Application of the U.S. Decision Support Tool for Materials and Waste Management

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Abstract
The U.S. Environmental Protection Agency (EPA) launched the Resource Conservation Challenge in 2002 to help reduce waste and move towards more sustainable resource consumption. The RCC hopes to help communities, industries, and the public think in terms of materials management rather than waste disposal. Reducing cost, finding more efficient and effective strategies to manage municipal waste, and thinking in terms of materials management, requires a holistic approach that considers life-cycle environmental tradeoffs. The EPA's National Risk Management Research Laboratory (NRMRL) has led the development of a municipal solid waste decision support tool (MSW-DST). The computer software can be used to calculate life-cycle environmental tradeoffs and full costs of different waste management plans or recycling programs. The environmental methodology is based on the use of life-cycle assessment (LCA) and the cost methodology is based on the use of full-cost accounting (FCA). Life-cycle inventory (LCI) environmental impacts and costs are calculated from the point of collection, handling, transport, treatment, and disposal. For any materials that are recovered for recycling, offsets are calculated to reflect potential emissions savings from use of virgin materials. The use of the MSW-DST provides a standardized format and consistent basis to compare alternatives. This paper provides an illustration of how the MSW- DST can be used by evaluating ten management strategies for a hypothetical medium-sized community to compare the life-cycle environmental and cost tradeoffs. The LCI results from the MSW- DST are then used as inputs into another EPA tool, the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), to convert the LCI results into impact indicators. The goal of this paper is to demonstrate how the MSW-DST can be used to identify and balance multiple criteria (costs and environmental impacts) when evaluating options for materials and waste management. This type of approach is needed in identifying strategies that lead to reduced waste and more sustainable resource consumption. This helps to meet the goals established in EPA's Resource Conservation Challenge.

Keywords: Decision Support for Strategic Waste Management Planning, Resource Conservation and Recovery, Sustainability, Materials Recovery, Waste Disposal

1. Introduction and Background

The need for credible and science-based information for making more informed waste management decisions precipitated the development of a decision-support tool for municipal waste. Often decision makers are faced with conflicting and incomplete information that can have major economic and environmental implications. In the U.S., more than 214 million metric tons of municipal solid waste (MSW) was generated in 2003 and more than $40 billion dollars was spent on its management. (EPA, 2003a) Finding more efficient options can help reduce cost and reduce environmental burdens.

The U.S. EPA recognizes the need for finding flexible, yet protective, ways to conserve national resources. The Resource Conservation Challenge (RCC) was launched in 2002 to help the U.S. move away from solid waste to materials management (EPA, 2003c and 2004). This is to be done through: (1) pollution prevention, recycling, and reuse of materials; (2) reduction of the use of toxic chemicals; and (3) conservation of energy and materials. The objectives are to encourage more sustainable resource use and to minimize waste. The MSW-DST helps support the goals for the RCC by identifying materials/waste management strategies that balance resource consumption, environmental burdens, and cost. The MSW-DST can also be used to identify the "best" management option for individual materials. (Thorneloe, et al., 2001, 2003, 2004).

With the transition from waste management to materials management, it is even more important to have tools available that consider life-cycle environmental tradeoffs. Determining the best means to manage solid waste is not straightforward. Questions that arise include: Should food waste be composted or landfilled? Should newsprint be recycled, landfilled, or combusted? What is the environmental benefit or burden from increasing the recycling rate in a community or adopting a curbside recycling program? What about increased air pollution from waste collection and transport? Is it better to export waste to a larger regional facility or continue use of an existing near-by facility that may not have the same degree of environmental controls? Are there changes within a community's existing infrastructure that could improve efficiency and reduce cost and environmental burdens?

The economics of solid waste management are also becoming increasingly important as communities face higher energy costs, and competing priorities. To address budgetary concerns, recycling programs are often targeted for reduction and even elimination, which occurred in New York City (it was later restored). Are there potential savings from finding more regional solutions to solid waste management? If so, then what are the actual savings in terms of reduced costs and environmental burdens?

The MSW-DST was developed through a partnership between Federal, state, and local government, private sector, and environmental interest groups. The goal of this research was to develop information and a computer program and supporting database to evaluate the relative cost and environmental performance of integrated MSW management strategies. The primary audience for the outputs is local government and solid waste planners. However, the outputs are also of value to Federal agencies, environmental and solid waste consultants, industry, LCA practitioners, and environmental advocacy organizations.

Over 80 stakeholders were active participants in the development of the process models and tool. Funding for the research was provided by the U.S. EPA and the U.S. Department of Energy. The work was conducted through a cooperative agreement between EPA's National Risk Management Research Laboratory (NRMRL) and RTI International. (Thorneloe, et al., 1999a, 2001 and 2003) The research team included North Carolina State University (NCSU) who had a major role in the development of the LCI and cost models as well as MSW-DST. The University of Wisconsin was responsible for development of the life-cycle inventory (LCI) data and process models for mixed MSW and yard waste composting (Ham, et al., 2003). Funding was also provided by the Environmental Research and Education Foundation (EREF) for the development of LCI data and process models for municipal solid waste landfills (Ecobalance, 1999). The methodology, process models, MSW-DST, and documentation went through extensive review including that of stakeholders, series of external peer-reviews, in addition to peer, quality assurance, and EPA administrative review.

To account for differences in environmental benefits for recycling different MSW components, research was also conducted to develop LCI data sets for aluminium, glass, plastic, paper, and steel. RTI International worked in cooperation with private-sector partners, environmental interest groups, Franklin Associates, and Roy F. Weston to develop the LCI datasets. Each industry sector provided review and/or LCI data. Extensive effort was put into ensuring comparability of the LCI data. Environmental interest groups were also active participants in the development and review of LCI data including Environmental Defense and the Natural Resources Defense Council. (Weitz, 2003; and Thorneloe, et al., 2003)

Figure 1 provides an illustration of the MSW life-cycle. All activities are considered from the point of collection to its ultimate disposition, whether that be in a landfill, compost that is applied to the land, energy that is recovered from combustion, or materials that are recovered and reprocessed into new products. The computer software can track up to 26 components (e.g., yard waste, food waste, paper, plastic, metals, and glass) from residential, multi-family dwellings, and commercial sectors. Differences in MSW composition and management can be tracked for these different sectors helping to identify where they may offer more environmental benefit or cost savings from expanding recycling programs or making improvements to existing waste management programs.

The MSW-DST provides a standard approach for evaluating the life-cycle environmental tradeoffs and full costs of MSW management. Over 40 unit processes have been modeled covering waste collection, transportation, materials recovery, transfer stations, treatment, and disposal. An illustration of a unit process is provided in Figure 2. A list of the unit processes is provided in Table 1. The process models calculate the cost, energy consumption and LCI emissions for 32 pollutants from each solid waste unit operation based on the quantity and composition of waste processed. Each process model contains peer-reviewed default values that can be adjusted to reflect site-specific data. The allocation of cost, resource and energy consumption, and environmental releases for individual MSW components is described in Table 1 for each unit process.

Over 50 applications of the tool have been conducted on community, state, and national basis. (Thorneloe, et al., 2001, 2003, 2004). The tool was recently used in a study for the State of California to compare waste conversion technologies. Several other studies are underway currently in helping communities develop solid waste management plans and improving the environmental benefit or cost of recycling programs. Studies have varied from just comparing different options for waste collection and transportation to identifying options that help maximize recycling targets. Some studies have been conducted that evaluate the relationship between waste management and greenhouse gas emissions (Weitz, et al., 2002). A study was conducted to compare the life-cycle environmental burdens between disposal and combustion of CCA-treated wood (Jambeck, et al., in press). The MSW-DST is available through either RTI International or NCSU for conducting studies. A web accessible version of the MSW-DST (which is a simplified version) is under development. It is expected to be released in 2007 once final reviews have been completed.

Different materials (i.e., aluminum cans, green glass, newsprint, office paper, PET beverage containers, steel cans, and yard trimmings) have different LCI burdens depending upon extraction of raw materials, materials processing, manufacturing, use, and waste management. Accounting for these differences help communities identify which components to target for recycling programs to help maximize environmental and economic benefits. The MSW-DST provides the methodology, LCI data, and other information for making these evaluations through a comprehensive mathematical model that accounts for cost, energy, and environmental emissions. The model is implemented through an interactive decision support system (Harrison et al., 2001). This type of analysis helps communities to identify more sustainable solutions that minimize environmental burdens and maximize resource conservation and recovery. (Coleman et al., 2003; McDougall et al., 2001; White et al., 1995)

The purpose of this paper is to illustrate the use of the MSW-DST for evaluating different MSW management strategies. The scenarios, identified in Table 2, were selected to help illustrate the change in LCI environmental tradeoffs with increased materials recovery, differences in landfill gas capture and control, waste combustion with energy recovery, and differences in waste transport. The scenario analysis also helps to document environmental improvements from strategies that are now more typical in the U.S. (Scenarios 5 through 10) versus what was more typical in the 1970s (Scenario 1) with minimal recycling and control of landfill gas. The scenarios were calculated for a medium size community with a population of 750,000 and a waste generation rate of approximately 1.6 kg (3.5 lbs) per person per day (EPA, 2003a and b).

2. MSW Management Scenarios and MSW-DST Input Data

Using information available from EPA's Office of Solid Waste, ten scenarios were developed to help illustrate the types of management strategies that are typical in the U.S. As of 2003, the amount of municipal waste generated in the U.S. was 214 million metric tons or 2 kg/person/day (Figure 3, EPA 2003a). Statistics on waste composition are also available as are recycling rates for individual MSW components (Figure 4; EPA, 2003a). Paper is the largest component in municipal waste with 37% (or 79 million metric tons). Of the paper that is collected, 45% is recycled (or 40 million metric tons). Yard waste represents 12% of the total waste. Of the yard waste that is collected, 57% is composted (or 15 million metric tons). The national average recycling rate which includes composting is 30% (Figure 5, EPA 2003a). The Resource Conservation Challenge has identified a recycling goal of 35% for the U.S. by 2005 (EPA, 2004). Statistics are not yet available to determine if this has been met. However, individual communities and states have reported recycling rates of 40%.

Ten scenarios were defined to help compare environmental and economic tradeoffs between different waste management strategies. These are summarized in Table 2. The first 4 scenarios illustrate the transition between minimal recycling as was done in the 1970s versus increasing recycling to 40%. This will capture different MSW components as identified in Figure 6. The fifth scenario is typical of most U.S. cities with a 30% recycling rate and residuals being landfilled. Landfill gas is controlled and flared. The next two scenarios were selected to quantify the benefit of landfill gas recovery to produce electricity (Scenario 6) and to offset fuel oil in nearby industrial plant (Scenario 7). Approximately 14% (or 29,000 million metric tons) of MSW in the U.S. is combusted with energy recovery. Scenario 8 represents a typical "waste to energy" (WTE) facility in the U.S. which recovers any metals in the ash and meets stringent Clean Air Act requirements. The last two scenarios were chosen to help illustrate the differences in environmental impacts when waste is long hauled using semi-tractor trucks (Scenario 9) or rail (Scenario 10). These scenarios are identical to Scenario 5 except that the waste is hauled to a transfer station prior to transport 800 kilometers to a landfill. This operation is becoming more frequent in the U.S. with the closing of smaller, older landfills and the use of larger, more modern, regional landfills. These scenarios do not account for all of the diversity that exists in different geographical regions of the U.S. They also do not account for differences that exist between urban, suburban, and rural communities. However, these scenarios are thought to help illustrate the differences in waste or materials management strategies that are thought to have the greatest impact on life-cycle environmental tradeoffs or costs.

The same quantity of solid waste was used for each scenario (437,000 metric tons/year), which is considered to be a medium-sized community in the U.S. with a population of 750,000. Weekly collection of waste and recyclables was assumed, with all items collected on the same day from residential, multi-family dwellings, and commercial sectors. The waste composition is based on national averages (Figure 4). Costs were calculated using model defaults, which reflect national and regional averages. Key assumptions for each process model are identified in Table 3.

The diversion rates in each scenario were met through a combination of recycling and yard waste composting. The MSW-DST uses linear optimization software to find the most efficient solution based on minimum cost or environmental objective (e.g., minimum release of greenhouse gases) (Solano, et al., 2002a and 2002b). Multiple criteria can be used which could combine cost and environmental objectives to find more efficient solutions for waste and materials management. For this analysis, cost was used in identifying which mix of components would meet the diversion goals set in each scenario (i.e., we solved for the least cost mix that would meet scenario goals). The analysis did not try to maximize resource conservation and recovery although this has been done in previous publications (Barlaz, et al., 1999b; Harrison, 2001). Therefore, this will be sensitive to the market value for recyclables. When used for a site-specific analysis or in solid waste management planning, different values can be used to reflect current prices and to evaluate market impacts on management practices.

The mix of materials that were captured by the 10, 20, 30, and 40 percent recycling goals is presented in Figure 6. The 10 percent diversion rate was met by using recycling only (i.e., no yard waste composting). The recycling consisted of commingled recyclables from residential and multi- family housing and presorted recyclables from commercial entities. To reach the 20, 30, and 40 percent diversion rates (or recycling goals), the model included both recycling and yard waste composting from the residential sector. Note that for reaching a 40% recycling target, there is almost 100% capture of metals.

Modeling of energy has been found to have a significant impact on the life-cycle environmental tradeoffs (Finnveden et al., 2002). Energy emissions include extraction, production, consumption, and offsets for energy conservation. In the U.S. the marginal energy source to be displaced is typically coal-fired power plants (Weitz et al., 2002). Therefore, the energy offsets that were used for Scenarios 6 and 8 are for coal combustion. For Scenario 7, the most likely offset is fuel oil which was used in calculating the energy offset.

Assumptions regarding landfill gas control can also have a significant impact (Ecobalance, 1999; Barlaz et al., 1999a). For the scenarios with landfill gas control (i.e., Scenarios 4, 5, 7, 8, 9, and 10), a landfill gas collection efficiency of 75% was assumed. This is consistent with EPA's guidelines for developing emission inventories (EPA, 1997). However, some sites will obtain greater capture efficiency while some sites may have less. Most large landfills in the U.S. (i.e., greater than 2.5 million tons of waste) collect and control landfill gas. However, some sites exist that are below the size threshold for the Clean Air Act gas control requirements (i.e., they do not have gas control). However, the trend in the U.S. is towards larger, regional landfills with gas control. About 300 U.S. landfills have energy recovery (Thorneloe, et al., 2001). Life-cycle environmental emissions and costs were calculated over a 100-year time frame. More detail on the life-cycle landfill model is provided in a report that was prepared for the Environmental Research and Education Foundation (Ecobalance, 1999).

More detailed descriptions of how individual waste management processes are modeled have been provided in previous publications (Barlaz et al., 1999 a and b; Ham and Komolois, 2003; Harrison et al., 2001; Thorneloe and Weitz, 2001 and 2003; and Weitz, 2003). Key process model assumptions and allocation procedures are summarized in Table 2.

3. Results and Discussion

The standard output of the MSW-DST is annualized cost, energy consumption, and life-cycle environmental emissions for 32 pollutants. (Solano et al., 2002a and 2002b). The life-cycle emissions data were used as inputs to EPA's Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI, Version 2.0) (Bare, 2002 and Bare et al., 2003). TRACI is computer software that allows storage of inventory data, classification of stressors, and characterization of impact categories within various life-cycle stages. Impact categories include climate change, acidification, eutrophication, trospospheric ozone, and human and ecosystem health.

3.1 Cost

The cost results generated by the MSW-DST are based on a full cost accounting (FCA) approach. This is a systematic approach for accounting for past and future costs, overhead (oversight and support services) costs, and operating costs. Historically, cash flow accounting has been used by local government to track the flow of financial resources regardless of when the money is spent. This does not reflect the time value of money which is needed to compare waste management alternatives or any option where there are past and future costs to be accounted for.

Waste management can involve significant expenditures both before and after the operating life of management facilities. Focusing solely on the use of current financial resources will misrepresent the actual cost of MSW management. For example, a landfill includes the cost of permitting, design, construction, operation, and long-term monitoring. In full cost accounting, all of these costs are included when calculating the net annualized costs. (Ecobalance, 1999)

Another advantage is that system-wide costs are being compared (collection, transport, materials recovery facility, treatment, and disposal). In addition, the market value of recyclables is also factored in. Many of these parameters can vary over time and within different geographical regions. The defaults in the tool can be adjusted to account for site-specific values such as labor rates, land values, regional market prices for recyclables and energy, and any special permit requirements for licensing a facility. The information can also be used to benchmark the costs to compare to similar communities or norms.

Figure 7 provides a comparison of the total net (i.e., cost minus revenues from the sale of materials and/or energy) annual cost for the 10 scenarios analyzed. The lowest cost scenario is scenario 2 at 20% recycling and the remainder is landfilled. As recycling is increased to 30% and 40% in scenarios 3 and 4, the cost increases by 42% and 69%, respectively, because it becomes more difficult and costly to recover the marginal recyclable (given a fixed infrastructure). Similarly, when the rate of recycling is reduced to 10% in scenario one, the cost increases. This suggests that there are cost benefits of increasing recycling levels past 10% but diminishing returns somewhere in the 20-30% range (assuming fixed infrastructure, recycling program participation, and separation efficiencies). The highest cost management option is the WTE scenario (scenario 8).

3.2 Energy Consumption

The results for total net energy consumption are shown in Figure 8. All scenarios show a net negative energy consumption which highlights the significance of materials recycling in terms of energy consumption. Even recycling at the 10% level in scenario one results in a net energy savings over the total system. As shown in Figure 8, the energy savings are largest with the higher recycling level (40% for scenario four) and where energy recovery is greatest (in the scenario 8 WTE). The large jump in energy savings between the 30% and 40% recycling scenarios is due largely to the addition of metals recycling in scenario 4 to meet the 40% rate. Metals’ recycling has a high energy savings potential compared to most other recyclables. If another material (or mix of materials) had been used to meet the 40% recycling rate, the energy savings likely would not have increased as much. The specific material that the MSW-DST selects for inclusion in recycling portion was based on a minimum cost criterion. Therefore, the least cost items to recycle are selected first to meet the recycling target. The higher cost of metals recycling is likely due to the longer distances for transporting metals to remanufacturing facilities as compared to the other materials.

3.3 Climate Change

Figure 9 presents a comparison of the net carbon emissions using MSW-DST life-cycle emissions results for methane and carbon dioxide as inputs to TRACI. The results from TRACI are in units of grams of CO_2 equivalent. These units were converted to kilograms of CO_2 equivalent for presentation in Figure 9. Previous research shows that as waste management technologies have evolved, greenhouse gas (GHG) emissions have been reduced (Weitz et al., 2002). This study shows similar results. The first four scenarios illustrate recycling benefits increasing from 10 to 40% recovery with no residuals being landfilled. For these four scenarios, no landfill gas control was assumed. The transition between these scenarios and scenario 5 helps illustrate the importance of landfill gas control. A significant reduction in greenhouse gases can be achieved through increased recycling and control of landfill gas. About 300 U.S. landfills have energy recovery (Thorneloe, et al., 2001).

The most attractive strategy from a GHG perspective is Scenario 8. The negative offset is due to energy conservation, increased metals recovery, and absence of landfilling any biodegradable waste (only residual being landfilled is combustion ash).

Scenarios 9 and 10 provide the GHG impact of long hauling using either semi-tractor trailers or rail. In the U.S., there is an increasing trend towards transporting waste over long-distances. Typical distances vary from 480 to 800 km (300 to 500 miles). As smaller, older landfills reach capacity and are closed, communities are often transporting waste over longer distances. Typically, waste is collected and transported to a transfer station where the waste is compacted for long haul using either semi-tractor trailers or rail. For the rail-haul, typically there is a transfer station at both ends of the rail line. For this analysis, a long-haul distance of 800 km (500 miles) was assumed. The results show a slight increase in GHG emissions for long-haul transport as compared to Scenario 5 where waste is transported to near-by landfill.

3.4 Acidification

The pollutants calculated by the MSW-DST that contribute to acidification include SOx, NOx, ammonia, and HCl. These pollutants are tied to (1) fuel combustion, and (2) electrical energy production and consumption (including mining of coal or raw materials extraction). The results in Figure 10 for acidification increase or decrease from scenario to scenario depending on how much fuel and electrical energy are consumed. TRACI was used to model acidification based on moles of H+ equivalents. The results for all scenarios are negative indicating a net savings or avoidance of acidification related pollutants for each scenario. The negative values are directly tied to materials and/or energy recovery from the scenarios.

The WTE scenario (scenario 8) shows the greatest offset of acidification-related pollutants primarily because it results in the largest energy offset. One might expect that the 40% recycling scenario, which had the greatest net energy offset, would also have the greatest acidification offset. However, it appears that while the addition of metals recycling saves a significant amount of energy, it does not necessarily save as much in terms of acid precursors. This may be due to the longer transportation distances for metals remanufacturing and/or emissions during the remanufacturing processes. There is also an increase in the offset of acidification that results from landfill gas to energy projects (see scenario 5 versus scenarios 6 and 7). Scenarios 9 and 10 show the negative affects that long-hauling waste have in terms of acidification.

3.5 Eutrophication

Eutrophication results based on grams of nitrogen equivalents using TRACI indicate a net savings or avoidance of eutrophication related pollutants for each scenario. The pollutants that contribute to acidification include NOx and ammonia air emissions. Waterborne pollutants that contribute to eutrophication include ammonia, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and phosphate. Phosphate releases appear to be the most significant and are predominately tied to materials remanufacturing. Thus, the results for eutrophication will generally increase or decrease from scenario to scenario depending on the quantity and type of material recycled.

Paper production and remanufacturing appear to be the key material driving the eutrophication results. Paper recycling is increased significantly from scenario one (10% recycling) to scenario two (20% recycling) and then remains relatively constant through the remaining scenarios and thus the eutrophication results also follow this pattern.

3.6 Trospospheric Ozone (or smog)

TRACI's model for smog is based on grams of NOx equivalents. The results presented in Figure 12 indicate a net reduction or avoidance of smog related pollutants for each scenario. The pollutants that contribute to smog formation include NOx, carbon monoxide and methane with NOx being the most potent of the smog forming pollutants. NOx and carbon monoxide emissions are generally tied to the combustion of fuels while methane emissions are largely tied to the degradation of organic material in landfills. Although methane emissions from landfills are quite large, their smog equivalent is relatively low. This is illustrated when comparing scenario 3 (where landfill gas is vented) to scenarios 5 through 7 (where landfill gas is controlled). The results for smog are most significantly governed by transportation related activities and materials recycling (in general). Thus, an increase or decrease from scenario to scenario will depend on how much fuel and electrical energy are consumed. The negative values are directly tied to materials and/or electrical energy recovery from the scenarios.

The WTE scenario (scenario 8) shows the greatest offset of smog related pollutants because it offsets the most electrical energy. One might expect that the 40% recycling scenario, which had the greatest net energy offset, would also have the greatest smog offset. However, it appears that while the addition of metals recycling saves a significant amount of energy, it does not necessarily save as much in terms of smog related gases. There is also a slight increase in the offset of smog that results from landfill gas to energy projects (see scenario 5 versus scenarios 6 and 7). Scenarios 9 and 10 show the negative affects that long-hauling waste have in terms of smog production.

3.7 Human Health

Human health impacts are modeled in TRACI for cancer, non-cancer, and criteria pollutant categories. The indicator used for each of these categories is as follows (1) cancer: grams of benzene equivalent; (2) non-cancer: grams of toluene equivalent; and (3) criteria: grams PM2.5 equivalent. For presentation purposes, TRACI results were converted to kilograms of respective equivalent. The results for the three human health categories are shown in Figures 13 through 15.

The key pollutants reported by the MSW-DST to model cancer impacts include lead releases to the air and water and arsenic and cadmium releases to water. Of these pollutants, arsenic is the most potent cancer agent. However, it is insignificant relative to lead and cadmium releases. Figure 13 indicates relatively little difference between the scenarios for cancer related health effects except for Scenario 10 which transports waste using long-haul by rail. This is related to higher cadmium and lead water releases associated with the production and combustion of fuel for rail engines.

For non-cancer human health impacts (Figure 14), the results are negative for all scenarios because of a net offset of non-cancer related pollutants. The non-cancer pollutants reported by the MSW-DST and used in the non-cancer TRACI model include air releases of ammonia, HCl, and lead and water releases of iron, ammonia, copper, cadmium, arsenic, mercury, selenium, lead, and zinc. The pollutant that appears to drive this non-cancer category is zinc through water releases. In reviewing the LCI results, zinc releases (or in this case offset of releases) result from materials remanufacturing operations and thus the results are tied to materials recycling. Specifically, paper recycling is driving the non-cancer health results. As paper recycling increases from scenario 1 to 2, the non-cancer health offset increases but as paper recycling remains steady for the remaining scenarios, the non-cancer results also remain steady.

For criteria pollutants, the TRACI model converts U.S. EPA criteria air pollutants to PM 2.5 equivalents. Figure 15 shows the criteria pollutant human health results for this study based on life-cycle emission results from the MSW-DST for PM, SOx, and NOx. All results are negative indicating that there is a net savings or avoidance of criteria air emissions for all scenarios. In reviewing the LCI results, these air emissions (or in this case offset of releases) result from materials remanufacturing operations as well as electrical energy consumption/production and thus the results are generally tied to these two activities. The WTE scenario (scenario 8) has the highest offset due to its 30% recycling and high recovery of electrical energy from the remaining portion of the waste stream. Scenario 1 has the lowest net offset because it has the lowest level of recycling.

3.8 Ecological Toxicity Results

For ecological toxicity, TRACI converts specific pollutants (air and water) to grams of 2,4-D equivalents. The results presented in Figure 16 are reported in kilograms. All scenarios indicate a net offset of eco-tox related pollutants. The eco-toxicity pollutants reported by the MSW-DST and used as inputs in the TRACI model include (1) ammonia, HCl, and lead for air releases and (2) iron, ammonia, copper, cadmium, arsenic, mercury, and selenium for water releases.

In reviewing the TRACI equivalency factors and results, it appears that zinc releases to the water are the driving pollutant for eco-tox and thus the results are directly tied to this pollutant. In reviewing the LCI results, zinc releases (or in this case offset of releases) result from materials remanufacturing operations and thus the results are tied to materials recycling. Specifically, paper recycling is driving the non-cancer health results. As paper recycling increases from scenario 1 to 2, the eco-tox offset increases but as paper recycling remains steady for the remaining scenarios, the non-cancer results also remain steady.

4. Conclusion

With EPA's Resource Conservation Challenge there is increased interest in finding more sustainable solutions for waste management. This paper provides an evaluation of scenarios to illustrate the tradeoffs in life-cycle emissions, energy consumption, and micro-economic costs between different strategies for waste and materials management. The results are based on a medium-sized community using national or average defaults. Cost results capture the full-costs of managing the defined tonnage of waste through its life (varies by waste management operation). Environmental results capture the full life cycle burdens and benefits of waste and materials management. Although actual results for a specific community will vary, the general trends are thought to be realistic. The use of MSW-DST in evaluating management strategies can help a community identify site-specific strategies that maximize environmental benefits and minimize cost.

Multi-criteria analysis did not result in any clear winner. For example, WTE appears to be the most attractive option in terms of net carbon emissions, acidification, and smog. However, this option had a higher cost as compared to the other options using landfills. The option with the lowest cost is Scenario 2 which had a 20% recycling rate. The option with the most attractive net energy consumption is the option with a 40% recycling target. This is due to offsets from primary production which includes extraction and mining environmental burdens.

In general the recovery of materials and energy helps to reduce environmental impacts as illustrated by the results. Criteria based on improving environmental and economic performance would have to be developed on a site-specific basis to help determine which scenario is preferred depending upon a community's objectives and constraints. Some communities may have greater concern over water quality issues whereas others may value air quality concerns more. Constraints to consider include whether there is sufficient waste to fuel a WTE plant or available land to build a landfill. Uncertainty is also a factor and important in decision making (Özge Kaplan et al., 2005) to be considered in future analysis. In a cursory review of the results, Scenario 6 (30% recycling, residual landfilled, and landfill gas recovered to produce electricity using IC engines) might be viewed as preferred because of its mid-range cost, 30% recycling rate, and life-cycle environmental performance. However, if environmental performance was given more weight than cost, then one might prefer Scenario 8 (30% recycling rate and residual managed using WTE facility).

How might this analysis change for a given community? The results could be quite different when model defaults for land values, labor rates, facility costs, and environmental burdens are adjusted to represent site-specific values. The results presented in this paper are based on a limited number of pollutants. For some options, metals, hazardous air pollutants, and toxics, are calculated for some options (e.g., combustion and landfills) but not for all because there is no consistent data across all options. Also, the remanufacturing numbers seem to dominate the impact results. It would be interesting (perhaps in a future paper) to separate the impacts from waste activities from those associated with energy and materials production.

Next steps include conducting further applications of the MSW-DST for regional and local decision making. Work on a web-accessible version of the MSW-DST is also progressing. Once reviews are complete, a web-accessible version will be released (planned for 2007) providing easier access and more wide-spread use. The web accessible version is to include TRACI for allowing impact assessment for comparing materials and waste management strategies. Updates will be conducted as newer data and information become available. For further information about the MSW-DST, refer to the project web site at www.rti.org (or Keith Weitz at kaw@rti.org).

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Table 1. Process Model Assumptions and Allocation Procedures

	Key Assumptions and Design Properties	Allocation Procedures[a]
Collection	Location specific information (e.g., population, generation rate, capture rate) is model input.	Environmental releases are allocated based on mass. Cost is based on volume and mass.
Transfer Station	User selects between several default design options based on how the MSW is collected.	Same as collection
Materials Recovery Facility (MRF)	Design of the MRF depends on the collection type (mixed waste, commingled recyclables, etc.) and the recyclables mix. Eight different designs are available.	Same as collection. Also includes revenue from the sale of recyclables.
Combustion (with and without energy recovery)	The default design is a new facility assumed to meet the most recent U.S. regulations governing combustion of MSW. Designs to model older facilities are also available.	Environmental releases are allocated based on mass and stoichiometry. Cost is based on mass and includes revenue from sale of metal scrap and electricity (based on Btu value of the waste and the heat rate of the facility).
Refuse-Derived Fuel (RDF) and Processed-Refuse Fuel (PRF)	Traditional RDF and PRF design options are available. The facilities are designed to meet the U.S. Clean Air Act regulations for MSW combustion.	Same as combustion.
Composting (both yard and mixed MSW)	A low and high quality mixed MSW and yard waste compost facilities are included. All use the aerated windrow composting process as the default design.	Same as MRFs. However, no revenue was assumed for sale of compost for this analysis.
Landfill (traditional, bioreactor, and ash)	The default design meets U.S. federal requirements (i.e., RCRA Subtitle D and Clean Air Act). Process model also includes design for wet/bioreactor landfills (with leachate recirculation) and ash (monofills).	Cost and emissions for operations, closure, and post-closure are allocated equally over the mass of refuse buried. Landfill gas and leachate are allocated to MSW items.
Electrical Energy	Regional electrical energy grids are used for waste management processes; national grid for upstream processes.	Environmental releases are based on the fuel source used by regional or national electricity grids. Regional grids are used for waste management operations; National grid used for manufacturing operations. Cost is not considered.
Inter-Unit Process Transportation	Distances between different unit operations are key input variables.	Environmental releases are based on mass. Cost is based on volume and mass, and is considered only for transportation necessary for waste management.
Materials Production	Primary (virgin) and Secondary (recycled) closed-loop production processes are included.	Environmental releases are based on mass. Cost is not considered.

[a]Allocation of costs, resource and energy consumption, and environmental releases to individual MSW components

Table 2. Description of Scenarios Used to Illustrate Potential Environmental and Economic Tradeoffs

Scenario	Description
1	10% recycling, 90% landfilled with no gas collection and control
2	20% recycling, 80% landfilled with no gas collection and control
3	30% recycling, 70% landfilled with no gas collection and control
4	40% recycling, 60% landfilled with no gas collection and control
5	30% recycling, 70% landfilled; landfill gas is collected and combusted using flare
6	30% recycling, 70% landfilled; landfill gas is combusted using internal combustion engines to produce electricity
7	30% recycling, 70% landfilled; landfill gas is piped to nearby industrial facility and combusted in boiler (displacing fuel oil)
8	30% recycling, 70% combusted using waste to energy facility (generating electricity and recovery of metals)
9	Same as Scenario 5 except waste is collected and transported to transfer station, and then long-hauled 800 kilometers (500 miles) to landfill using semi-tractor truck
10	Same as Scenario 9 except waste is long-hauled to landfill by rail

Table 3. Summary of Key Assumptions Used in This Study

Parameter	Assumption
General	
Waste Generation	437,000 metric tons/year
Waste Composition	National average[a]
Collection Frequency	1 time per week
Transportation Distances	
Collection to Transfer Station	16 kilometers one way
Collection to MRF	16 kilometers one way
Collection to Compost	16 kilometers one way
Collection to WTE	16 kilometers one way
Collection to Landfill	16 kilometers one way
Transfer Station to Landfill	800 kilometers one way (used in long-haul scenarios)
Materials Recycling Facility	
Basic Design	Semi-automated, commingled recyclables
Equipment	Magnet, eddy-current separator, glass crusher
Separation Efficiency	90% for all materials
Compost Facility	
Basic Design	Yard waste, windrow
Windrow Turning Frequency	2,270 kg/week
Compost Residence Time	168 days
Compost Curing Time	90 days
WTE Facility	
Basic Design	Mass burn
Heat Rate	18,600 kJ/kWhr
Waste Input Heating Value	Varies by waste constituent
Ferrous Metal Recovery Rate	90%
Utility Sector Offset	Baseload coal
Landfill	
Basic Design	Subtitle D
Time Period for Calculating Emissions	100 years
Landfill Gas Collection Efficiency	75%
Landfill Gas Management	Varied (vent, flare, and energy recovery)
Utility Sector Offset	Baseload coal (for ICE) or fuel oil (for boiler).

[a]From EPA's Office of Solid Waste (http://www.epa.gov/msw/msw99.htm)

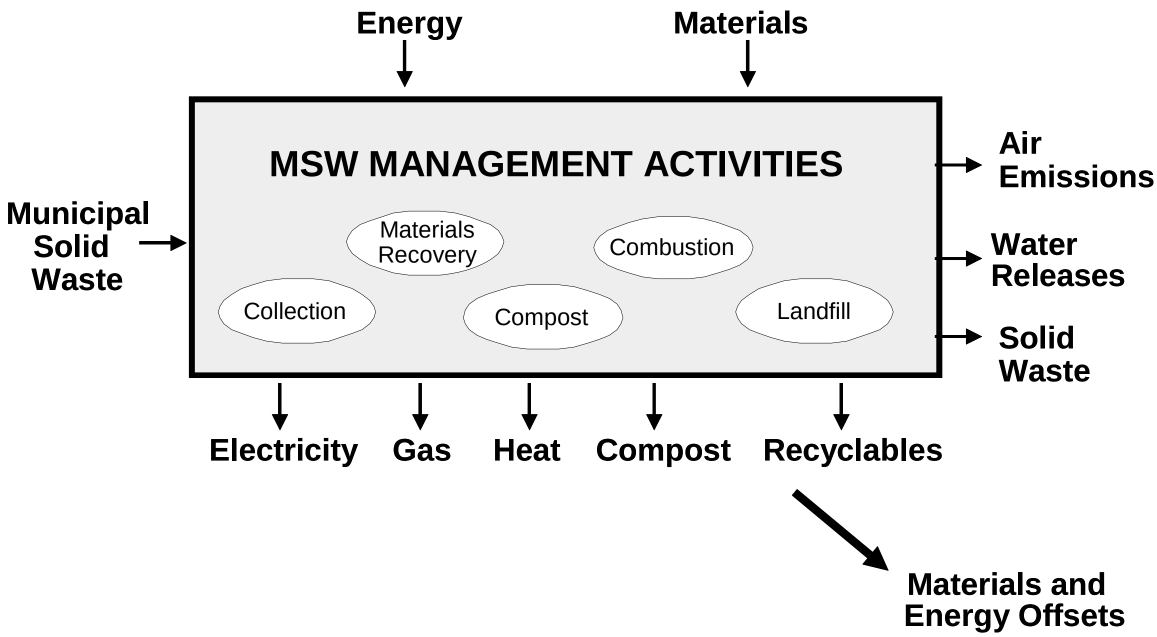


Figure 1. Illustration of MSW Life-Cycle

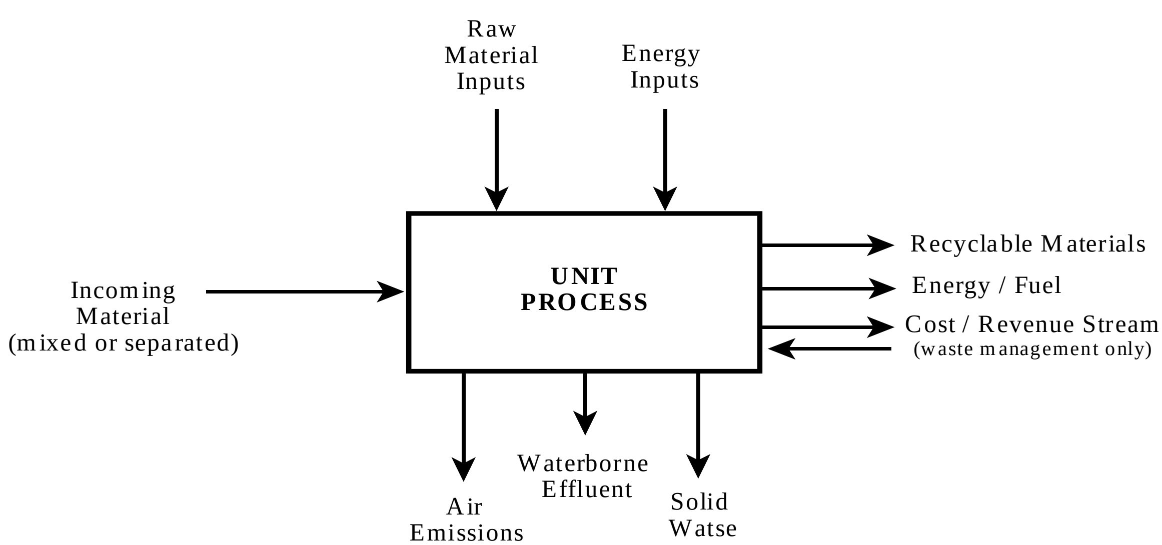


Figure 2. Illustration of a Unit Process
A given quantity and composition of material flows into each unit process. Default facility designs and operating conditions are used to estimate the energy and resource use, environmental releases, and cost (or revenue) for each unit process. These values are then partitioned to individual MSW components using the allocation provided in Table 2.

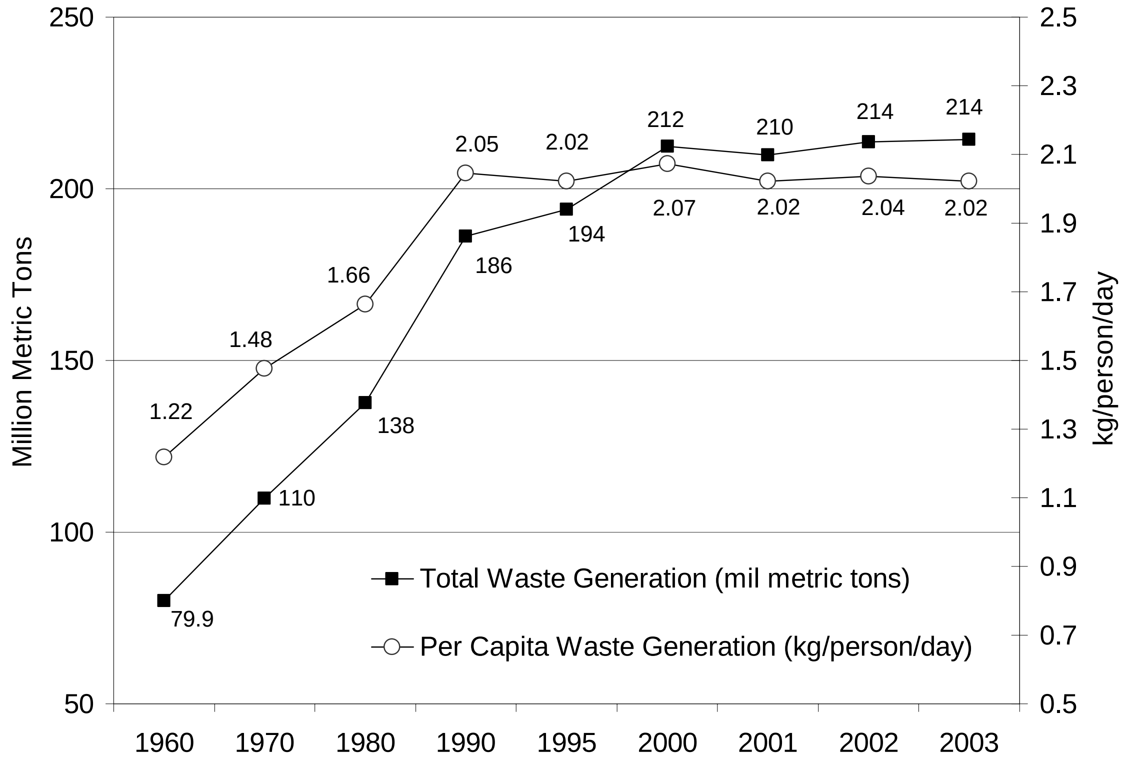
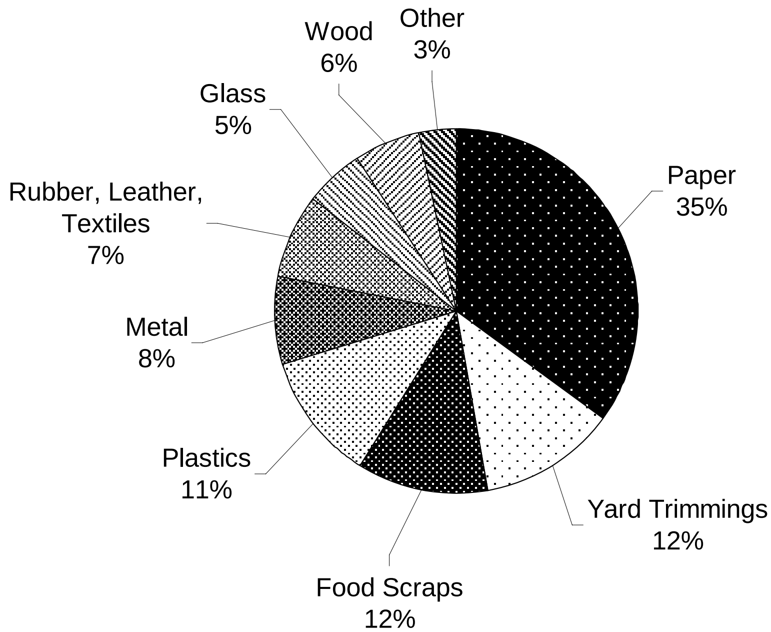


Figure 3. Trends in U.S. MSW Generation (EPA, 2003a, b)



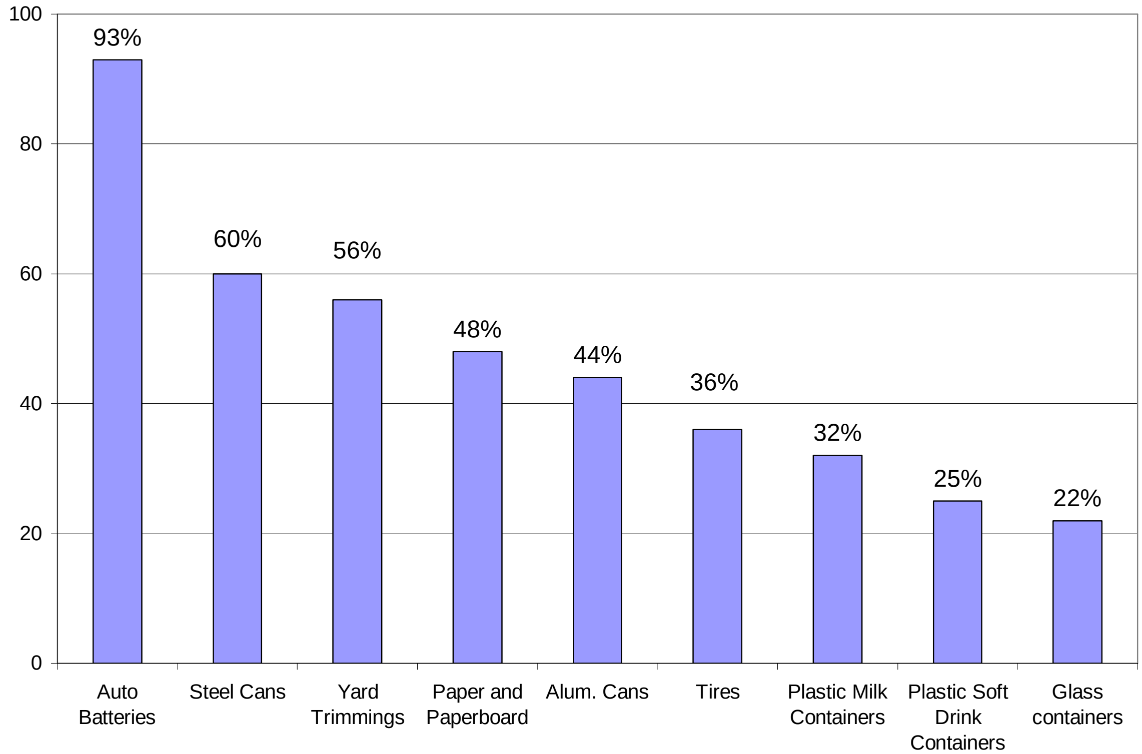


Figure 4. Composition of MSW in the U.S. and Selected Recycling Rates (EPA 2003a)

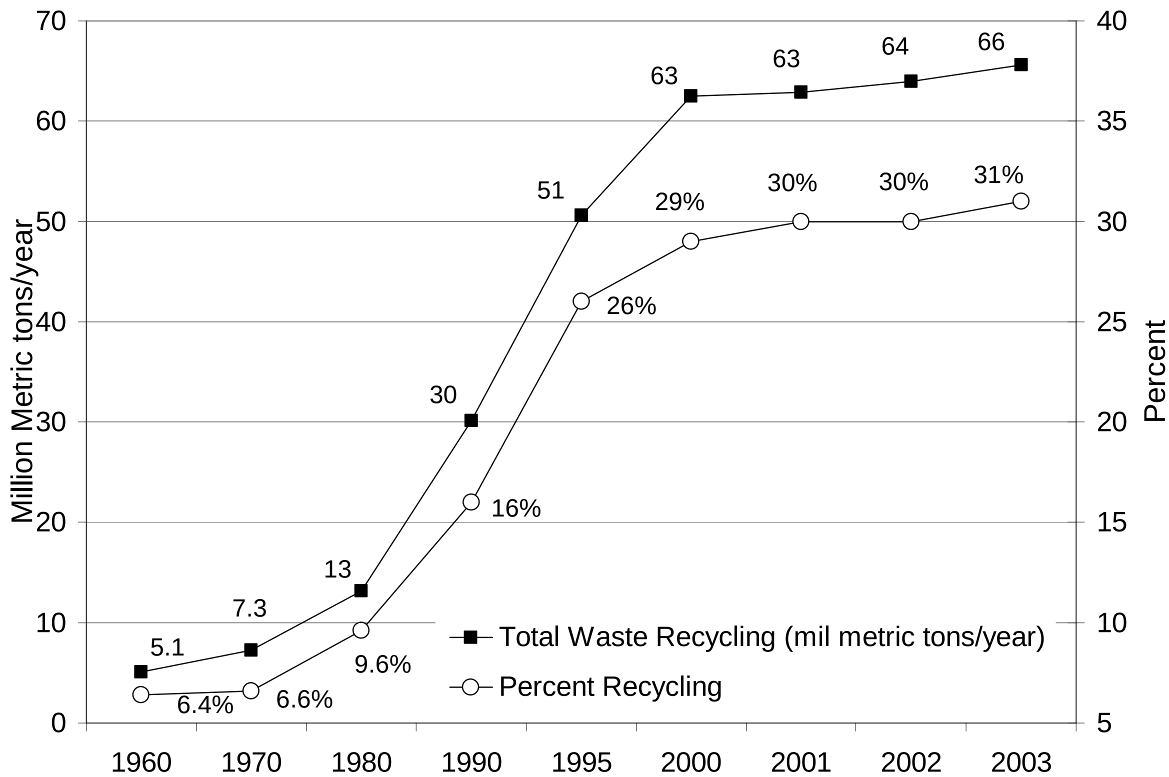


Figure 5. U.S. Waste Recycling Rates 1960-2001 (EPA 2003a)

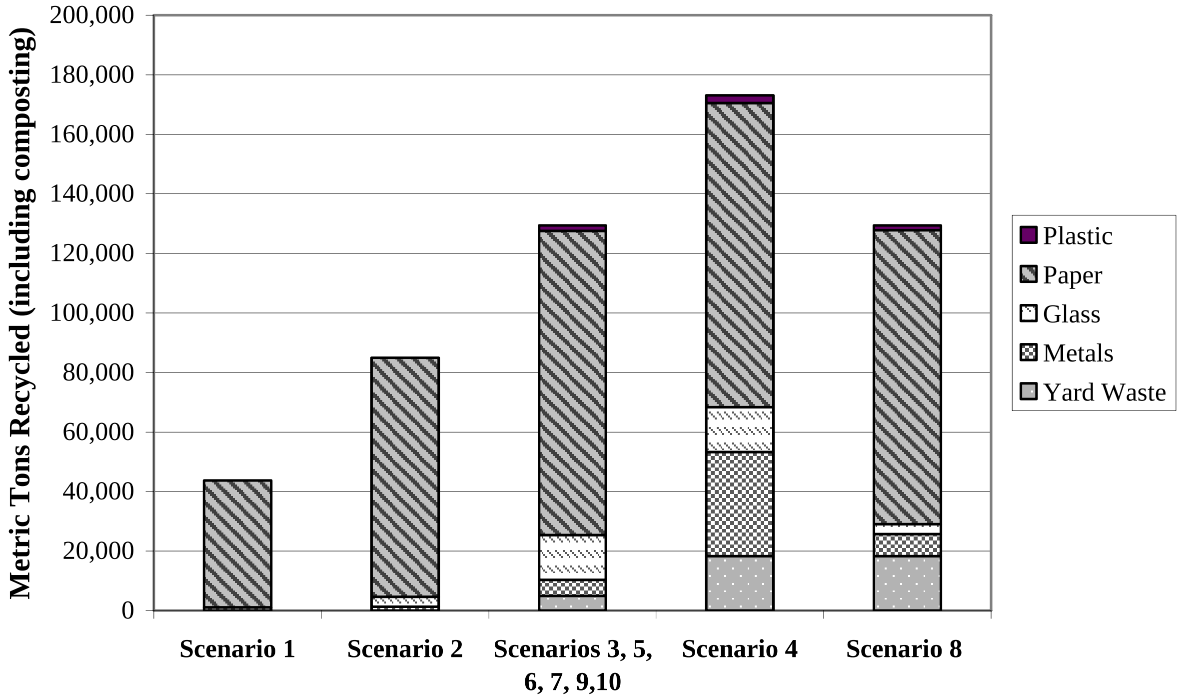


Figure 6. Composition of Materials Captured by Tonnage for Management Scenarios

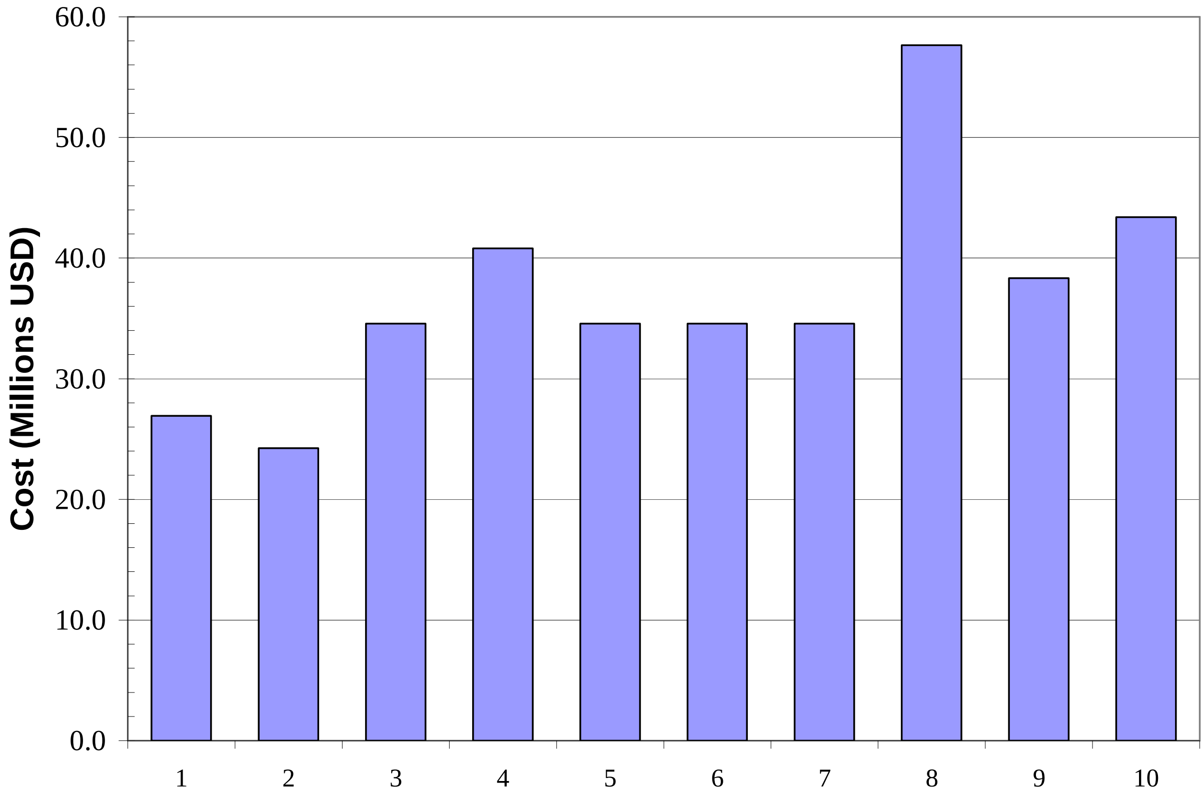


Figure 7. Net Annualized Cost by Scenario

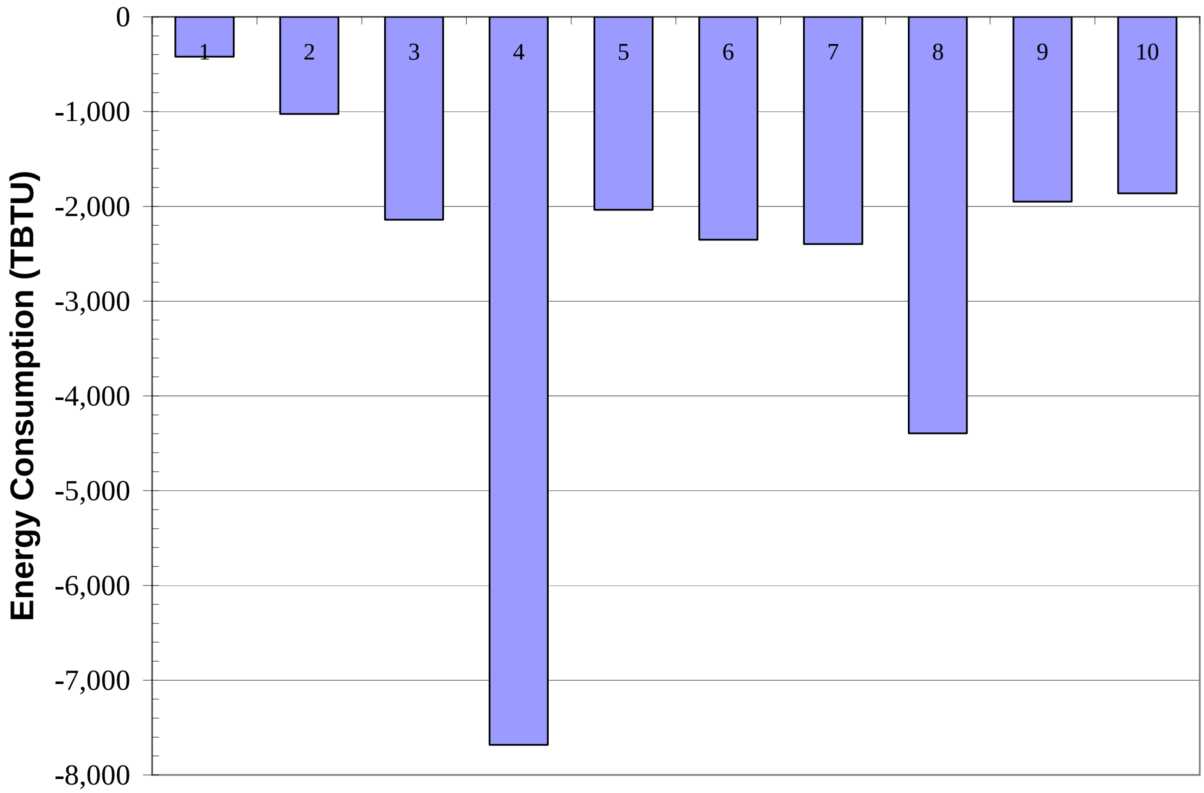


Figure 8. Net Energy Consumption by Scenario

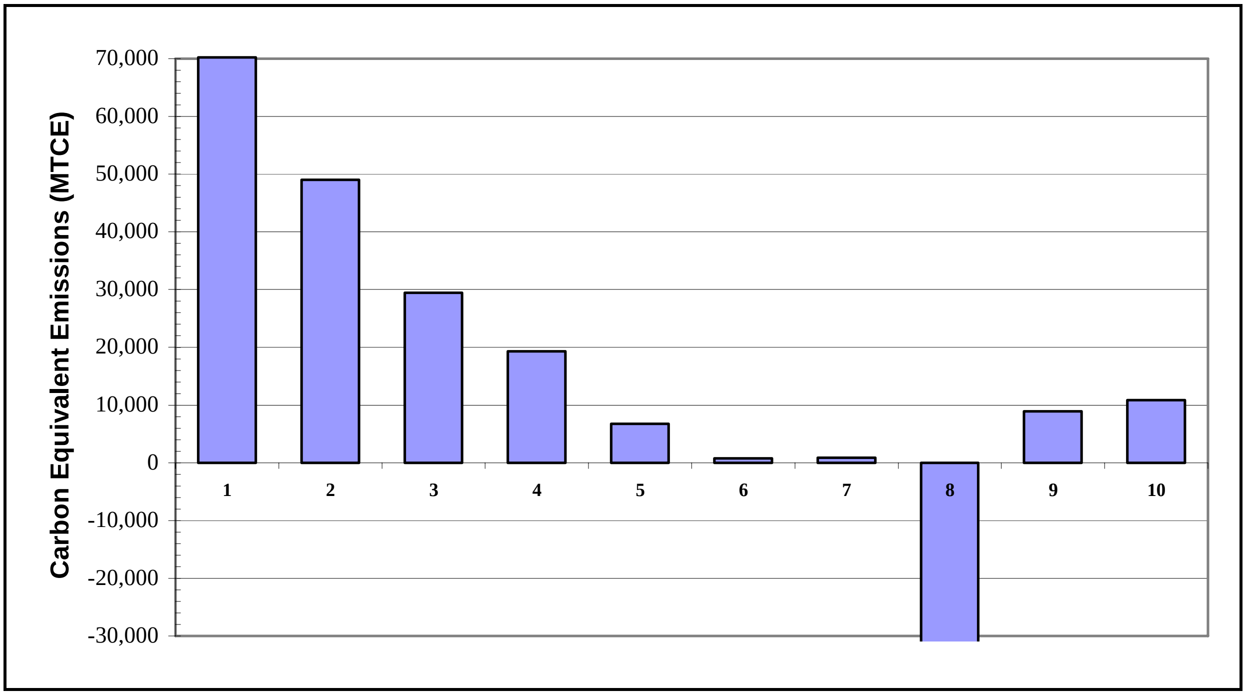


Figure 9. Net Global Climate Change Emissions by Scenario

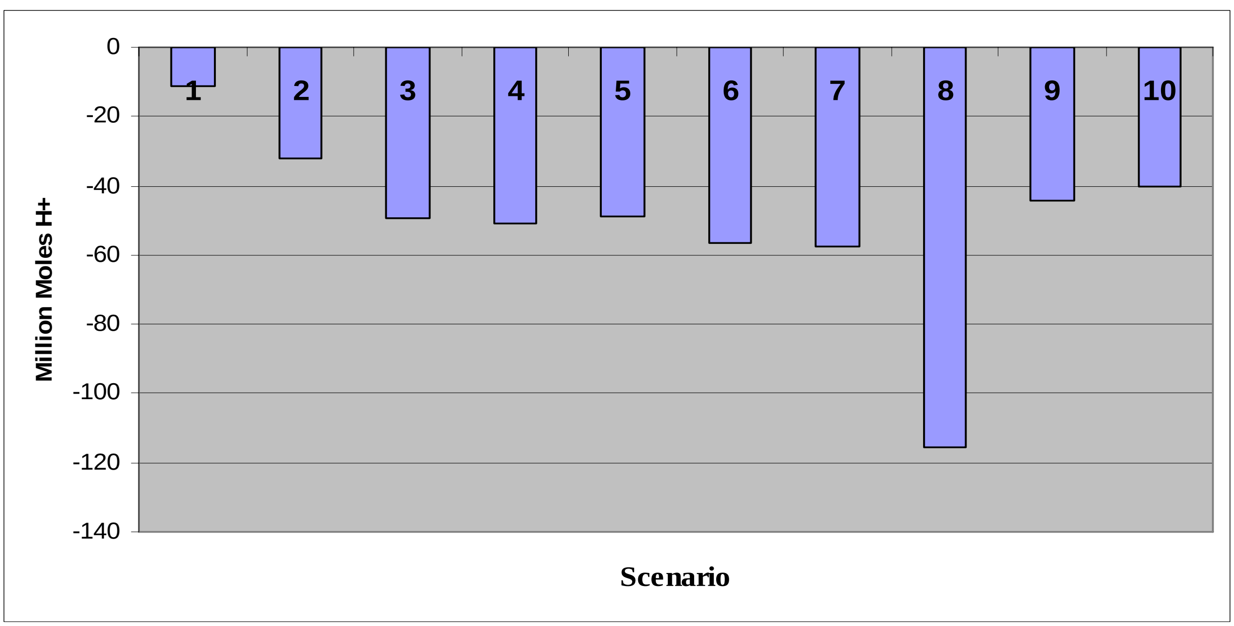


Figure 10. Acidification Results by Scenario

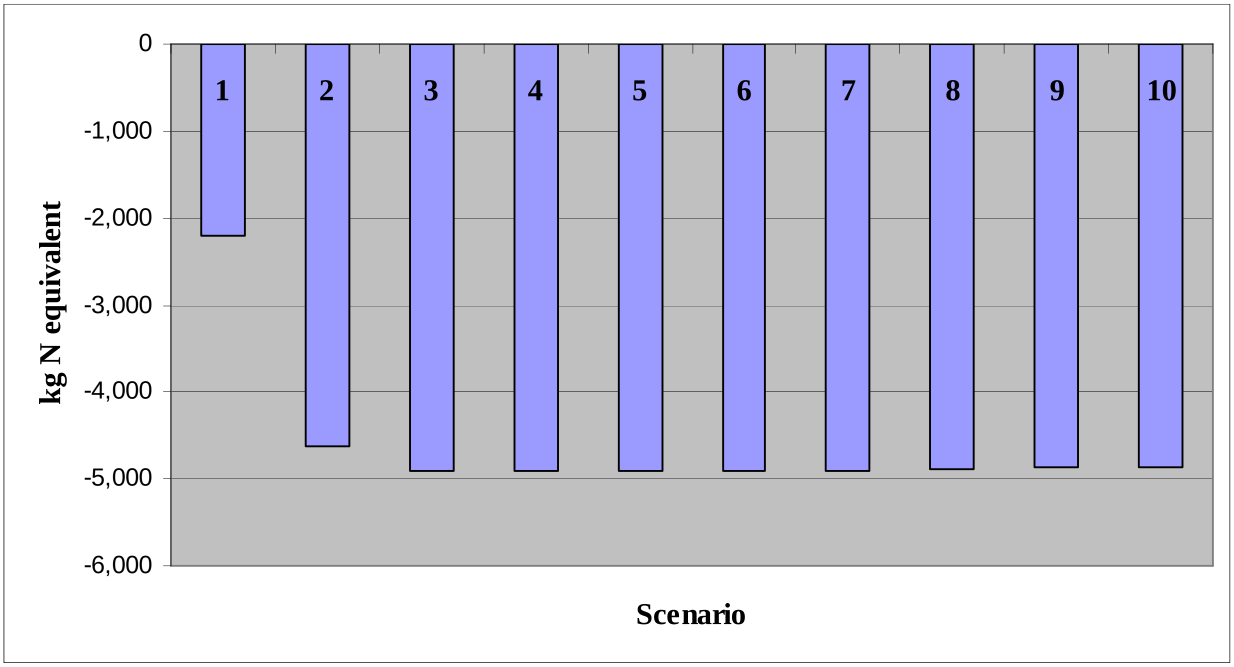


Figure 11. Eutrophication Results by Scenario

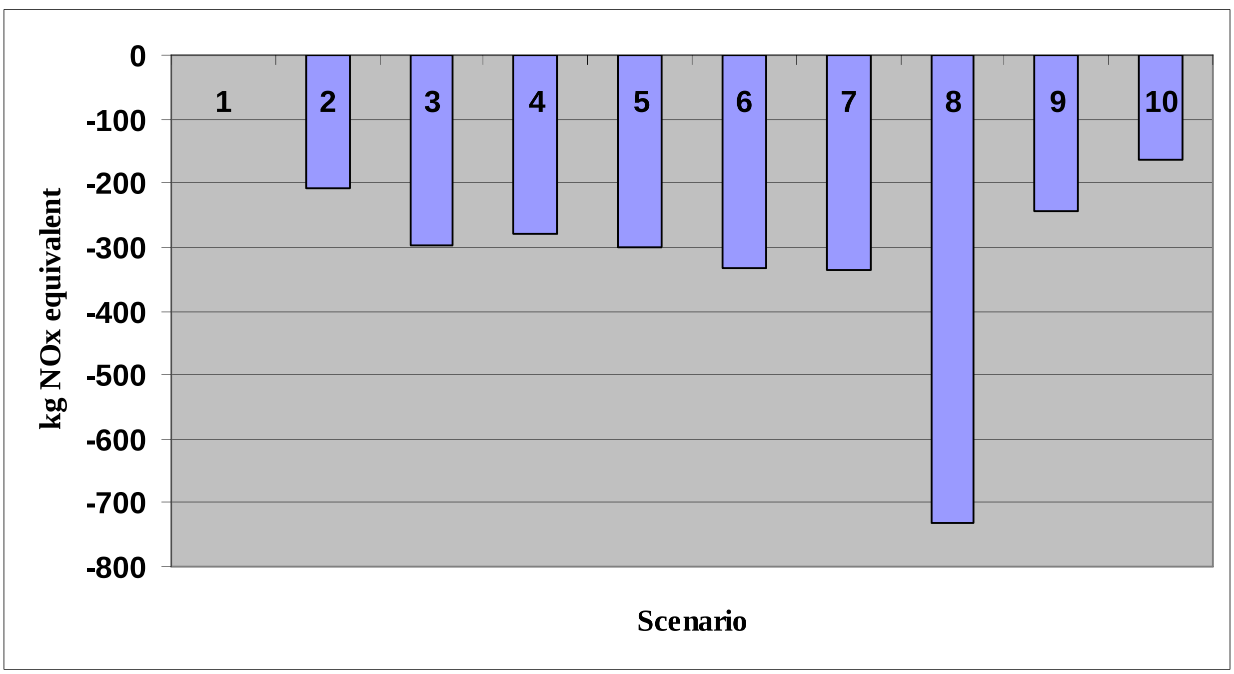


Figure 12. Smog Results by Scenario

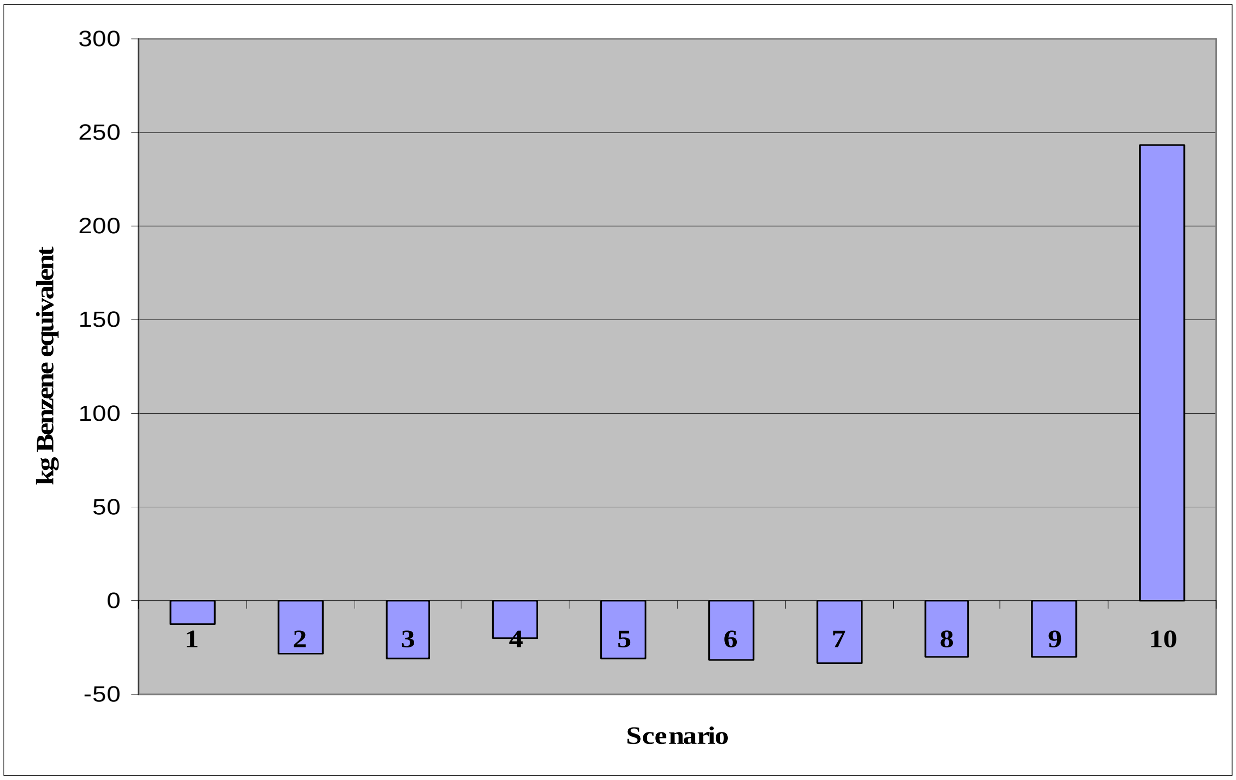


Figure 13. Human Health Cancer Results

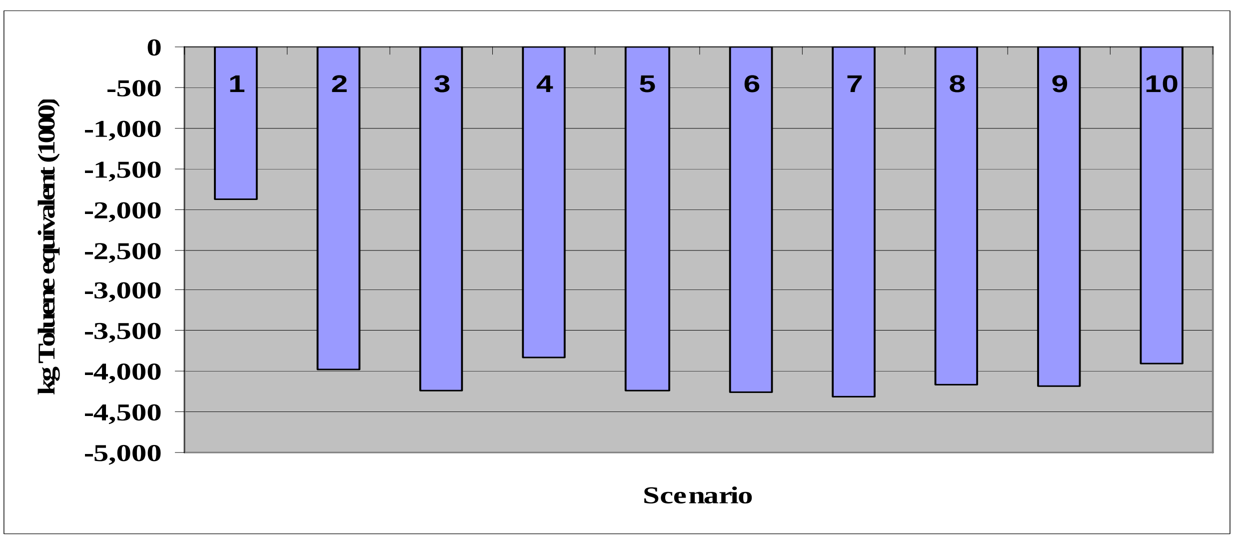


Figure 14. Human Health Non-Cancer Results

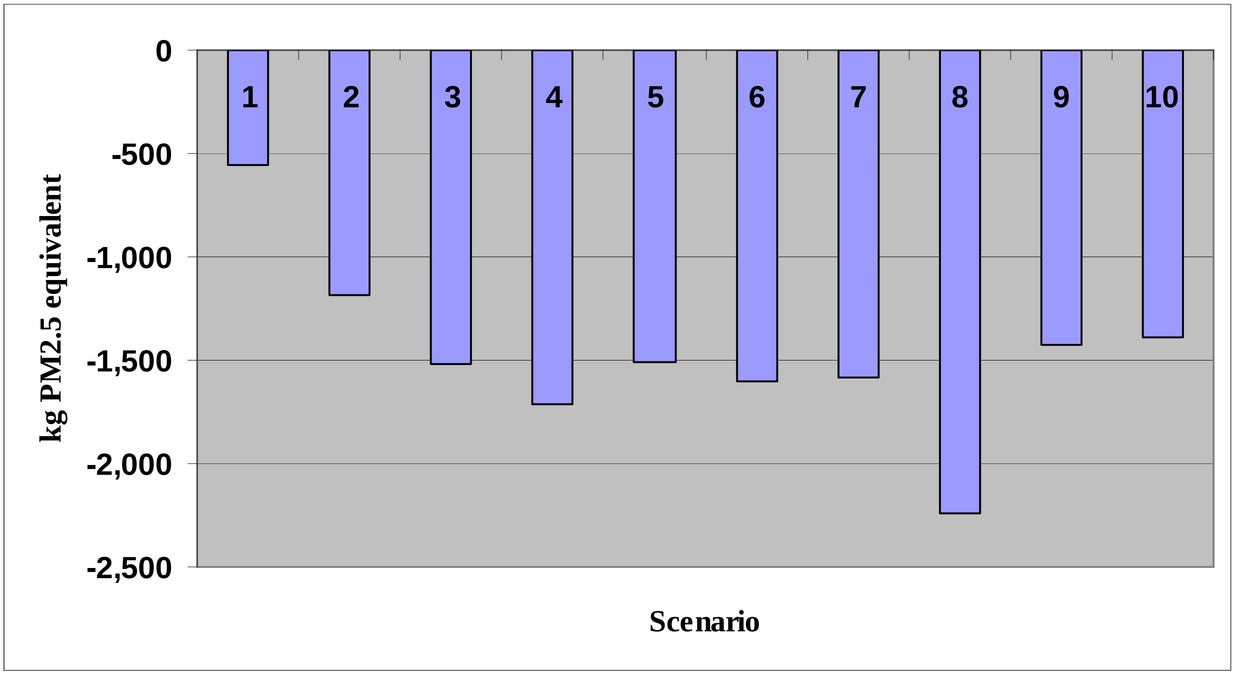


Figure 15. Human Health Criteria Air Pollutant Results

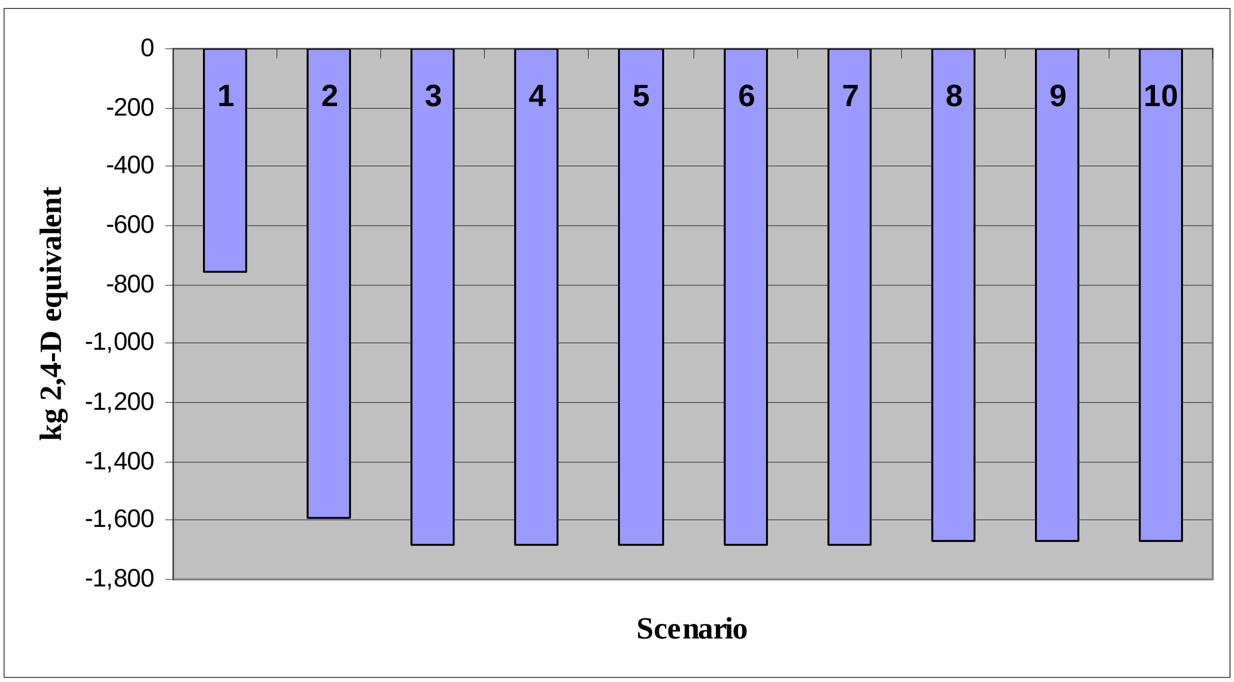


Figure 16. Ecological Toxicity Results