used in WARM.[54]

- Landfilling of municipal waste combustion ash is considered in the model, including emissions from transport to an ash landfill. Virtually all carbon is assumed to be combusted in the incineration process. Thus, for modeling purposes MWC ash contains no carbon.

- Traditional MWC reduces the volume of waste by 90%. This is consistent with the assumptions used in U.S. EPA's Decision Support Tool.

- For MWCs, 70% of ferrous metal is assumed to be recovered from ash and recycled. This is consistent with the DST assumptions.

- Emissions from operational activities at landfills and MWC facilities, such as use of heavy equipment as well as landfill leachate and MWC ash management, are based on the DST and taken into account.

- The electrical energy generated from combusting landfill gases or thermal treatment of MSW is assumed to offset electricity on the regional grid that would otherwise be generated using natural gas, the region's marginal fuel type.[55]

---

[53] U.S. EPA, *Solid Waste Management and Greenhouse Gases: A Life Cycle Assessment of Emissions and Sinks*, May 2002, p. 12.

[54] It also is a mid-range value between those landfill experts who claim a modern landfill gas collection system will capture 95% of LFGs, and those who claim that the effective LFG collection efficiency is 50% or less because installation of the gas collection system is typically delayed until some months or more after a landfill cell begins receiving waste and because there is no guarantee that the LFG collection system will continue to operate after landfill closure for as long as LFGs continue to be generated.

[55] This is an important assumption and differs from EPA's WARM model, which assumes a coal-heavy national average fossil fuel mix used by utilities, as the fuel type that is offset. This fuel mix generates about 66% more eCO_2 offset per kWh than natural gas. (See U.S. EPA, 2002, Exhibit 6-4).

- The generation of electricity from landfill gas is assumed to be done using internal combustion engines.
- Collection, transfer and transport distances are assumed to be similar across disposal technologies. Waste transport of up to 100 miles by truck and 400 or more miles by rail is modeled for transport emissions calculations.
- Recycled materials are assumed to be hauled up to 500 miles one-way by truck from MRF to end use, or 2100 miles by rail.

C. Comparison of Emissions & Energy Generation Potential by Waste Management Approach

Emissions

The MEBCalc model was used to calculate the relative emissions of the various waste management approaches under consideration in this report. Table III-2 presents a summary of the life-cycle emissions per ton of solid waste as calculated using the MEBCalc model.

Table III-2: Summary of Per Ton Emissions by Management Method

Management Method *	Pounds of Emissions (Reduction)/Increase Per Ton – Summary *						
	Climate Change	Human Health - Particulates	Human Health - Toxics	Human Health- Carcinogens	Eutrophi-cation	Acidifi-cation	Ecosystem Toxicity
	(eCO_2)	(ePM2.5)	(eToluene)	(eBenzene)	(eN)	(eSO2)	(e2,4-D)
Recycle/ Compost	(3620)	(4.78)	(1587)	(0.7603)	(1.51)	(15.86)	(3.48)
Landfill	(504)	2.82	275	0.0001	0.10	2.38	0.21
WTE Incineration	(143)	(0.30)	68	0.0019	(0.01)	0.04	0.29
Gasification/ Pyrolysis	(204)	(0.36)	(1)	(0.0000)	(0.05)	(0.93)	0.09

* Quantitative performance data from anaerobic digestion facilities comparable to that for the other facility types are not readily available for the modeled emissions categories and therefore not included in the table.

It is important to note that for modern landfills, waste-to energy incinerators, as well as the gasification and pyrolysis plants, the emission factors used to compare environmental performance are based largely on modeling and/or vendor claims for modern, state-of-the art facilities, as opposed to actual operational data from real world experience. This puts these facilities in the best light possible from an environmental performance standpoint. For example, actual operating performance for Massachusetts WTE facilities has been shown to produce far higher emissions than the modeled figures. Similarly, there remains significant uncertainty as to whether commercial scale gasification/pyrolysis facilities processing MSW and generating energy can perform as well as the vendor claims or modeled emissions.

For each of the seven major emissions categories modeled, recycling/composting reduces per ton emissions more than any other waste management technology. Most of these benefits come from pollution reductions in the manufacture of new products made possible by the replacement of virgin raw materials with recycled materials and the replacement of synthetic petroleum-based fertilizers with compost. For most pollutants, the relative benefits of upstream diversion are quite dramatic. For example, recycling reduces energy-related eCO_2 emissions in the manufacturing process and avoids emissions from waste management. Moreover, paper recycling maintains the ongoing sequestration of carbon in trees that would otherwise need to be harvested to manufacture paper. On a per ton basis, recycling saves more than seven times eCO_2 than landfilling, and almost 18 times eCO_2 reductions from gasification/pyrolysis facilities.

Among the other technology options – landfilling, waste-to-energy incineration, and gasification/pyrolysis – **no technology performs better than the others across *all* the emissions categories reviewed.**[56] **However, reported per ton emission factors for gasification/pyrolysis facilities are lower than for WTE incineration facilities for all pollutants, and lower than landfill emissions for all except carbon dioxide (eCO_2).**

Preference among the alternative technology options based on environmental performance is dependent on the relative importance placed on eCO_2 emissions versus the other pollutants. For example, on a per ton MSW basis, modern landfills with efficient gas capture systems reduce two and a half times as much eCO_2 as gasification and pyrolysis facilities, and three and a half times as much as waste-to-energy incinerators.[57] In addition to the reduction in eCO_2 emissions due to methane

---

[56] The literature review in section II of this report also considered anaerobic digestion facilities. While qualitative statements can be made about the environmental performance of such facilities, quantitative performance data from anaerobic digestion facilities comparable to that for the other facility types is not readily available for the modeled emissions categories and therefore not included in the table.

[57] The eCO2 figures in Table III-2 differ from those cited by EPA in its October 2006 report, Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks, for several reasons. First, the MEBCalc model assumes energy generated from solid waste, whether from landfill methane or from combusting MSW directly, offsets electricity produced from natural gas, the "marginal fuel" in New England, while EPA uses a national average fossil fuel mix, with eCO_2 emissions nearly twice those of natural gas. Also, the EPA report expresses GHG emissions in terms of metric tons carbon equivalents (MTCE), while in the current report we follow the international standard and express emissions

capture for energy generation, a key factor contributing to this is the role that landfills play in storing carbon. Specifically, the portion of the disposal stream with embedded fossil fuels (e.g., plastics, rubber), as well as certain organic material that does not decompose in a landfill, is essentially stored. In the case of thermal technologies, all of the carbon from the waste is converted into CO_2.[58]

It should be noted that the lack of comprehensive data for disposal facility emissions profiles, other than for GHGs,[59] makes results for the other six environmental impacts – acidification, eutrophication, releases of particulates damaging to human health, and releases of toxics and carcinogens damaging to human health and ecosystems – less certain. Limited emissions estimates for many pollutants as well as small sample sizes for available emissions profiles mean that new or refined emissions profile data could alter the rankings of landfilling and combustion for any of the six (non-CO_2) impact categories. In addition, the net environmental impacts from combustion of landfill gases in an internal combustion engine to generate electricity need further research. For example, emissions from landfill gas combustion equipment reduce the emissions offsets that such energy generation achieves in terms of reduced burning of fossil fuels for the electricity grid.

In order to determine whether the environmental impacts reported in Table III-2 for Massachusetts' MSW wastes might be obscuring differences between MSW wastes and C&D wastes, the project team also used MEBCalc to estimate emissions impacts for C&D wastes. In general the discussion based on relative environmental impacts for MSW is also accurate for C&D waste and for combined MSW and C&D wastes.

The summary graphs in Appendix 3 present the detailed results of the MEBCalc modeling, comparing recycling and composting to landfilling, waste-to energy incineration, and the emerging technologies of gasification and pyrolysis, all on a per ton per specific MSW materials basis. As mentioned above, the project team did not have access to sufficient emissions data for anaerobic digestion facilities for their inclusion in

---

in terms of carbon dioxide equivalents (eCO_2). The conversion between eCO_2 and CE is directly related to the ratio of the atomic mass of a carbon dioxide molecule to the atomic mass of a carbon atom (44 to 12).

[58] Several factors contribute to landfills superior performance in terms of GHG emissions. Combustion of products/packaging containing fossil fuels (e.g., anything plastic or rubber) releases GHGs, and these materials are prevalent in the disposal stream. This applies to combustion of synthetic gases as well (e.g., making petroleum and natural gas into plastics, then gasifying those plastics to make a synthetic gas and then combusting that synthetic gas, whether on site or off site from the gasification facility, releases GHGs just as combusting petroleum or natural gas directly does). Also, landfill gas recovery systems can be very efficient at capturing methane. The MEBCalc model uses a 75% capture rate (the DST model uses 88% while WARM uses 75%).

[59] The carbon content of disposed materials is relatively well understood and documented, as is whether CO_2 is biogenic or anthropogenic.

the comparative analysis at this time. In addition to the seven emissions categories described above, the graphs also depict energy use and energy savings.

Energy Generation Potential

From a life-cycle net energy perspective, waste diversion through recycling provides the most benefit per ton of solid waste, saving an estimated 2,250 kWh per ton MSW. Of the other waste management technologies, gasification and pyrolysis facilities have the most potential for energy production at about 660 kWh per ton,[60] followed by waste to energy incinerators at 585 kWh per ton, anaerobic digestion, and landfilling.[61] The estimated energy potential of the various management methods used in the MEBCalc model are summarized in Table III-3, below.

Table III-3: Net Energy Generation Potential Per Ton MSW

Management Method	**Energy Potential** (kWh per ton MSW)
Recycling	2,250
Landfilling	105
WTE Incineration	585
Gasification	660
Pyrolysis	660
Anaerobic Digestion	250

[60] As described in Table II-1, given that fluid bed technologies for gasification facilities are considered to be more mature than fixed bed technologies, an energy potential of 400-500 kWh per ton may be more likely. Also, the 660 kWh per ton figure represents the high end of the reported range for pyrolysis.

[61] The sources for the energy potential estimates include: Jeffrey Morris' "Recycling versus incineration: An energy conservation analysis," *Journal of Hazardous Materials*, Vol. 47, May 1996, pp. 277-293; R.W. Beck, *Comparative Evaluation of Waste Export and Conversion Technologies Disposal Options, Draft Report*, May 2007; URS Corporation, *E*valuation of Alternative Solid Waste Processing Technologies, conducted for the City of Los Angeles, September 2005; United States Environmental Protection Agency, *Solid Waste Management and Greenhouse Gases, A Life-Cycle Assessment of Emissions and Sinks*, Research Triangle Institute, May 2002; "A Decision Support Tool for Assessing the Cost and Environmental Performance of Integrated Municipal Solid Waste Management Strategies: Users Manual," Draft for U.S. EPA, 1999.

Note that per-ton energy potential estimates are dependent on a number of factors including: the composition of the MSW stream, the specific technologies considered (e.g., fluid bed versus fixed bed for gasification), and the source of the data.

The above estimates put the potential energy generation from the thermal technologies in a favorable light. For example, the energy generation potential of pyrolysis facilities ranges from 400-700 kWh per ton. This report uses a figure towards the high end of this range in the current analysis, though there is little supporting operating data from large-scale commercial facilities. Also, the energy production from WTE incinerators represents new state-of-the-art facilities, not the older facilities currently operating in MA. On the other hand, the estimated energy potential of landfills reflects older style, less efficient, combustion equipment. Estimates of net energy potential from the capture and burning of landfill gases can be well over 200 kWh per ton, and an effort is currently under way to improve the performance of internal combustion engines burning landfill gases.

D. Scenario Modeling Results

Using the MEBCalc model emission factors described above, three scenarios were modeled to assess the relative environmental and energy impacts of alternative waste management practices for managing the Commonwealth's waste stream through the year 2020. As described more fully below, Scenario 1 posits no change in management practices or the fraction of waste diverted over this period; Scenario 2 assumes enhanced recycling and composting programs but no new technologies, while Scenario 3 includes both the enhanced diversion efforts from Scenario 2 plus the introduction of new alternative technologies – namely gasification and/or pyrolysis facilities – to manage some of the waste stream.

Scenario 1: Business-As-Usual, 2006 Practices Extended

Scenario 1 draws its major assumptions from DEP's *Solid Waste Master Plan* and the 2006 Solid Waste Data Update. The Massachusetts waste stream is assumed to grow 2% per year through 2020. The diversion rate from recycling and composting is assumed to keep pace with the growth in the waste stream and stay at 2006 levels on a percentage basis. No alternative technology facilities are assumed to be operating in Massachusetts in 2020. The existing incineration capacity (roughly 3.1 million tons per year) is expected to remain in place, but in-state landfill capacity in assumed to decrease from 1.9 million to just 630,000 tons per year by 2020. Massachusetts incinerator capacity is assumed to manage MSW components of the waste stream, while all C&D waste is assumed to be landfilled. In terms of waste management, the absolute growth in the post-diversion waste stream requiring processing or disposal (from 7.3 million tons in 2006[62] to 9.8 million tons in 2020) means that unless additional disposal capacity is built, waste in excess of MA capacity (about 6 million tons) will be exported.[63]

Scenario 2: Enhanced Diversion, No Alternative Technologies

This scenario also uses a 2% per year growth rate in solid waste generation. As in Scenario 1, existing incineration capacity (roughly 3.1 million tons per year) is expected to remain in place for MSW, and in-state landfill capacity is assumed to decrease significantly to 630,000 tons per year by 2020. However, enhanced recycling and composting rates that reflect the "realistic potential" diversion for recyclable and compostable materials are assumed.[64] Thus, the post-diversion waste stream is reduced from 7.3 million tons in 2006 to 6.8 million tons in 2020 (as opposed to growing to 9.8 million tons in Scenario 1). The three million ton reduction means that far less new capacity or waste exports (about 3 million tons) are required. No alternative gasification, pyrolysis or anaerobic digestion facilities are assumed to be operating in 2020 to manage this material.

Scenario 3: Enhanced Diversion with Alternative Technology Facilities

This scenario is identical to Scenario 2, except that it includes new gasification and/or pyrolysis facilities by 2020. Thus, waste generation grows 2% per year, enhanced waste diversion programs are successfully implemented, 3.1 million tons of existing incineration capacity remains in place to process MSW, and landfill capacity declines precipitously to 630,000 tons per year by 2020. All C&D continues to be landfilled, mostly outside of Massachusetts. Scenario 3 assumes that of the post-diversion waste, all MSW not sent to Massachusetts WTE facilities, or almost 1.9 million tons per year, is managed by new gasification and/or pyrolysis facilities. Thus, this scenario assesses the relative environmental and health implications as well as the additional energy generation potential of managing a significant fraction of the MSW (as opposed to C&D) with these new technologies.

---

[62] In these scenarios the post recycling/composting tonnage requiring disposal includes material used for landfill cover, called "Other C&D Diversion" in MA DEP's "2006 Solid Waste Data Update on the *Beyond 2000 Solid Waste Master Plan*."

[63] Virtually all of the exported waste is assumed to be landfilled. This is consistent with Tables 14 and 15 of the 2006 Solid Waste Data Update on the *Beyond 2000 Solid Waste Master Plan* and discussions with DEP staff in September 2008 interpreting the disposition of waste export data.

[64] "Realistic potential" figures were defined and estimated in Tellus Institute's 2003 report for MA DEP, *Waste Reduction Program Assessment and Analysis for Massachusetts*. These rates are informed by state and local programs around the U.S. that employ "best practices" and achieve high levels of diversion.

Emissions Impacts

Scenario 1 represents a "business as usual" approach to the Commonwealth's waste management through the year 2020. With current WTE facility capacity remaining in place, landfill capacity declining sharply, no new alternative technology facilities in place, and no change in current recycling/composting diversion rates (46.6%), continued growth in overall waste generation means that the amount of waste requiring disposal in 2020 will increases to about 9.8 million tons in 2020. Without enhanced upstream diversion efforts or the addition of new in-state management capacity, net waste exports would need to increase dramatically from about 1.3 million tons to about 6 million tons. The degree to which this level of out-of-state capacity will be available in 2020 is uncertain.

The main difference between Scenario 1 and Scenarios 2 and 3 is the level of upstream diversion through recycling and composting. The enhanced recycling and composting efforts assumed in Scenarios 2 and 3 increase the diversion rate from almost 47% to over 62%. This significantly reduces the disposal stream that must be managed and its associated emissions and energy use. Scenario 3 differs from Scenario 2 by introducing new gasification and pyrolysis facilities and shifting the 1.9 million tons of the non-C&D portion of the disposal stream from landfills to these new thermal processing technologies. Thus, the faction of the waste stream that is landfilled is reduced by about half, from almost 21% in Scenario 2 to less than 11% in Scenario 3, with this 10% of the waste stream assumed to be managed by gasification and pyrolysis facilities by 2020.

From an emissions standpoint, as Table III-4 demonstrates (see following page), **Scenario 1 produces significantly lower environmental benefits than the other scenarios across all categories considered. This is driven by the fact that there is not an enhanced recycling program in Scenario 1 and the disposal stream is about 3 million tons more than in the other scenarios**. Thus, in this scenario the Commonwealth would not reap the full benefits of avoiding the upstream emissions of materials and products that could be recycled or composted at higher levels. For most categories, emission reductions are between one half and two-thirds of the reductions achieved in the other scenarios. For CO_2, however, reductions are about 73% as much as in Scenarios 2 and 3, as the per ton benefits of landfilling mute the impact of the larger disposal stream. For particulates, Scenario 1 performs particularly poorly, achieving a third or less of the emission reductions of the other scenarios, due largely to the uncontrolled emissions from landfill operating and gas combustion equipment.

The emissions profiles for Scenarios 2 and 3 are very similar for virtually all emissions categories. Except for particulates, where Scenario 3 achieves 18% greater emission reductions than in Scenario 2, again due to less use of landfill equipment, the two scenarios produce emission reductions of the other pollutants within 5% of each other. As mentioned, CO_2 emissions are lower in Scenario 2 due to the greater reductions in greenhouse gas emissions provided by landfilling compared with gasification and pyrolysis. Given the significant differences in per ton emissions for certain pollutants between landfills and gasification/pyrolysis facilities, the relatively small differences in the overall emissions profiles of Scenarios 2 and 3 may be somewhat surprising. The impact on overall emissions is limited because the fraction of waste shifted from landfilling to gasification and pyrolysis is only about 10% of the total waste stream. Thus, the emissions associated with the large fraction of the waste stream that is recycled/ composted (62%) and incinerated in conventional waste to energy facilities (17%) in both scenarios has a determinative impact on the overall emissions profile.

Though the overall differences are small, the shifting of waste from landfilling to gasification and pyrolysis facilities that occurs in Scenario 3 results in lower overall emissions for all pollutants except eCO_2. This is consistent with the discussion of per ton emissions factors for the various waste management methods, in which landfills reduce eCO_2 emissions to a greater extent than WTE incinerators or the alternative thermal technologies.

Table III-4: Scenario Emission Impacts

2020 Scenario	Post-Diversion Technology	Tons Managed	% of Waste Stream	Climate Change	Human Health - Particulates	Human Health - Toxics	Human Health-Carcinogens	Eutrophication	Acidification	Ecosystems Toxicity
				(eCO2)	(ePM2.5)	(eToluene)	(eBenzene)	(eN)	(eSO2)	(e2,4-D)
Scenario 1 No Max Diversion No Alt Tech	Recycled/Composted	8,537,028	46.6%	(8,949,381)	(12,464)	(3,312,275)	(1,135)	(2,989)	(36,131)	(10,542)
	Landfilled w/ 75% + Energy	6,690,532	35.9%	(1,433,889)	7,470	875,678	0	343	7,611	771
	Modern WTE Incineration	3,100,000	17.5%	(64,544)	(164)	113,550	3	7	(120)	484
	Totals	**18,327,560**	**100.0%**	**(10,447,814)**	**(5,158)**	**(2,323,047)**	**(1,131)**	**(2,638)**	**(28,640)**	**(9,286)**
Scenario 2 Maximum Diversion No Alt Tech	Recycled/Composted	11,395,364	62.2%	(13,834,435)	(18,527)	(5,598,739)	(2,271)	(5,380)	(57,545)	(15,661)
	Landfilled w/ 75% + Energy	3,832,196	20.9%	(698,727)	3,536	454,292	0	194	3,970	423
	Modern WTE Incineration	3,100,000	16.9%	(7,991)	(33)	112,976	3	15	(234)	483
	Totals	**18,327,560**	**100.0%**	**(14,541,153)**	**(15,024)**	**(5,031,471)**	**(2,268)**	**(5,171)**	**(53,809)**	**(14,754)**
Scenario 3 Maximum Diversion Plus Alt Tech	Recycled/Composted	11,395,364	62.2%	(13,834,435)	(18,527)	(5,598,739)	(2,271)	(5,380)	(57,545)	(15,661)
	Landfilled w/ 75% + Energy	1,955,335	10.7%	(441,634)	1,108	204,081	0	97	1,797	197
	Modern WTE Incineration	3,100,000	16.9%	(7,991)	(33)	112,976	3	15	(234)	483
	Gasification/Pyrolysis	1,876,861	10.2%	36,760	(243)	(1,392)	(0)	(47)	(855)	90
	Totals	**18,327,560**	**100.0%**	**(14,247,299)**	**(17,696)**	**(5,283,074)**	**(2,268)**	**(5,315)**	**(56,837)**	**(14,891)**

Energy Impacts

In terms of the net energy potential, the fraction of waste recycled or composted has a dominant impact on the overall system energy profile for all three scenarios. This is due to a combination of the size of the recycled/composted waste stream (47% in Scenario 1, 62% in Scenarios 2 and 3), plus the high energy savings per ton of diverted waste.

As summarized in Table III-5, in 2020 Scenario 1 has a net energy potential of almost 22 million MWh, over 88% of which is related to the energy savings from recycling/ composting. The assumed enhanced recycling/composting activities in Scenarios 2 and 3 boost the overall solid waste management system's net energy potential by about 6.1 million MWh or 28% over Scenario1. Introducing the gasification and pyrolysis facilities in Scenario 3, described above, and shifting non-C&D MSW from landfills to these new thermal treatment facilities increases overall net system energy potential by an additional one million MWh.

Table III-5: Scenario Energy Impacts

2020 Scenario	Post-Diversion Technology	Tons Managed	kWh/Ton	MWh Potential
Scenario 1 No Max Diversion No Alt Tech	Recycled/Composted	8,537,028	2,250	19,208,313
	Landfilled w/ 75% + Energy	6,690,532	105	702,506
	Modern WTE Incineration	3,100,000	585	1,813,500
	Totals	18,327,560		**21,724,319**
Scenario 2 Maximum Diversion No Alt Tech	Recycled/Composted	11,395,364	2,250	25,639,568
	Landfilled w/ 75% + Energy	3,832,196	105	402,381
	Modern WTE Incineration	3,100,000	585	1,813,500
	Totals	18,327,560		**27,855,449**
Scenario 3 Maximum Diversion Plus Alt Tech	Recycled/Composted	11,395,364	2,250	25,639,568
	Landfilled w/ 75% + Energy	1,955,335	105	205,310
	Modern WTE Incineration	3,100,000	585	1,813,500
	Gasification/Pyrolysis	1,876,861	660	1,238,728
	Totals	18,327,560		**28,897,107**

As with pollutant emissions, the scenario energy impacts point to the significant net energy benefits of broadening and strengthening the Commonwealth's recycling and composting diversion programs and the relatively modest additional benefits associated with shifting non-C&D MSW from landfills to new thermal processing facilities.

IV. Successful Waste Reduction / Materials Management Experience Elsewhere

A. Background

The Massachusetts Solid Waste Master Plan continues to identify waste reduction as the highest priority at the top of the solid waste management hierarchy. This section of the report focuses on waste reduction and reuse activity throughout North America and internationally. It is intended to provide an understanding of the leading programs and techniques for solid waste reduction implemented in other jurisdictions, as a means of informing DEP as to the most promising techniques, policies and programs to consider for its next revision of the Master Plan. The following summary draws heavily from recent reviews the Project Team completed for the Washington State Department of Ecology and the Oregon Department of Environmental Quality. In carrying out this research, the Project Team conducted a literature review, examined program reports, and interviewed selected program managers to gain a full understanding of the scope and impacts of the various efforts.

As outlined below, we have identified six major strategies for waste reduction and reuse activities and have organized the detailed review in Appendix 1 accordingly. They are:

- Resource Productivity Improvements
- Alternative Business Models
- Public Awareness and Action
- Economic Incentives
- Regulatory Requirements
- Government Leadership by Example

For each strategy, we have summarized and assessed what are considered to be among the most successful programs. In addition, the detailed review in Appendix 1 is organized by jurisdiction, providing descriptions of the various programs in each location.

To provide an additional perspective to policymakers concerning the nature and target of the programs reviewed, the Project Team has identified three broad categories of waste reduction strategies: **supply-side** efforts that focus on waste prevention in the production and sale of goods and services by manufacturers and retailers, **demand-side** initiatives that address sustainable consumption opportunities by consumers and communities, plus **policy-side** efforts by government through legislation, regulation and programmatic initiatives. This framework is intended to help DEP consider and prioritize the alternative strategies most appropriate for Massachusetts.

B. Scope of Review

The review of waste reduction and reuse efforts outside of Massachusetts is intended to provide DEP with an understanding of the successful programs and techniques for solid waste prevention implemented in other jurisdictions in the U.S. and internationally. It focuses heavily on state-level programs, as these will be most relevant to the needs of DEP. In addition, our review pays special attention to "sustainable consumption" initiatives in Europe. The working definition of sustainable consumption, produced at the 1994 Oslo Roundtable on Sustainable Production and Consumption hosted by the Norway Ministry of the Environment, is "the use of services and related products which respond to basic needs and bring a better quality of life, while minimizing the use of natural resources and toxic materials so as not to jeopardize the needs of future generations." These European initiatives are at the cutting edge of waste prevention efforts and address deep issues concerning values and lifestyle choices. Their potential for waste reduction goes far beyond conventional programs.

The review encompasses leading national and international solid waste prevention and reuse programs in order to provide a thorough understanding of the possibilities and effectiveness of "best practices."

Waste Prevention Programs Reviewed

Ultimately, our review included the following North American waste prevention programs:

- Alameda County Waste Management Authority & Recycling Board
- California Integrated Waste Management Board
- Florida
- King County, Washington
- Maine
- Minnesota Office of Environmental Assistance, Product Stewardship Initiative
- New York City, Bureau of Waste Prevention and Recycling
- Oregon Department of Environmental Quality
- San Francisco, California
- Seattle, Washington
- Vermont Builds Greener Program
- Washington State Department of Ecology, Beyond Waste Program
- Alberta
- British Columbia, Canada, Product Stewardship Program
- Canadian National Office of Pollution Prevention, Extended Producer Responsibility, Life Cycle Management, and Eco-Labeling Programs
- Ontario

Internationally, programs considered include:

- European Commission, proposed new strategy for waste prevention
- European Union, Sustainable Consumption initiatives
- Germany, Packaging Ordinance, Green Dot, Integrated Product Policy, and Sustainable Consumption Program
- Netherlands, Extended Producer Responsibility Program
- United Kingdom, Waste Prevention Project of the National Resource & Waste Forum

In addition, our literature review drew on several key organizations active in the waste prevention arena, including the U.S. Green Building Council and U.S. EPA.

This represents a plethora of waste prevention and reuse programs that have been developed and tested in the U.S. and abroad in recent years. These include leasing and "servicizing," sustainable consumption efforts, environmentally preferable purchasing (EPP), extended producer responsibility (EPR), grasscycling and xeriscaping, on-site management/reuse of organic waste, remanufacturing, industrial ecology, materials exchanges, paper reduction efforts, policy and legislative initiatives, and many others. Programs are often defined by location (home, office, school or campus), sector (construction, hospitality, auto) or by product/material (packaging, paper, mercury). Many of the most successful programs involve partnerships among government, business, and consumers.

For purposes of this report, we have organized these programs into six major strategies:

- Resource Productivity Improvements
- Alternative Business Models
- Public Education and Awareness
- Economic Incentives
- Regulatory Requirements
- Government Leadership by Example

We have identified three broad categories of waste reduction strategy: **supply-side** efforts that focus on waste prevention in the production and sale of goods and services by manufacturers and retailers (Resource Productivity Improvements and Alternative Business Models), **demand-side** initiatives that address sustainable consumption opportunities by consumers and communities (Public Awareness and Action), plus **policy-side** efforts by government through legislation, regulation and programmatic initiatives (Economic Incentives, Regulatory Requirements, Government Leadership by Example). Note that it is not uncommon for a jurisdiction's waste prevention or reuse initiatives, or even a single program, to fall within more than one of these categories.

In considering the leading programs under each category, it is important to keep in mind that the individual program elements are related to one another and, as MA DEP has done in the Master Plan, they should be seen as part of a coherent and well-coordinated overall strategy. The synergies among programs can be just as important as the individual programs. For example, Design for Environment efforts are often at least partially motivated by Extended Producer Responsibility (EPR) requirements, enhanced environmental reporting requirements (life-cycle and supply chain included), or other initiatives.

Appendix 1 reviews, evaluates and summarizes the most relevant information and experiences regarding each of the six major strategies that DEP should consider in expanding and enhancing its waste reduction and reuse programs. It is important to note that many of the waste prevention and reuse programs and policies reviewed here are relatively new and few have been systematically evaluated by either the agencies responsible for their implementation or independent agencies. Moreover, as mentioned above, waste prevention is often difficult to measure and quantify. Thus, many findings are more qualitative than quantitative, though our review tries to identify organizations and programs that appear to be most effective and offer the best models for further reuse and waste prevention efforts.

C. Waste Reduction Experience - Summary Findings

- **Individual waste reduction and reuse programs should be integrated in a coherent overall strategy to maximize effectiveness.** Stand-alone elements such as education or technical assistance for home composting, for example, are much more effective when combined with economic or policy incentives such as Pay-As-You-Throw pricing or disposal bans. Similarly, technical assistance efforts for Design for Environment programs have greater impact in the context of Extended Producer Responsibility (EPR) programs or requirements. For maximum impact, strategies should incorporate supply-side, demand-side, and policy-side initiatives in a consistent and mutually reinforcing framework.

- **Sustainable consumption initiatives, such as those underway in Europe, offer significant waste prevention potential**, well beyond the levels currently deemed achievable in the U.S. The potential is greatest where the focus is not limited to technological improvements and dematerialization, but includes consideration of values and lifestyle changes such as downsizing of living space, increased reliance on public transit and car-sharing rather than private vehicle ownership, and adopting life-cycle and precautionary approaches as a consumer of goods and services.

- **Focus on priority materials and/or sectors** based on waste reduction potential assessment, including both prevention and reuse. In order to prioritize their programmatic resources and achieve the "best bang for the buck" from waste reduction initiatives, Massachusetts and a few other states, including Washington, have targeted materials and sectors based on tonnage remaining in the disposal waste stream and their waste reduction potential. The Commonwealth's programmatic focus on commercial and residential organics and certain C&D wastes is informed by this approach. Washington has a similar focus on C&D waste, which accounts for 25% of annual waste generation in the state, and organics, which comprise another 25% of that state's annual generation.

- **Economic instruments such as taxes or fees should be part of the mix**, but should be linked to long-term waste reduction goals in the context of increasing resource productivity. Getting price signals right for goods and services by including environmental externalities is an important element for achieving the structural changes in the economy that are required to move towards a sustainable production and consumption system.

- **Measuring effectiveness of waste prevention programs is challenging but important.** The old sayings "what gets measured gets done" and "measure what matters" hold some truth. Measurement of waste prevention is critical for gauging progress and for targeting program efforts and resources. Unfortunately, waste prevention measurement is often quite challenging due to several factors. First, for educational and other programs, direct measurements are generally infeasible and alternative metrics must be used as a proxy; such as the numbers of people reached by a certain program. Second, there are many factors that impact the generation of waste, such as changes in general economic conditions. While some of these can often be addressed by normalizing the data (based on economic activity levels, for example), there is often a lack of good baseline data for comparison. And third, there is often a time lapse between the initiation of waste prevention programs and their impact, such as Design for Environment efforts to increase durability of appliances. Nonetheless, a number of jurisdictions (e.g., the OECD) have identified meaningful metrics for a variety of waste prevention techniques and DEP should consider doing so.

- **Government partnerships with the private sector, NGOs and other stakeholders are critical for the successful development and implementation of waste reduction and reuse programs.** Policies and programs developed by government agencies without meaningful involvement by the citizens, businesses, and other organizations ultimately responsible for changing their production or consumption patterns will not gain the support necessary for effective implementation.

Resource Productivity Improvement Findings

- Many Resource Productivity Improvement programs, in particular, pollution prevention and light-weighting, have already proven to be highly effective in preventing waste.
- Emerging approaches such as industrial ecology and dematerialization through micro- and nano-technology hold enormous promise, but the appropriate role of government and level of public effort have not yet been entirely worked out.

Alternative Business Models Findings

- The range of Design for Environment (DfE) experience indicates that incentives are key for getting manufacturers to redesign their products to reduce waste, toxicity, or other environmental impacts. To the extent possible, standardizing environmental purchasing criteria beyond an individual municipality or even state would ease the burden on manufacturers and suppliers for meeting waste prevention and other environmental criteria.
- To date, public policy has played little role in promoting servicizing (selling a service or a function rather than a product). There are however, a number of possible government policy initiatives (e.g., removal of virgin material and disposal subsidies, or tax policy which favors producer, not customer, ownership of durable goods) that could help realize the potential environmental gains associated with product-based services.

Public Awareness and Action Findings

- The most effective programs appear to be those that: (a) are well integrated into a larger strategy; (b) identify clear priorities; (c) are linked to quantitative and achievable waste reduction targets or goals, especially if these were developed through an inclusive stakeholder process; (d) include a tracking mechanism to measure success; and (e) relate to or are motivated by regulatory requirements.
- The effectiveness of public awareness and education programs is highly dependent on the level of resources these programs receive.

Economic Incentives Findings

- Coupled with other initiatives, Resource Management (RM) Contracting holds considerable promise as a means to help transform the waste management industry into a waste prevention and materials management industry. While RM Contracting is still relatively immature, program results to date primarily show enhanced material diversion rates. As new contractors gain experience and the

RM industry matures over time, the strategic alliances formed may enable RM contractors to influence upstream decisions related to product design and material choice, use, and handling, not just disposal practices.

- Pay-As-You-Throw programs for the municipal (residential) sector are already being implemented by more than 120 Massachusetts communities. Nonetheless, most of the largest cities in the Commonwealth have not instituted PAYT and based on the experience of other jurisdictions, there may be opportunity to refine implementation strategies to make it even more effective.

Regulatory Requirements Findings

- EPR programs offer governments a tool to shift responsibility for end-of-life product management by internalizing the external environmental costs of goods and services, and are a means to help reshape how society thinks about production and consumption behavior.

- While many programs do not systematically track their waste prevention impacts, and it is difficult to do so, establishing reduction targets and an accepted method for tracking progress can be an effective way to motivate businesses, consumers, and agency staff responsible for program implementation.

Government Leadership by Example Findings

- One of the greatest successes of Government Leadership by Example programs is in the area of Environmentally Preferred Purchasing (EPP). The Commonwealth's Operational Services Division operates the extensive MA EPP program, a leader nationally, and the breadth of products and services included in the MA program and others should continue to grow.

- The public sector in MA and other states has had considerable success in the green building area, and as states' experience has increased, many have moved from an EPP focus to an integrated design approach in which the whole building is looked at as an integrated system from the outset. This will result in greater environmental benefits, including in the C&D waste reduction area.