# Release of Trace Organics During MSW Decomposition and Environmental Implications of Waste Management Using Landfills and Waste to Energy


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# Introduction

- Limited understanding of factors affecting NMOC production
- Increasing interest among state regulators
  - potential for over estimates based on US EPA defaults
    - NMOC increases as Lo increases

# Introduction

## EPA Model

$$G = WL_o ke^{-kt}$$

- **G** is annual methane generation for a specific year t ($ft^3$ $CH_4$/yr);
- **W** is the annual burial rate (tons)
- $\mathbf{L_o}$ is landfill gas yield potential ($ft^3$ $CH_4$/ton of waste);
- **t** is time after initial waste placement (yr);
- **k** is first order decay rate constant (1/yr)

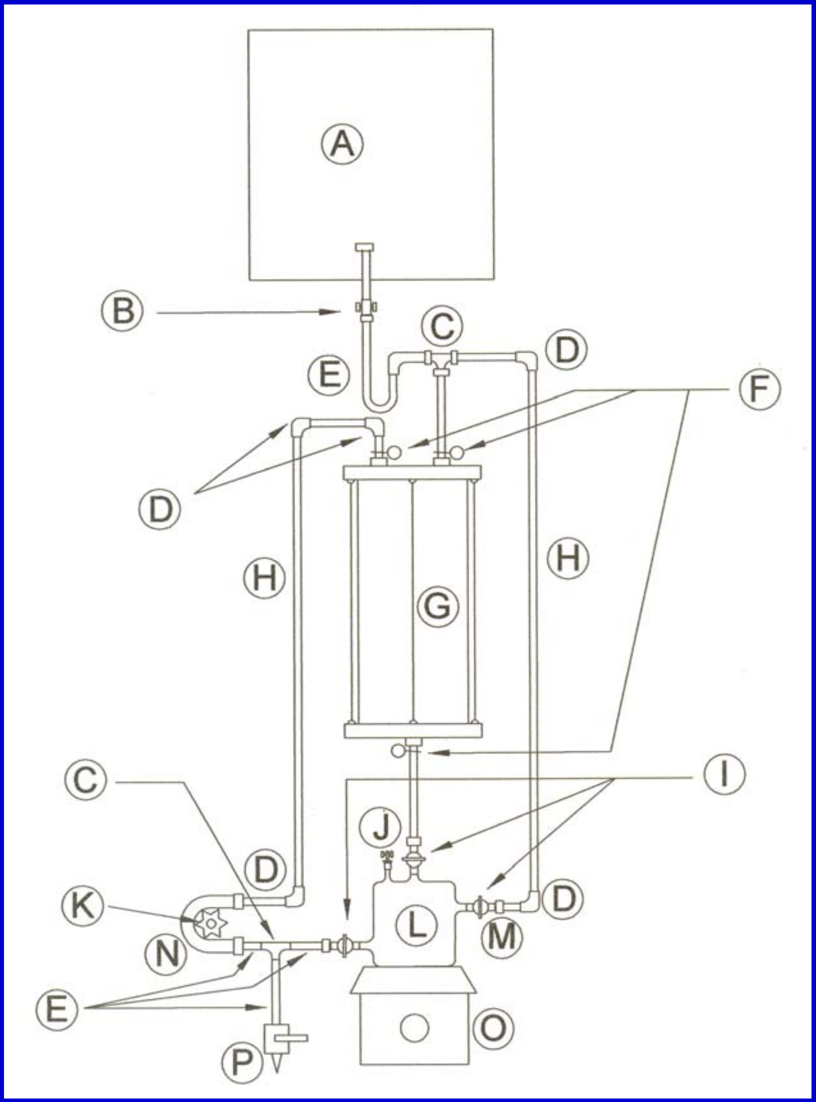
# Research Objectives

- Measure an ultimate NMOC yield for individual components
- Study the relationship between gas production and NMOC release
- Compare anaerobic and aerobic conditions
- Identify specific trace organic compounds

# Experimental Design

| | |
|---|---|
| • aerobic operation for 44/68 days prior to the onset of anaerobic conditions ( I& II) | • anaerobic decomposition of yard waste (I) |
| • traditional anaerobic operation (I & II) | • aerobic decomposition of yard waste (II) |
| • anaerobic decomposition of mixed paper (I) | • abiotic conditions (II) |
| | • control for background NMOC production from the leachate seed |
| • anaerobic decomposition of residential food waste (I & II) | |

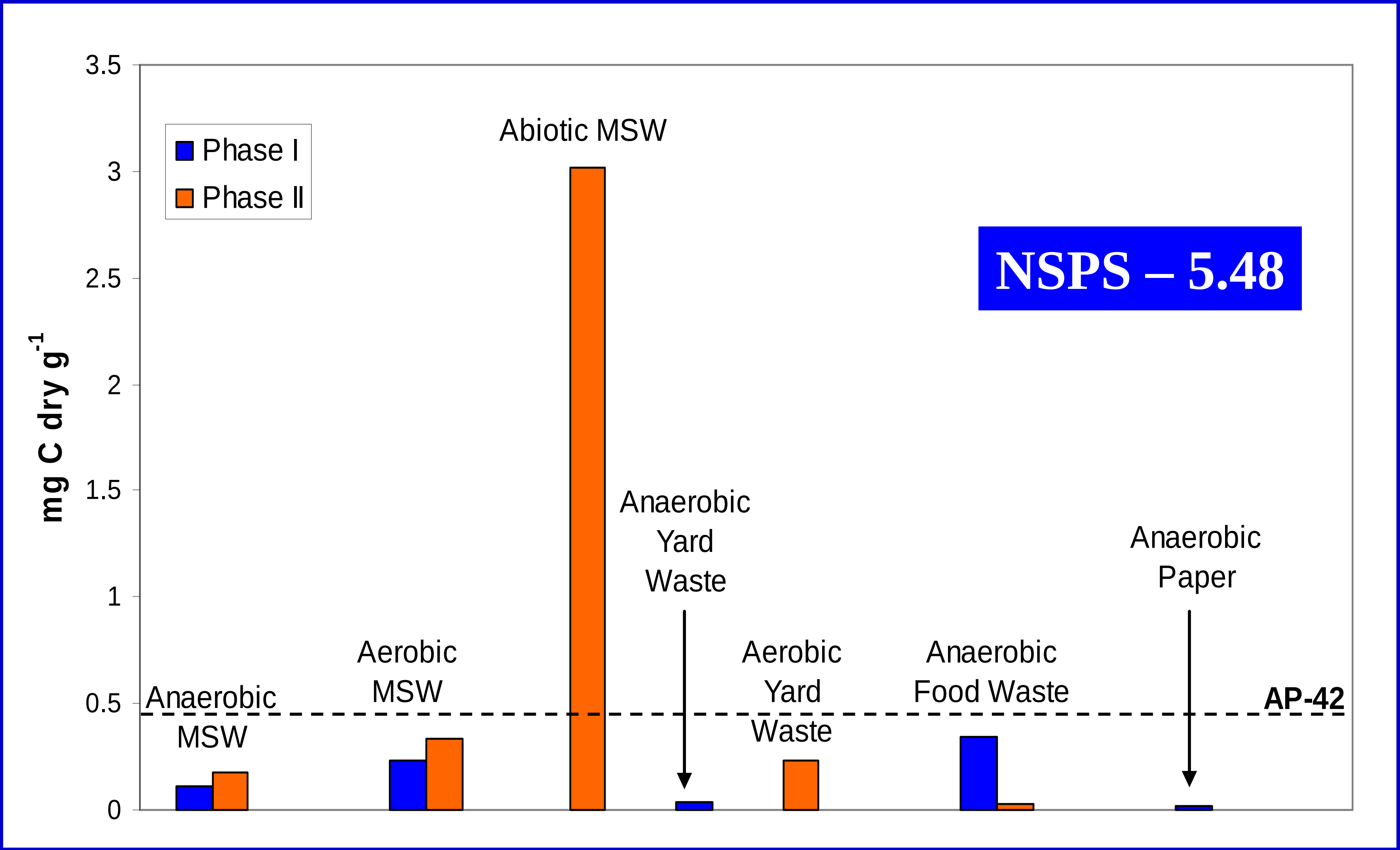
# Reactor Setup

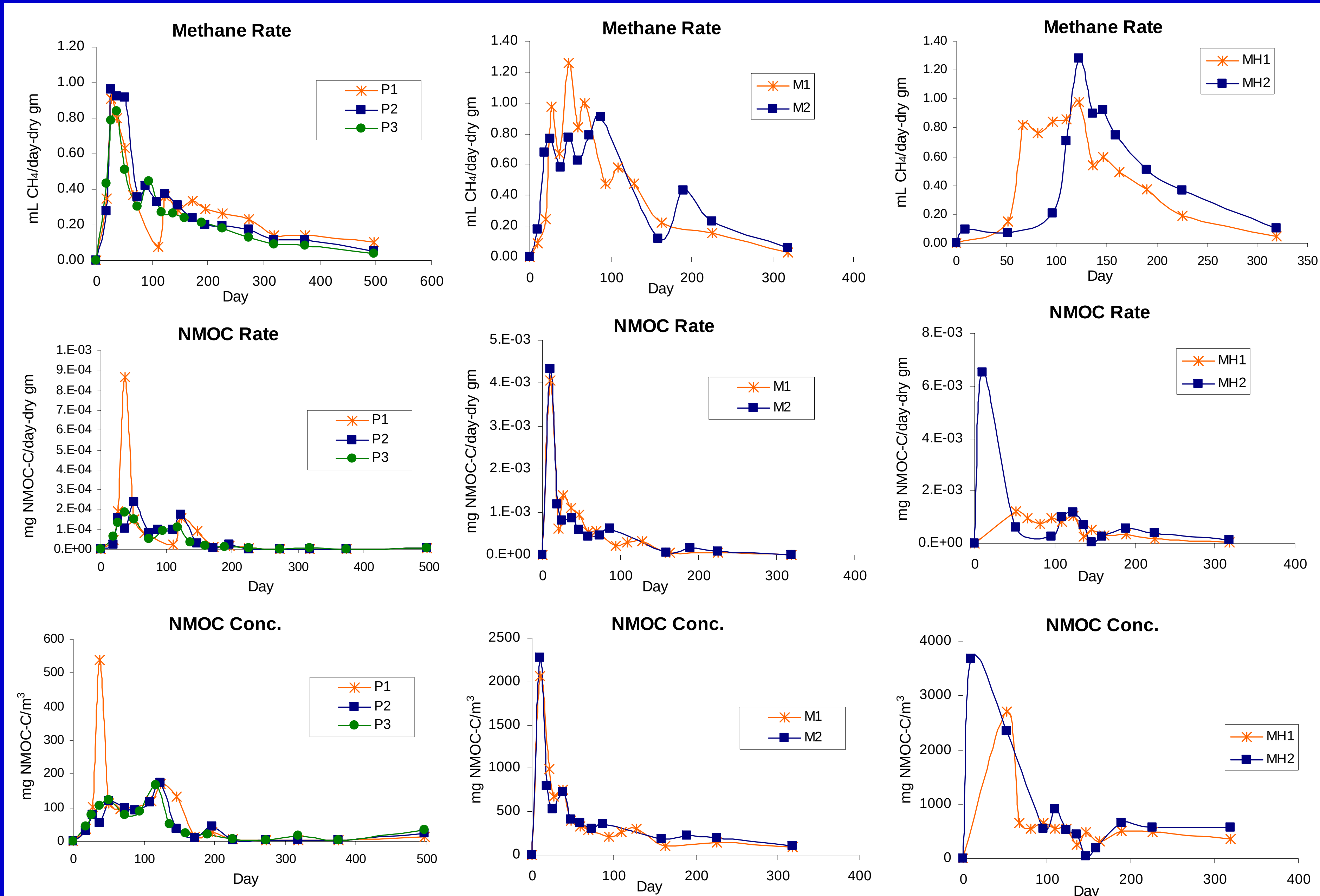
# Reactor Operation

- Triplicate 8-L reactors
- Seeded with leachate to initiate decomposition
- Operated with leachate recycle and neutralization at 37°C

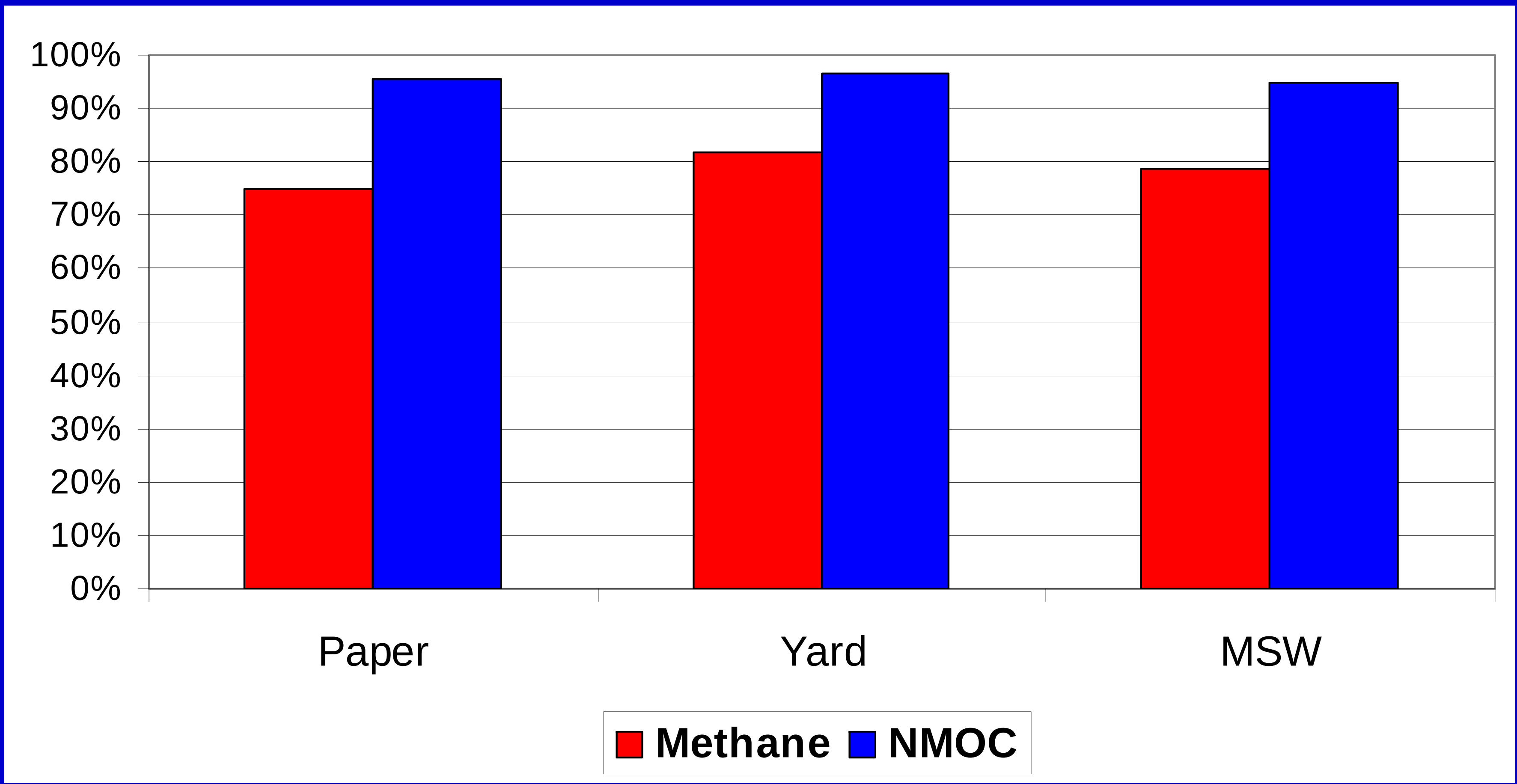
# NMOC Yields for Individual Components



# Paper MSW MSW + HHW

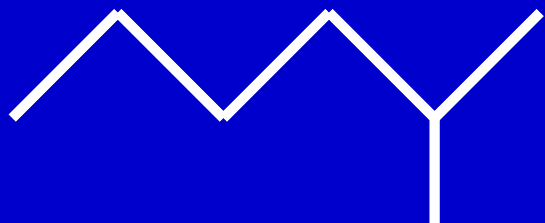


# Percent Yields for Methane and NMOCs at Midway Point of Operation

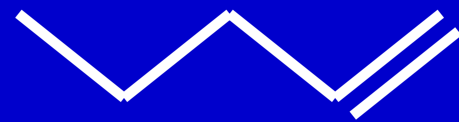


# Speciated Organic Compounds

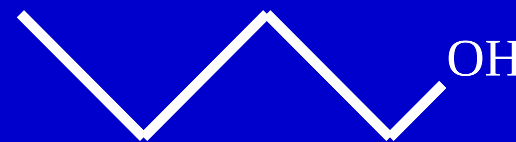
**Alkane**



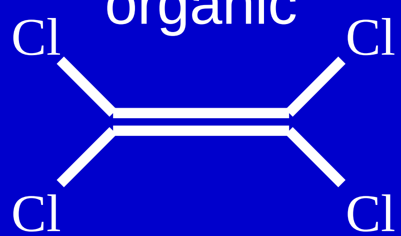
**Alkene**



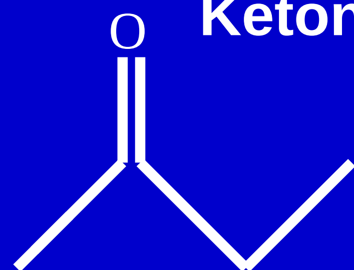
**Alcohol**



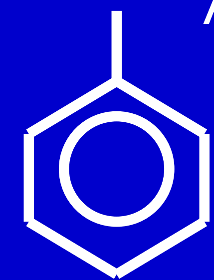

Chlorinated organic



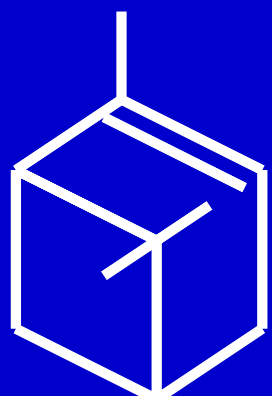

**Ketone**



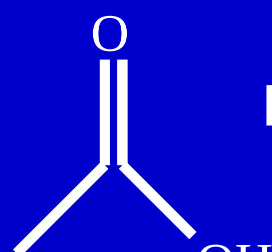

Aromatic



Terpene



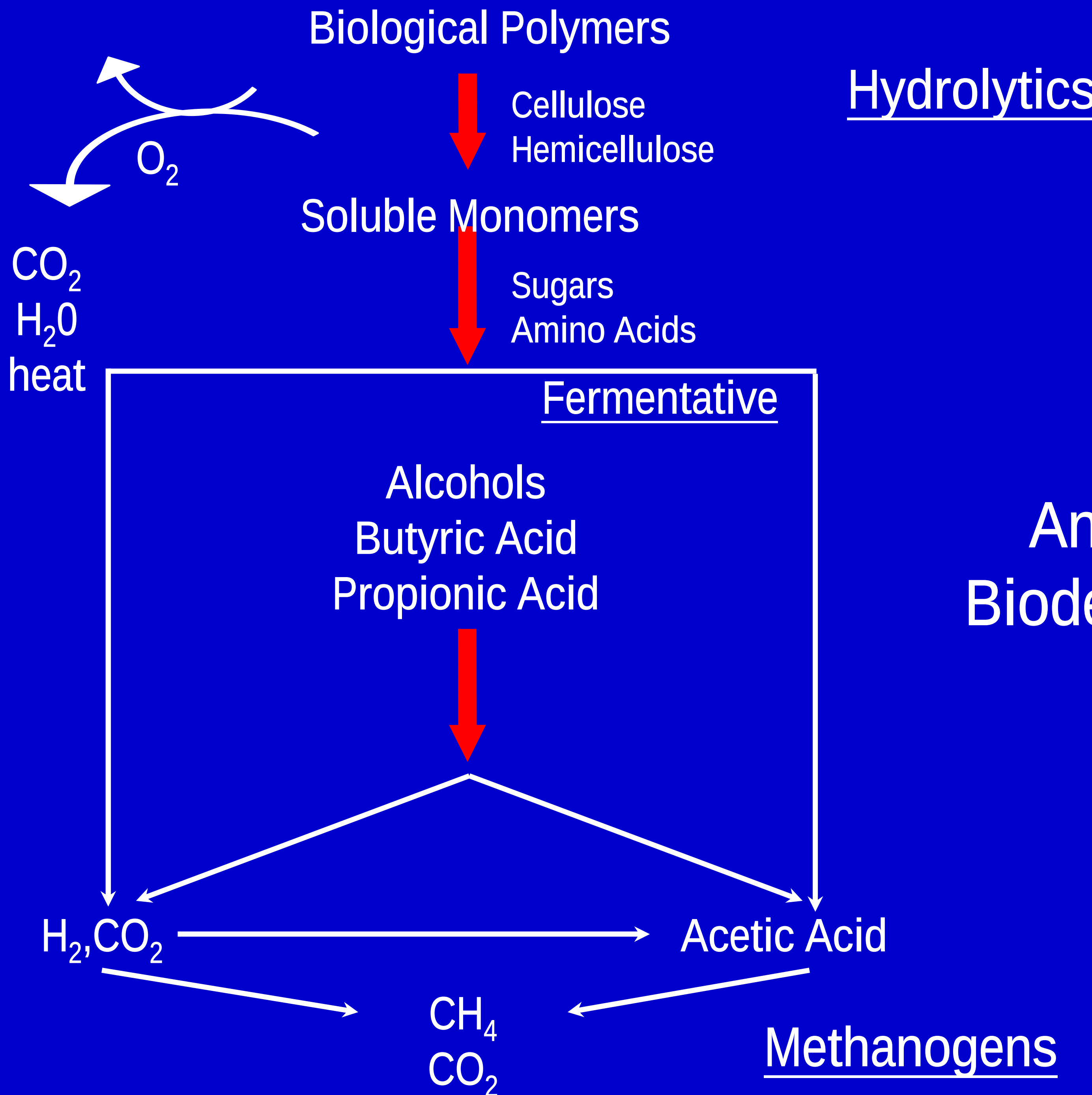
**Volatile Fatty Acid**



# Sources of Organics

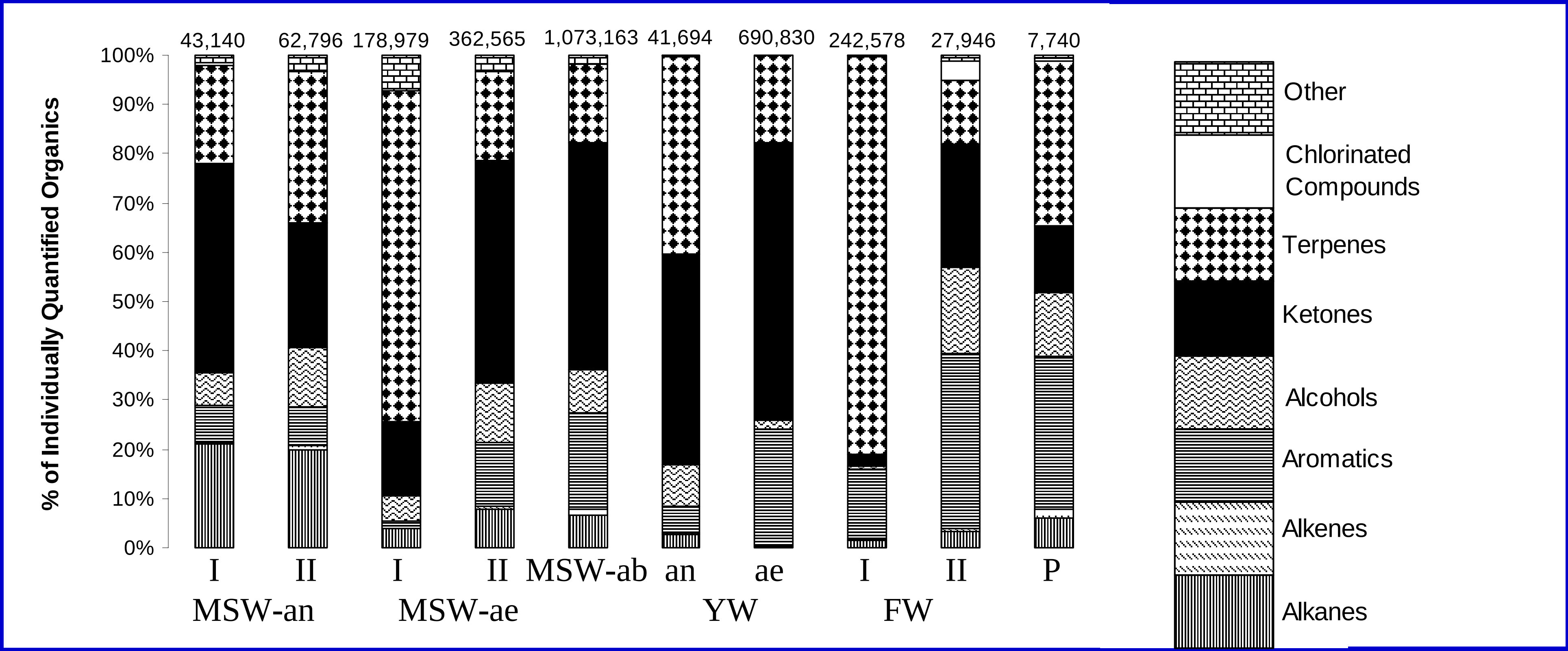
- Household Hazardous Waste
  - chlorinated compounds, aromatics, alkanes, alkenes
- Vegetative Matter
  - terpenes release after plant death
    - present in citrus peels
- Decomposition Intermediates
  - alcohols, ketones and fatty acids
- Food Packaging

# Anaerobic Biodegradation



# Organics Released from Waste Components

**43.1 62.8 179 363 1073 41.7 691 243 27.9 7.74 mg/dry gm**



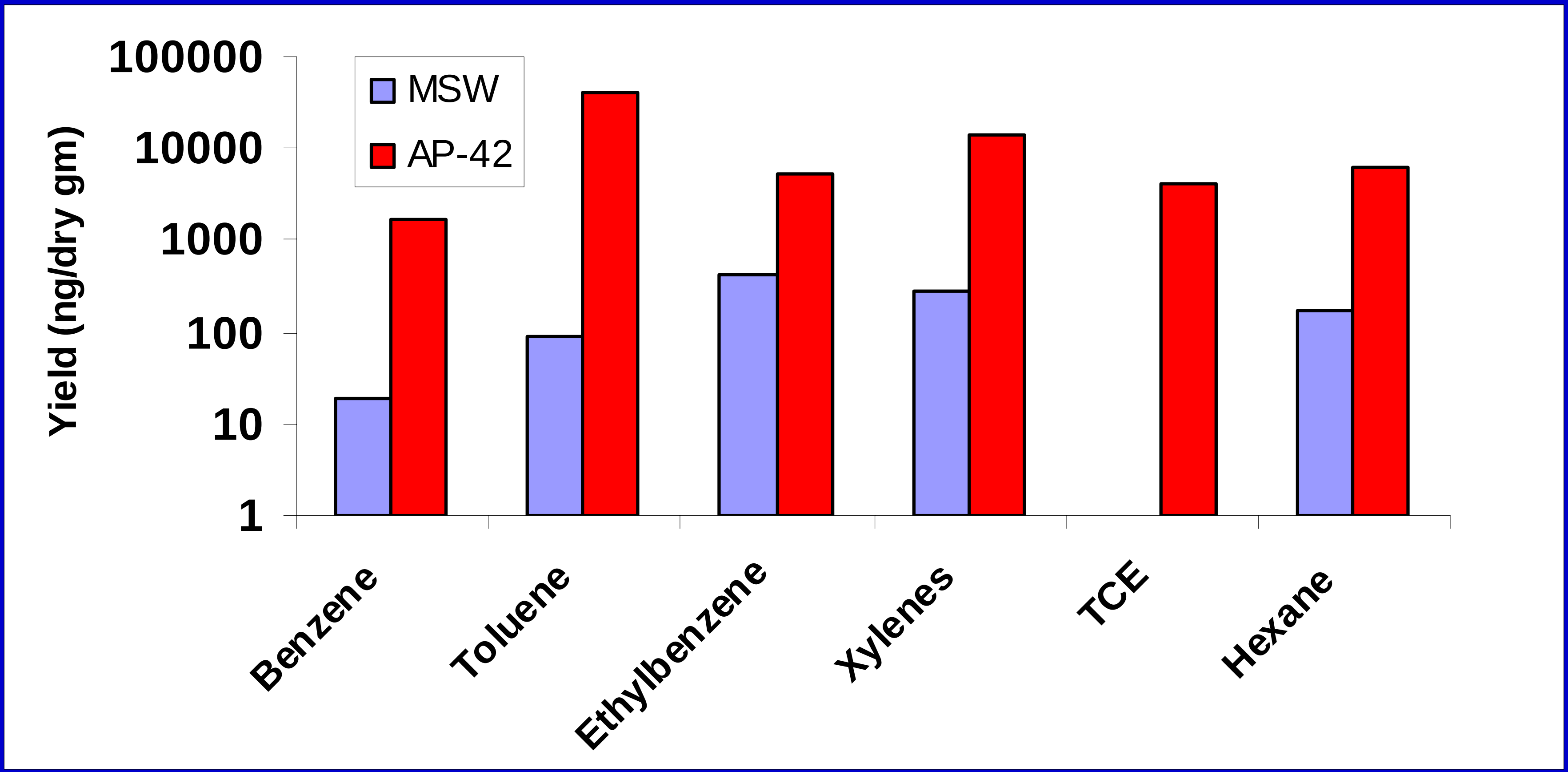
# Comments on Specific Compounds

- Terpenes and ketones were dominant for most treatments
  - 10-20 compounds could account for 80 – 99% of yield
- Elevated Phase 1 food waste attributed to high citrus content
  - Pectin analysis, observation
- Toluene in yard waste traced to soccer field paint
- Styrene and toluene reported in high fat foods (cheese, butter, doughnuts)

# Importance of Fatty Acids

- Acids analyses were conducted on worst case samples
  - High COD, low pH
- Acids accounted for 0.8% and 3.3% of NMOC yield for MSW-Ae treatments; and 3.3% for YW-ae
- Acids were not a significant contributor to NMOCs in any treatment

# Comparison of AP-42 and Measured HAP Yields for MSW



# Conclusions

- Lab-scale NMOC and VOC yields are considerably lower than regulatory estimates
- NMOC production is characterized by an initial “burst”, followed by much more gradual release
  - early gas collection is required to reduce NMOC emissions

# Conclusions

- Food waste can be high in NMOCs, but is not a source of HAPs
  - Seasonal variability is important
- Decomposition intermediates (fatty acids) were not a major contributor to NMOC yields

# Conclusions

- Aerobic treatment processes release significant NMOCs compared to anaerobic decomposition
  - Air sparging is a significant release mechanism based on the abiotic treatment
  - The elevated yields in the abiotic treatment suggests that significant biodegradation occurred in aerobic and anaerobic treatments

# The Application of Life-Cycle Analysis to Integrated Solid Waste Management Planning for the State of Delaware

Use a planning tool to evaluate multiple alternatives for solid waste management in Delaware

- Consider cost, emissions, energy consumption
- Consider scenarios that may differ from current practice

# Solid Waste Management is Complex: Many Options are Interrelated

- Recycling vs. waste-to-energy for recyclable paper and plastics (newsprint, cardboard, plastic)

- Relative benefits of landfilling or composting yard waste if we plan to recover methane?

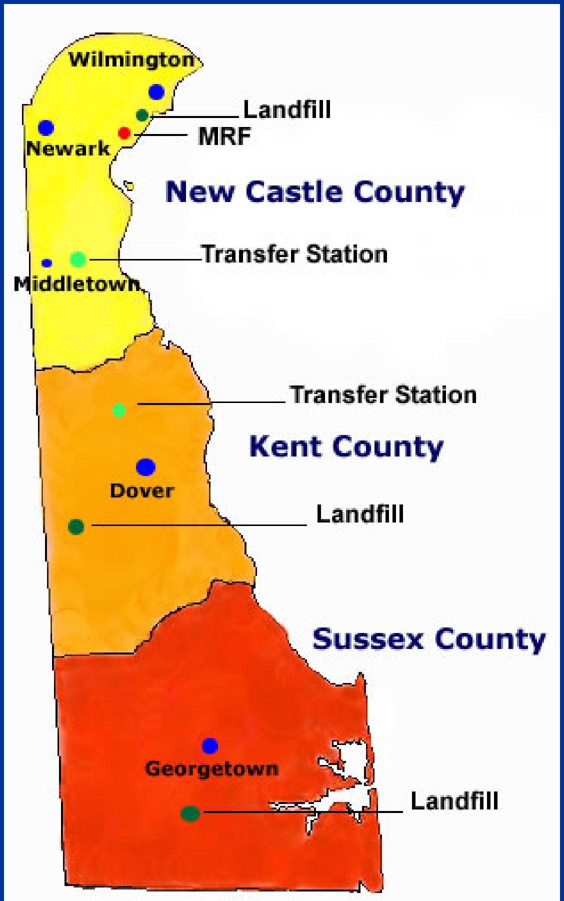
- How do the cost and environmental emissions change if we add a material to a recycling program?

# Solid Waste Management Life-Cycle Inventory Model

- A computer model to assist in decision making
  - Quantitative information to screen waste management alternatives, optimize
    - cost, energy consumption, emissions
  - Compare many alternatives
    - Identify an optimal solution
    - Model existing waste management system
  - Perform sensitivity analysis on uncertain model inputs
  - The person making a decision will still have to consider “unmodeled” factors

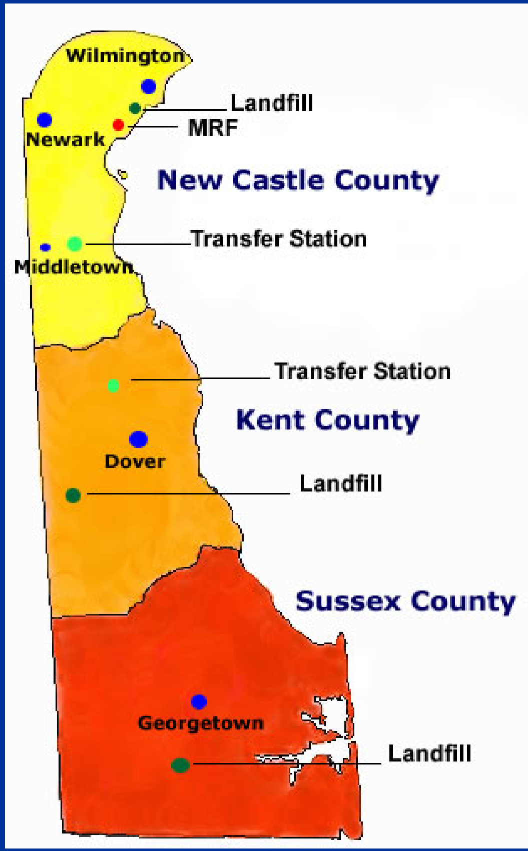
# Modeling Solid Waste Management System in Delaware

- New Castle County
  - Urban
  - 64% of the state population
- Kent County
  - Suburban to rural
  - 16% of the state population
- Sussex County
  - Suburban to rural
  - 20% of the state population



# Modeling Approach

- Each county was modeled separately
  - Represent individual facilities by county
  - Unique travel distances
  - More realistic
- Challenges
  - Appropriate combination of county-specific strategies to obtain appropriate statewide strategies

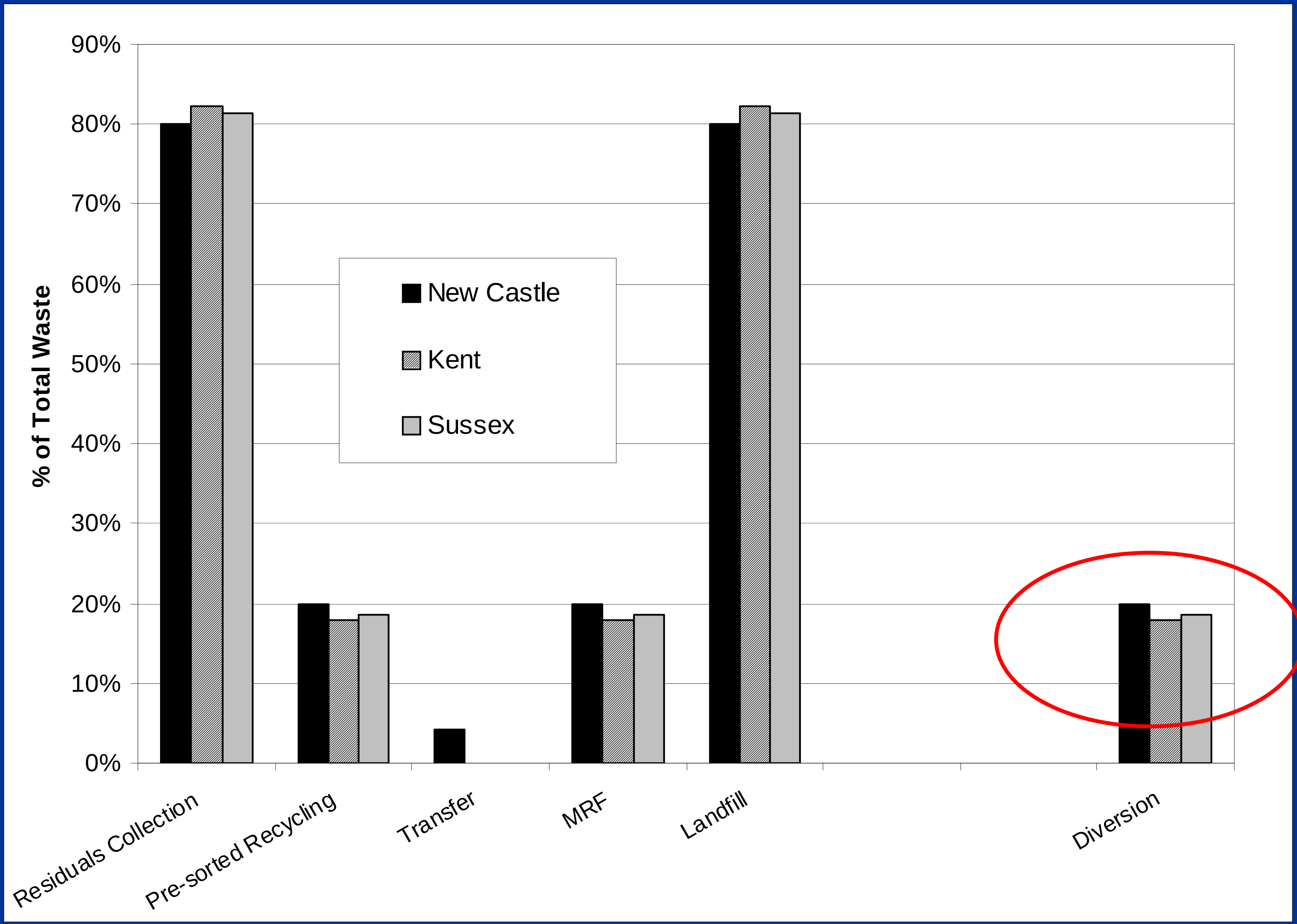


# SWM Strategies

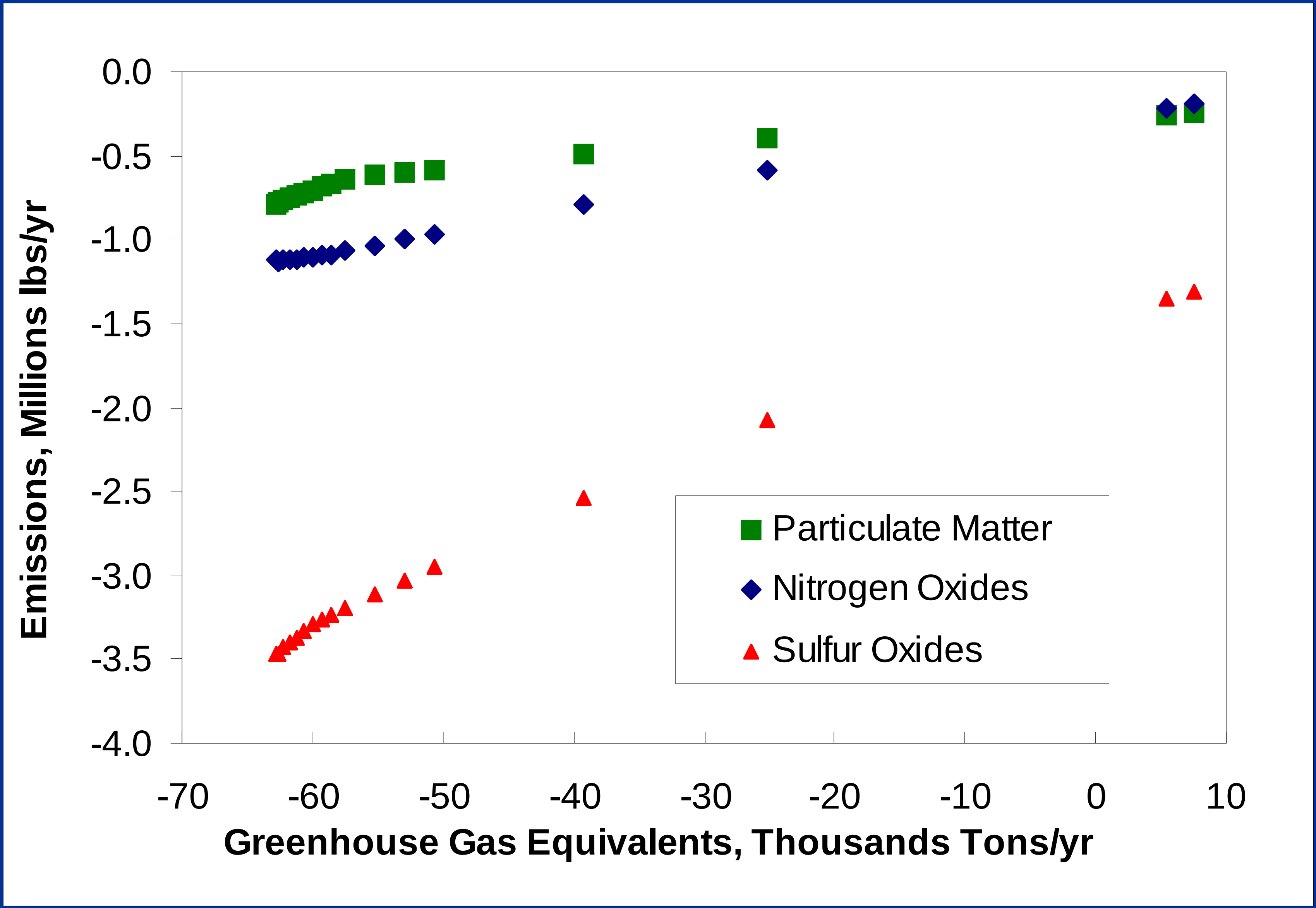
| | Least-Cost | | | | Least-GHE | |
|---|---|---|---|---|---|---|
| | Current | I | II | III | IV | V |
| Pre-sorted MRF | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Commingled MRF | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Mixed Waste MRF | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Yard Waste Composting | | | ✓ | ✓ | ✓ | ✓ |
| Combustion | | | | ✓ | | ✓ |
| Landfill | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

# Waste Flow Breakdown by Unit Operations

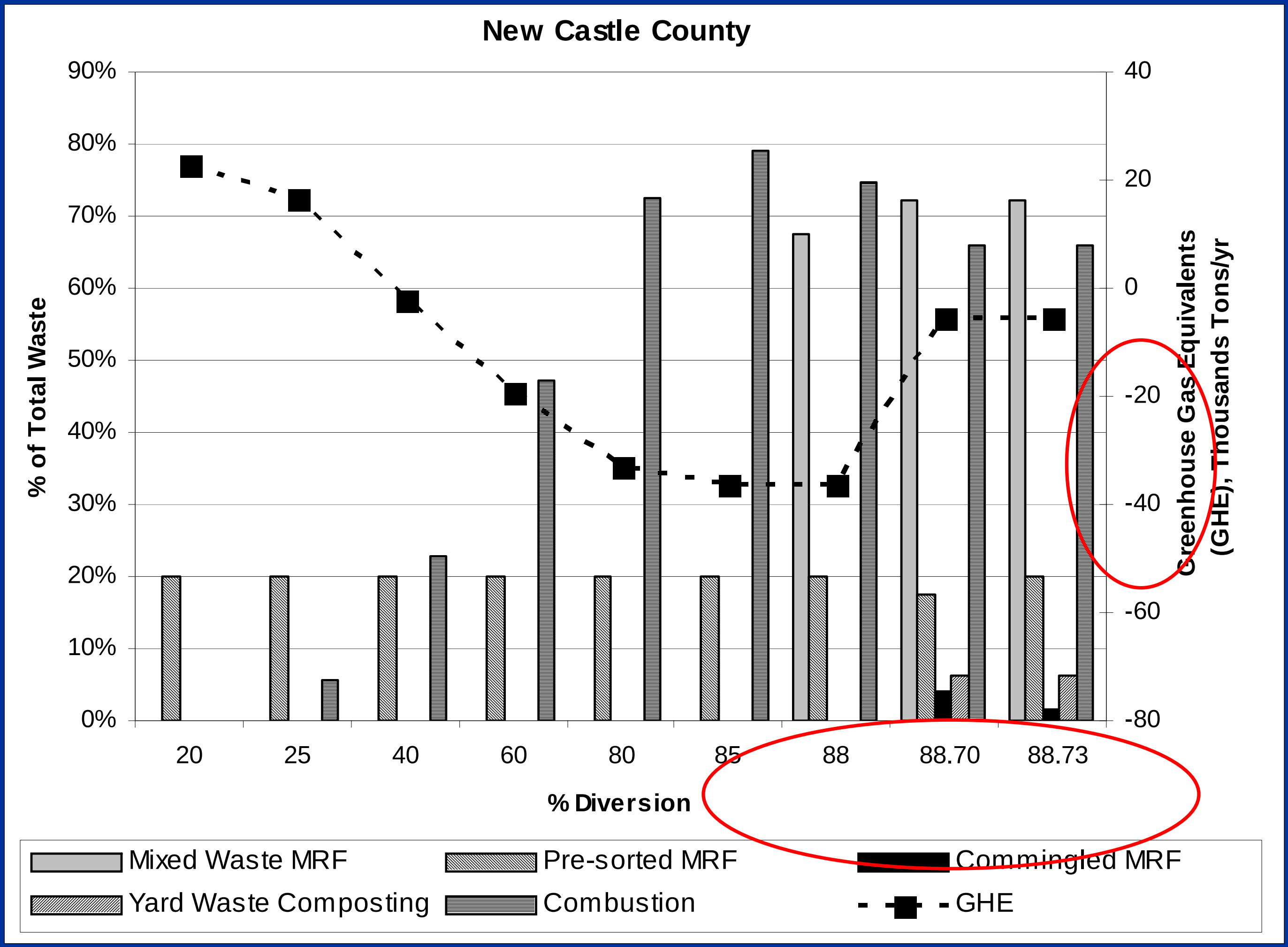
*[current practice (base case)]*



# Indicator Parameters for Environmental Emissions

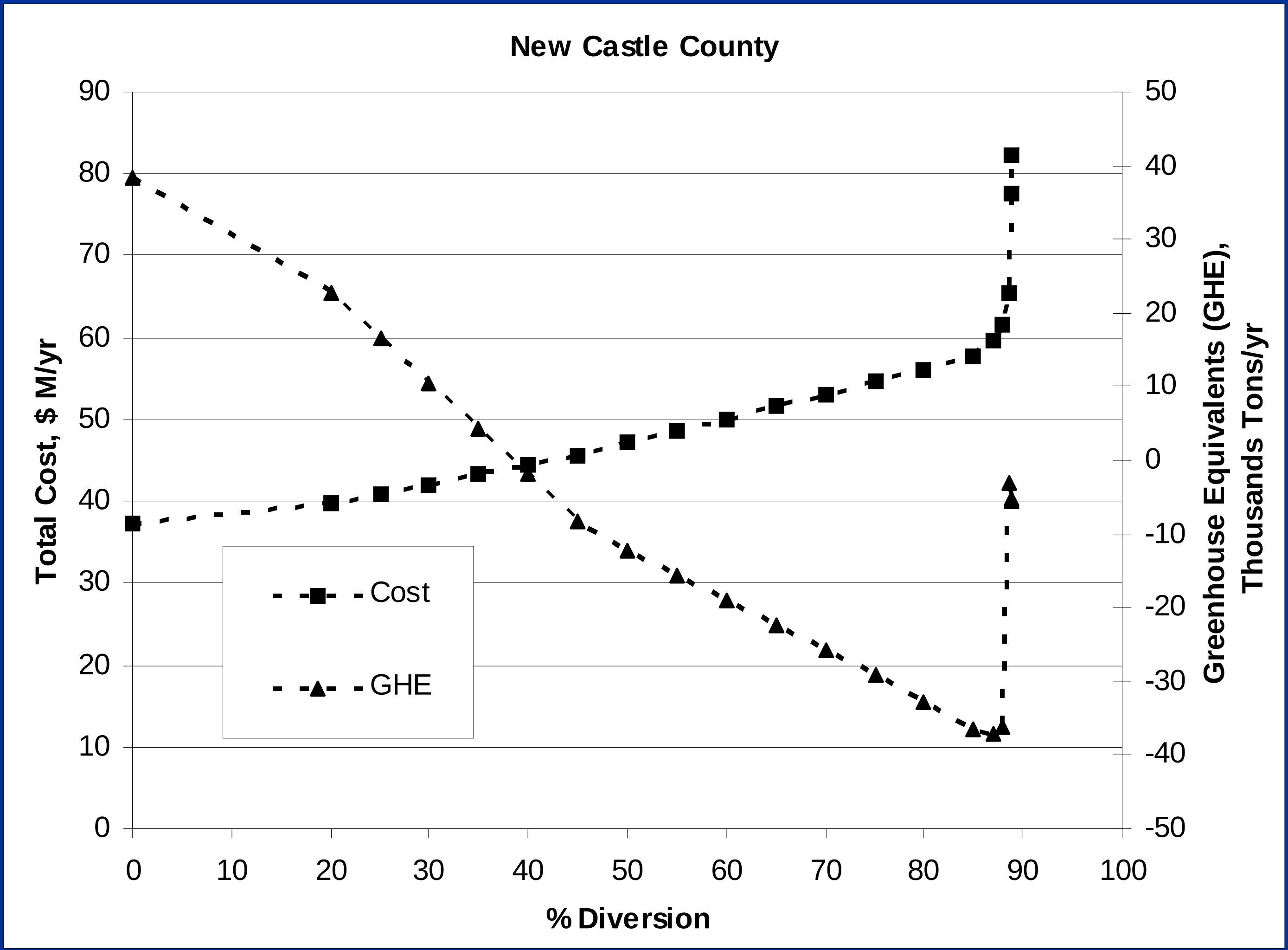


# Variation of Mass Flows & GHE with Diversion Least Cost: *curbside recycling + yard waste composting + combustion in New Castle County*




- Combustion is utilized to meet diversion constraint because it is estimated to be less expensive than alternatives
- Note partial implementation of combustion & utilization of a mixed waste MRF
- GHE increases near maximum due to composting

# Variation of Cost & GHE with Diversion *[curbside recycling + yard waste composting + combustion in New Castle County]*



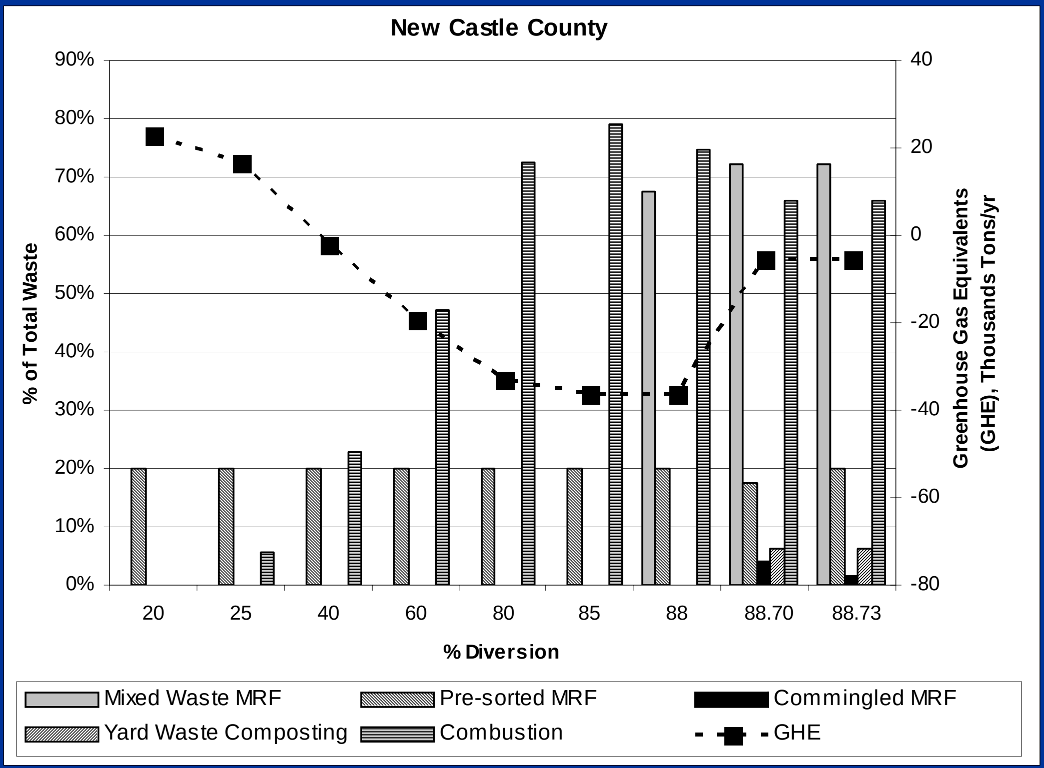

- Cost and GHE increase near maximum case illustrate extremes of numerical solution
- Ash content of yard waste leads to use of composting

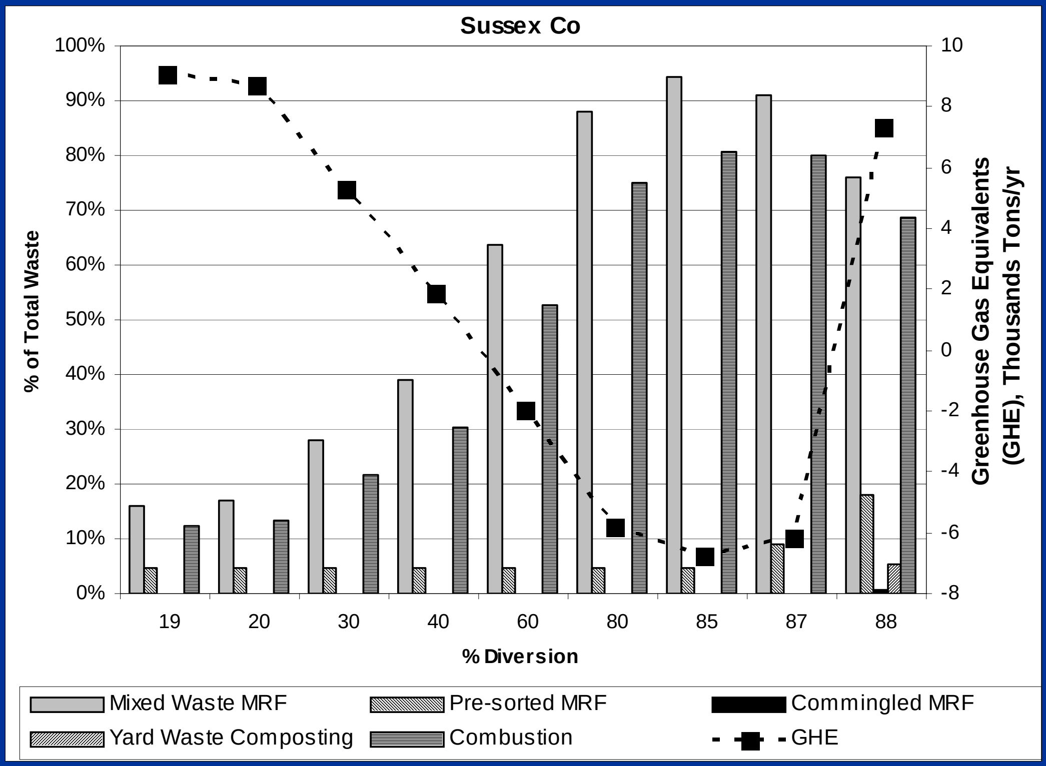
# Comparison of Cost and Emissions

| Parameter | Units | Least-Cost | | | | | | Least-GHE | |
|---|---|---|---|---|---|---|---|---|---|
| | | Current | Recycling | Recycling MAX | Recycling + Composting MAX | Recycling + Composting + Combustion | Recycling + Composting + Combustion MAX | No Combustion | Combustion |
| Cost | $/year | **9.80E+07** | 1.01E+08 | **1.62E+08** | **2.05E+08** | 9.89E+07 | **1.92E+08** | 1.19E+08 | 1.45E+08 |
| Energy | MBTU/year | -8.84E+05 | -2.02E+06 | -2.68E+06 | -2.27E+06 | -1.72E+06 | -2.71E+06 | -2.85E+06 | -5.24E+06 |
| Total PM | lbs/year | -1.84E+06 | -2.25E+06 | -2.35E+06 | -2.24E+06 | -1.68E+06 | -2.32E+06 | -2.36E+06 | -1.05E+06 |
| NOx | lbs/year | -3.80E+04 | -3.22E+05 | -3.37E+04 | 4.94E+05 | -3.79E+05 | 6.88E+04 | -4.91E+05 | -1.24E+06 |
| SOx | lbs/year | -1.85E+06 | -2.15E+06 | -2.31E+06 | -2.01E+06 | -2.42E+06 | -1.94E+06 | -2.35E+06 | -4.88E+06 |
| CO | lbs/year | -1.42E+06 | -9.05E+04 | -1.77E+06 | -1.40E+06 | 9.12E+05 | -1.37E+06 | -2.21E+06 | 3.89E+05 |
| $CO_2$-Biomass | lbs/year | 1.78E+09 | 4.98E+08 | 5.21E+08 | 4.66E+08 | 5.79E+08 | 3.39E+08 | 5.25E+08 | 9.68E+08 |
| $CO_2$-Fossil | lbs/year | -8.96E+07 | -6.42E+06 | -1.12E+07 | 7.06E+07 | -1.20E+08 | 5.60E+07 | -5.71E+07 | -5.54E+08 |
| GHE | tons/year | **3.81E+05** | 3.40E+04 | **3.19E+04** | **3.06E+04** | 1.90E+04 | **7.02E+03** | 2.53E+04 | -8.04E+04 |
| $CH_4$ | lbs/year | 1.37E+08 | 1.22E+07 | 1.17E+07 | 7.32E+06 | 1.24E+07 | -2.16E+05 | 1.15E+07 | -1.69E+06 |
| Diversion | % | **19%** | **25%** | **28.34%** | **34.88%** | **30%** | **88.47%** | **31.03%** | **85.29%** |

# Variation of Waste Flows, Cost, & GHE with Diversion

## *[curbside recycling + yard waste composting + combustion]*

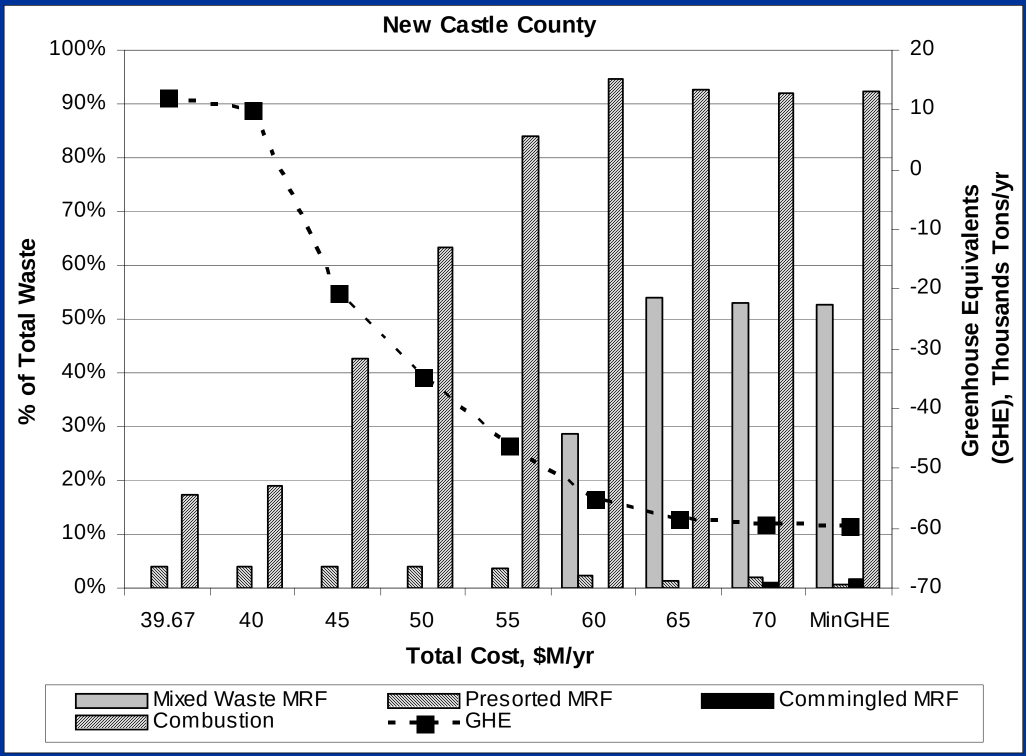


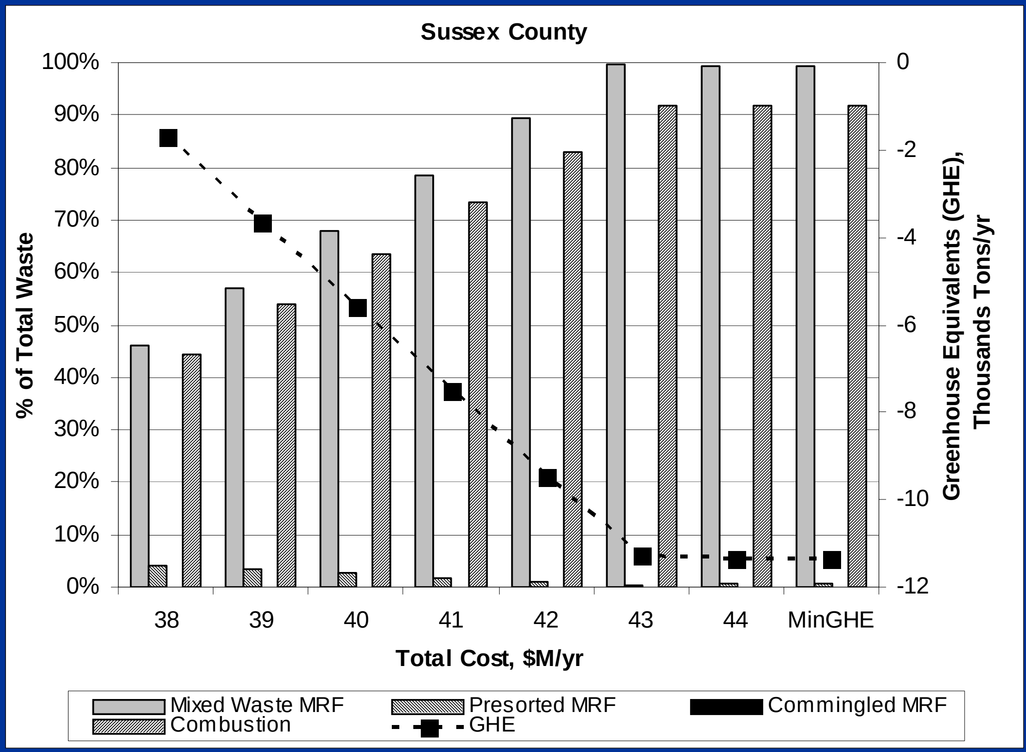




- In Sussex County, a mixed waste MRF is utilized upstream of combustion to reduce transport costs
- Composting and curbside recycling only used near maximum diversion with resultant increases in GHE emissions

# Variation of Waste Flows & GHE with Cost While **Minimizing GHE**

*[curbside recycling + yard waste composting + combustion]*




- Increasing Cost constraint
- Combustion most effective but a mixed waste MRF utilized upstream in Sussex County to reduce transport of waste to N. Delaware
- GHE levels off prior to min GHE scenario

# Comparison of Cost and Emissions

| Parameter | Units | Least-Cost | | | | | | Least-GHE | |
|---|---|---|---|---|---|---|---|---|---|
| | | Current | Recycling | Recycling MAX | Recycling + Composting MAX | Recycling + Composting + Combustion | Recycling + Composting + Combustion MAX | No Combustion | Combustion |
| Cost | $/year | **9.80E+07** | 1.01E+08 | 1.62E+08 | 2.05E+08 | 9.89E+07 | **1.92E+08** | **1.19E+08** | **1.45E+08** |
| Energy | MBTU/year | -8.84E+05 | -2.02E+06 | -2.68E+06 | -2.27E+06 | -1.72E+06 | -2.71E+06 | -2.85E+06 | -5.24E+06 |
| Total PM | lbs/year | -1.84E+06 | -2.25E+06 | -2.35E+06 | -2.24E+06 | -1.68E+06 | -2.32E+06 | -2.36E+06 | -1.05E+06 |
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| $CO_2$-Biomass | lbs/year | 1.78E+09 | 4.98E+08 | 5.21E+08 | 4.66E+08 | 5.79E+08 | 3.39E+08 | 5.25E+08 | 9.68E+08 |
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| GHE | tons/year | **3.81E+05** | 3.40E+04 | 3.19E+04 | 3.06E+04 | 1.90E+04 | **7.02E+03** | **2.53E+04** | **-8.04E+04** |
| $CH_4$ | lbs/year | 1.37E+08 | 1.22E+07 | 1.17E+07 | 7.32E+06 | 1.24E+07 | -2.16E+05 | 1.15E+07 | -1.69E+06 |
| Diversion | % | **19%** | **25%** | **28.34%** | **34.88%** | **30%** | **88.47%** | **31.03%** | **85.29%** |

# Observations from County-Wide Summary

- The least-cost and least GHE solutions vary by county
  - Use of a mixed waste MRF upstream of combustion
  - GHE from curbside recyclables collection in Sussex County
- Non-uniform utilization of curbside collection, combustion subject to a cost constraint
- Model led to counter-intuitive results
  - MRF upstream of combustion
  - Effectiveness of yard waste composting influenced by transport distance
- Model can be rerun with alternate assumptions

# Procedure to Identify Statewide SWM Strategies

- SWM strategies are generated for each county
- Combinations of these strategies are explored to identify
  - Cost-effective diversion strategies
  - GHE-minimizing strategies at different costs

# Identify the Cost-effective 30% Statewide Diversion Strategy?

| DIVERSION | | | | Cost [$/yr] | | | |
|---|---|---|---|---|---|---|---|
| New Castle | Kent | Sussex | State-wide | New Castle | Kent | Sussex | **Total** |
| 30% | 30% | 30% | **30.0%** | 42,050,377 | 21,0[illegible] | [illegible] | **99,024,811** |
| 30% | 35% | 30% | 30.7% | 42,050,377 | 21,3[illegible] | [illegible] | 99,317,194 |
| 30% | 30% | 35% | 30.9% | 42,050,377 | 21,0[illegible] | [illegible] | 99,403,794 |
| 30% | 40% | 25% | 30.5% | 42,050,377 | 21,6[illegible],004 | [illegible] | 99,258,166 |
| 35% | 25% | 20% | 30.7% | 43,245,513 | 20,778,283 | 35,145,802 | 99,169,597 |
| 35% | 20% | 25% | 30.9% | 43,245,513 | 20,485,900 | 35,524,785 | 99,256,197 |
| 35% | 25% | 20% | 30.7% | 43,245,513 | 20,778,283 | 35,145,802 | 99,169,597 |
| 35% | 20% | 20% | **30.0%** | 43,245,513 | 20,485,900 | 35,145,802 | **98,877,214** |
| 40% | 20% | 20% | 33.3% | 44,440,648 | 20,485,900 | 35,145,802 | 100,072,350 |
| … | … | … | … | … | … | [illegible] | … |
| … | … | … | … | … | … | [illegible] | [illegible] |
| … | … | … | … | … | … | [illegible] | [illegible] |

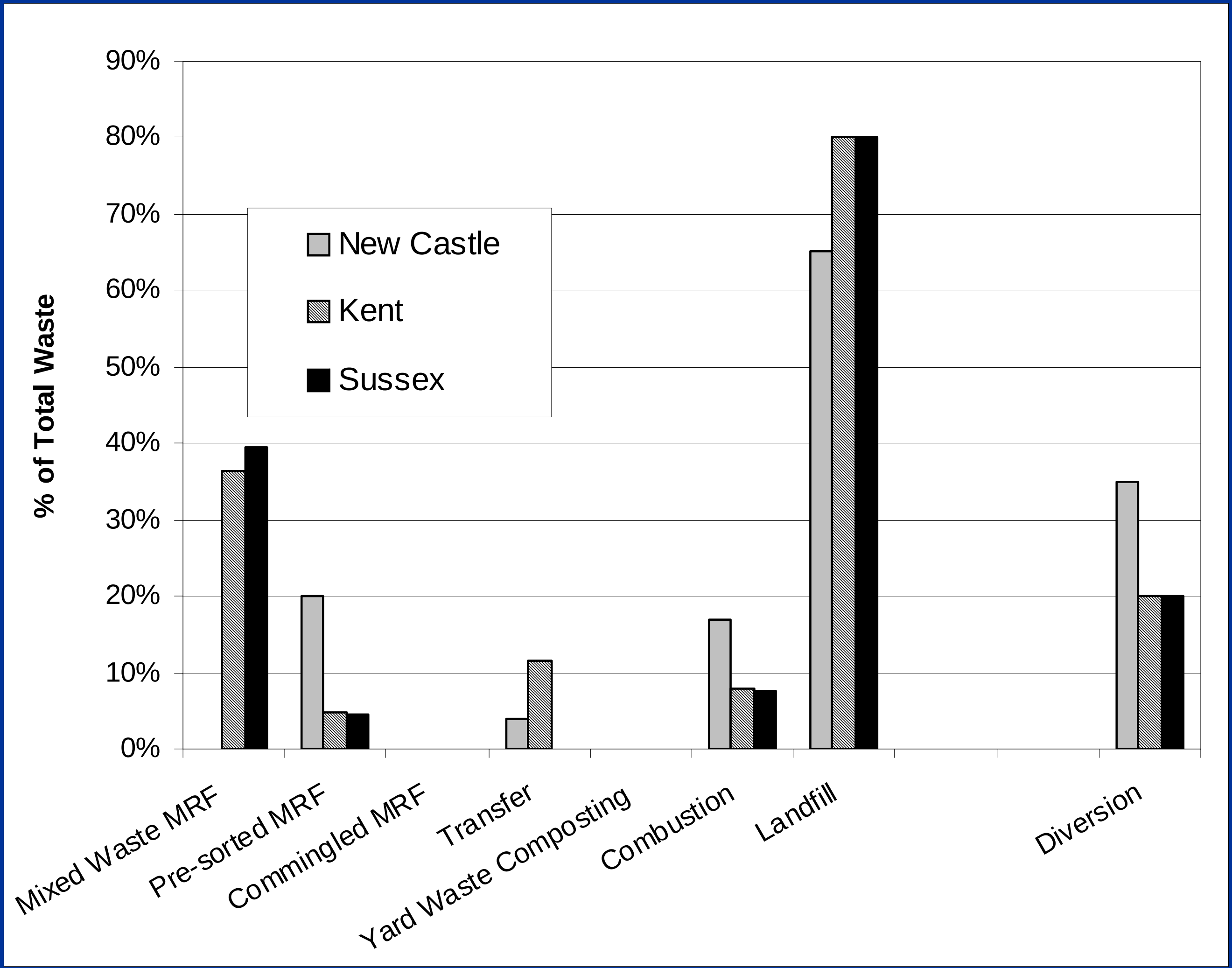
Uniform diversion is not least cost case

Least-Cost 30% Statewide Diversion

For each county approximately 17 SWM strategies exist (20 – 88% diversion):
17 x 17 x 17 = 4,913 combinations should be analyzed for minimum cost…

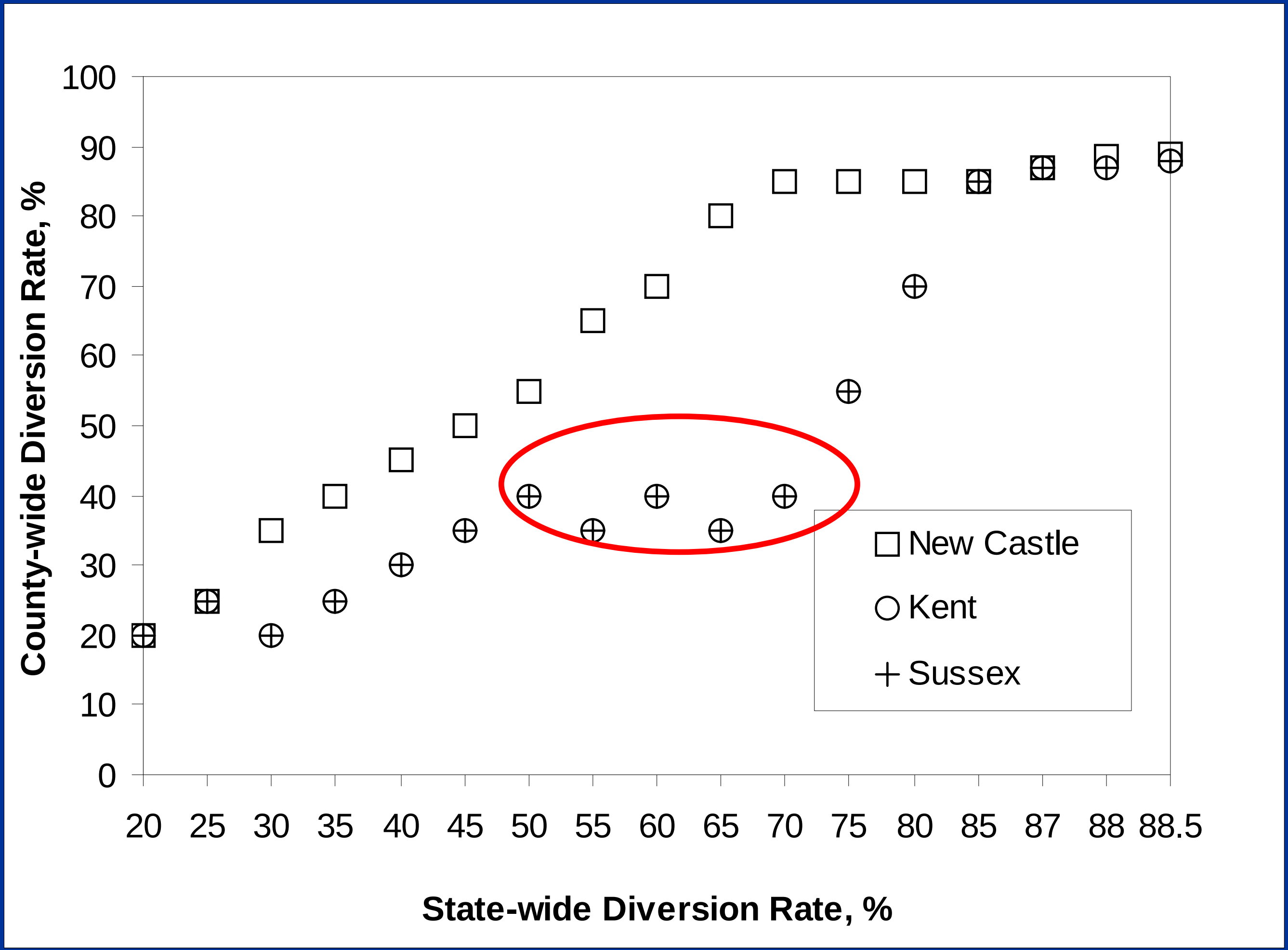
# Waste Flows in Cost-effective 30% Statewide Diversion Strategy

*[curbside recycling + yard waste composting + combustion]*




- Minimize cost subject to a diversion constraint
- Analysis similar to county specific analyses
- Combustion used subject to cost constraint
- Mixed waste MRF used in rural counties

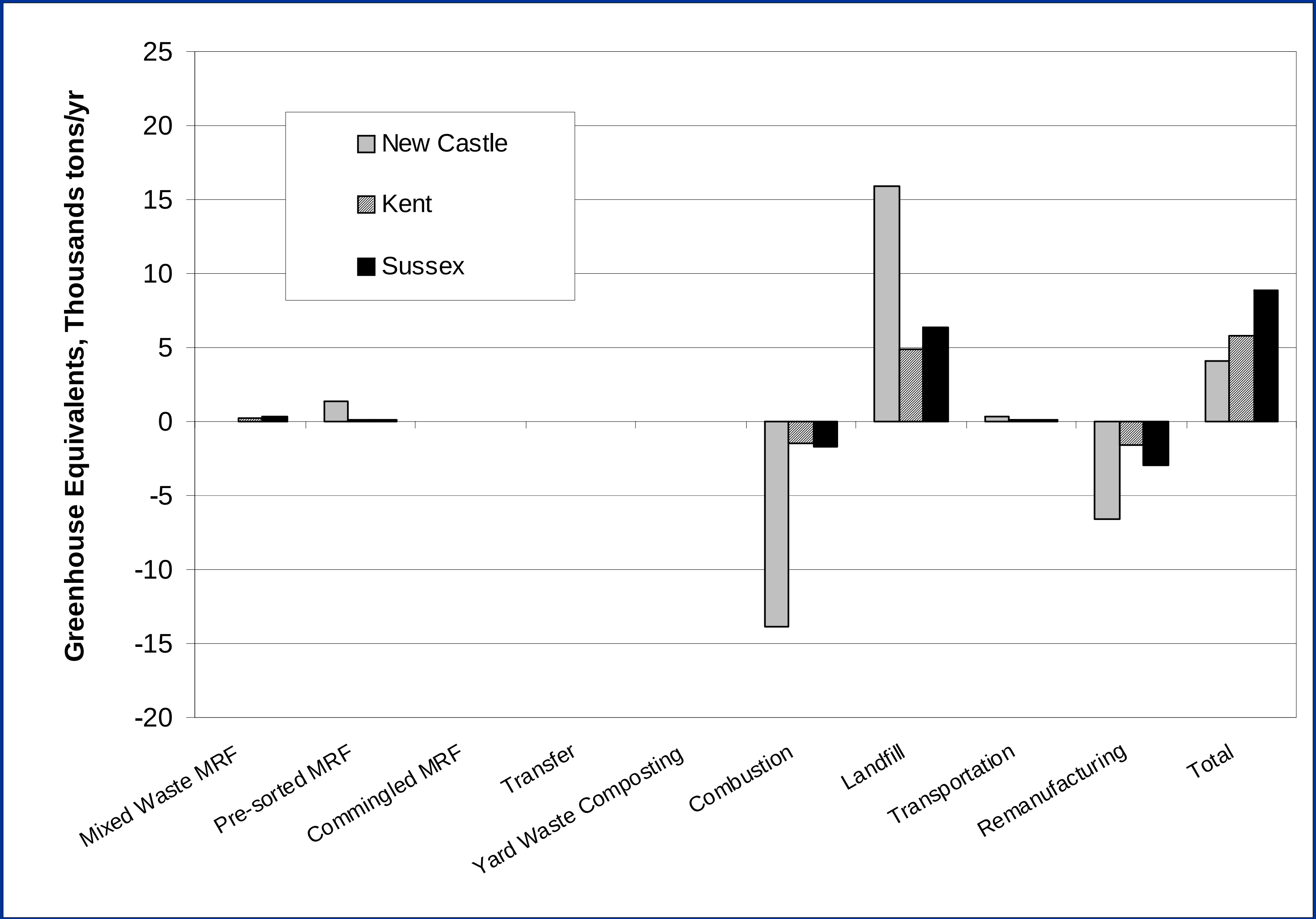
# County-Specific Contribution to Statewide Diversion
*[curbside recycling + yard waste composting + combustion]*




- The statewide optimum diversion strategy varies by county
- Between 50 and 70% diversion, all increases occur in New Castle County due to lower transport cost

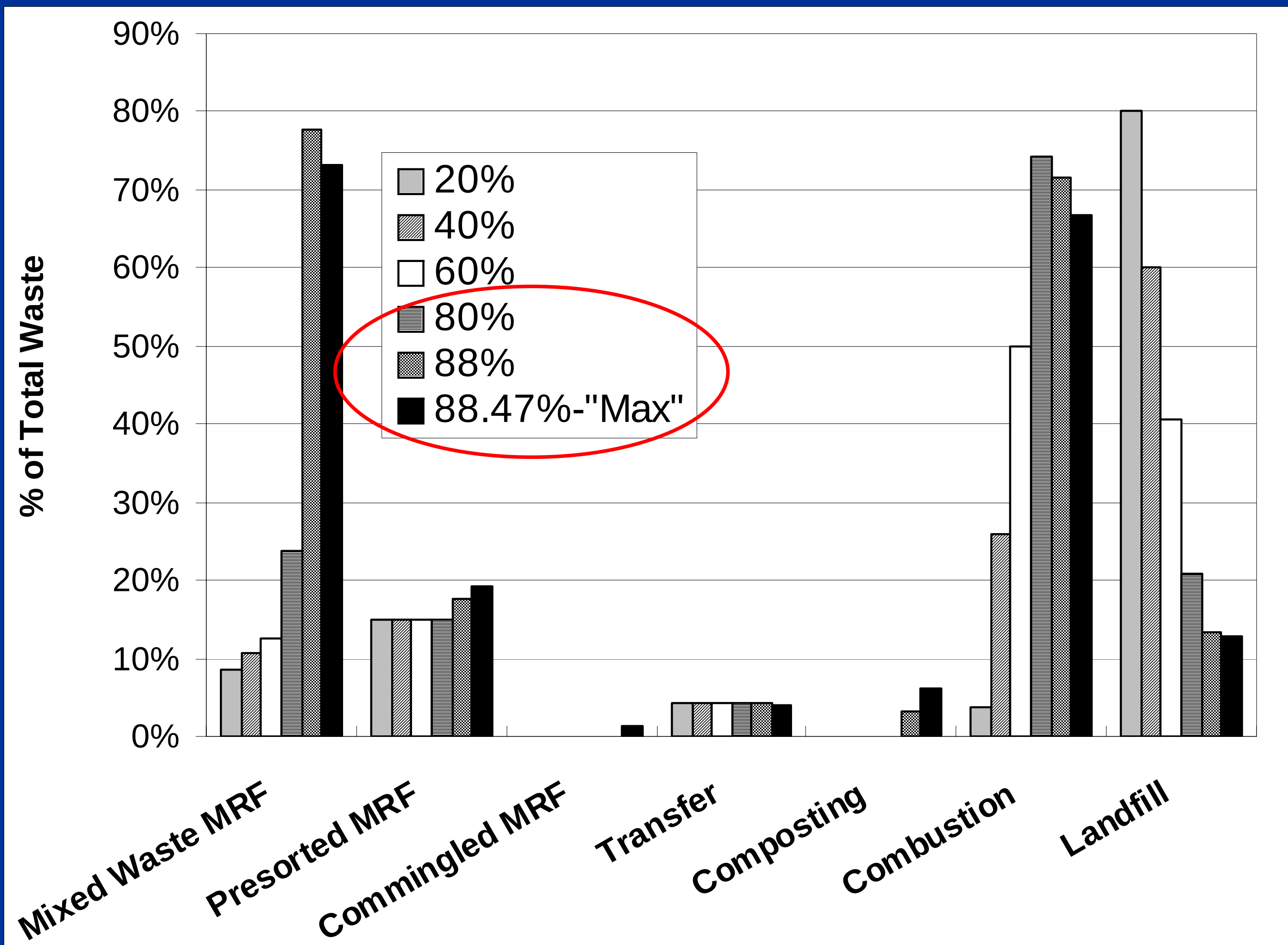
# GHE Breakdown in Cost-effective 30% Statewide Diversion Strategy

*[curbside recycling + yard waste composting + combustion]*



# Variation of Waste Flows in Cost-effective Statewide Diversion Strategy

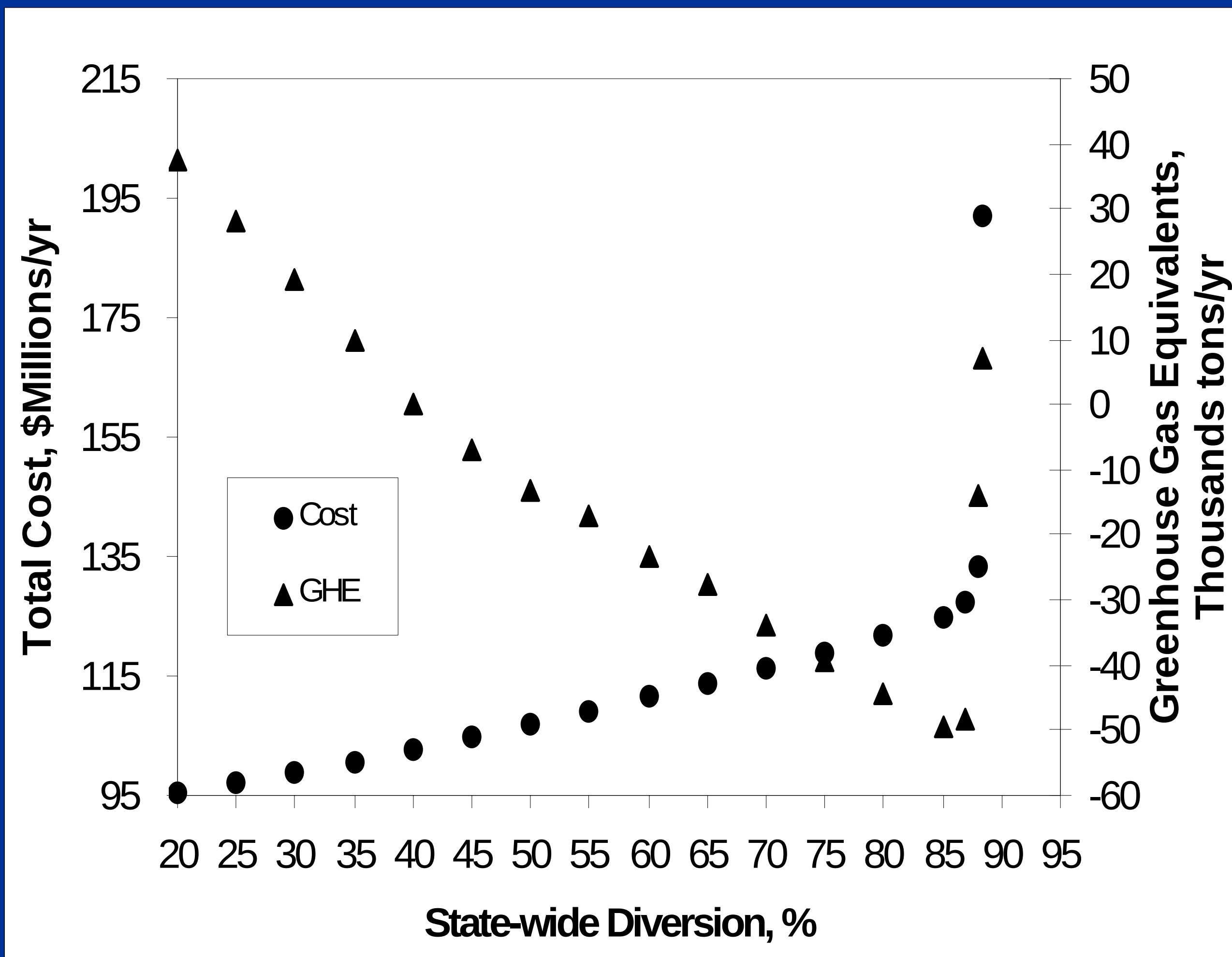
*[curbside recycling + yard waste composting + combustion]*




- Composting and curbside recycling only utilized near maximum diversion when combustion is enabled

# Variation of Cost & GHE with Diversion in Cost-effective Statewide Diversion Strategy

*[curbside recycling + yard waste composting + combustion]*




- GHE increases at the extreme due to implementation of composting and curbside recycling to meet diversion constraint

# Observations from Statewide Analyses

- The optimal statewide strategy is a combination of three unique SWM alternatives that are county-specific
  - a uniform statewide strategy will be sub-optimal

# Generating Alternative SWM Strategies

- Optimal solution may not be appropriate
  - political feasibility
  - capital intensive
  - facility siting
  - …
- Generate alternatives that maximize differences in unit operations & waste flow choices in SWM strategies

# Generating Alternative Strategies

Cost-effective 30% statewide diversion strategy includes:

- cost-effective 35% diversion from New Castle

  Cost: $43.2 M/yr $\xrightarrow{\text{relax the cost}}$ $48 M/yr

- cost-effective 20% diversion from Kent

  Cost: $20.2 M/yr $\xrightarrow{\text{relax the cost}}$ $22.5 M/yr

- cost-effective 20% diversion from Sussex

  Cost: $34.6 M/yr $\xrightarrow{\text{relax the cost}}$ $38.7 M/yr

# Waste Flows for Alternative SWM Strategies to Achieve 30% Statewide Diversion

| | | Least-Cost | NC-Alt 1 + K-Alt 2 + S-LC | NC-Alt 2 + K-Alt 2 + S-Alt2 |
|---|---|---|---|---|
| Mixed Waste Transfer | tons/yr | 24394 | 19894 | 5330 |
| Pre-Sorted Transfer | tons/yr | 719 | 7185 | 5829 |
| Mixed Waste MRF | tons/yr | 73554 | 83665 | 124772 |
| Presorted MRF | tons/yr | 86696 | 32717 | 17290 |
| Commingled MRF | tons/yr | 0 | 7431 | 5745 |
| Yard Waste Composting | tons/yr | 0 | 13115 | 12496 |
| Combustion | tons/yr | 80564 | 118017 | 130325 |
| Diversion | % | **30** | **30** | **30** |

Three of 27 cases considered at each diversion level based on generation of 2 alternatives per county ($3^3$)

# Consideration of Cost and Environmental Emissions Under Conditions of Uncertainty

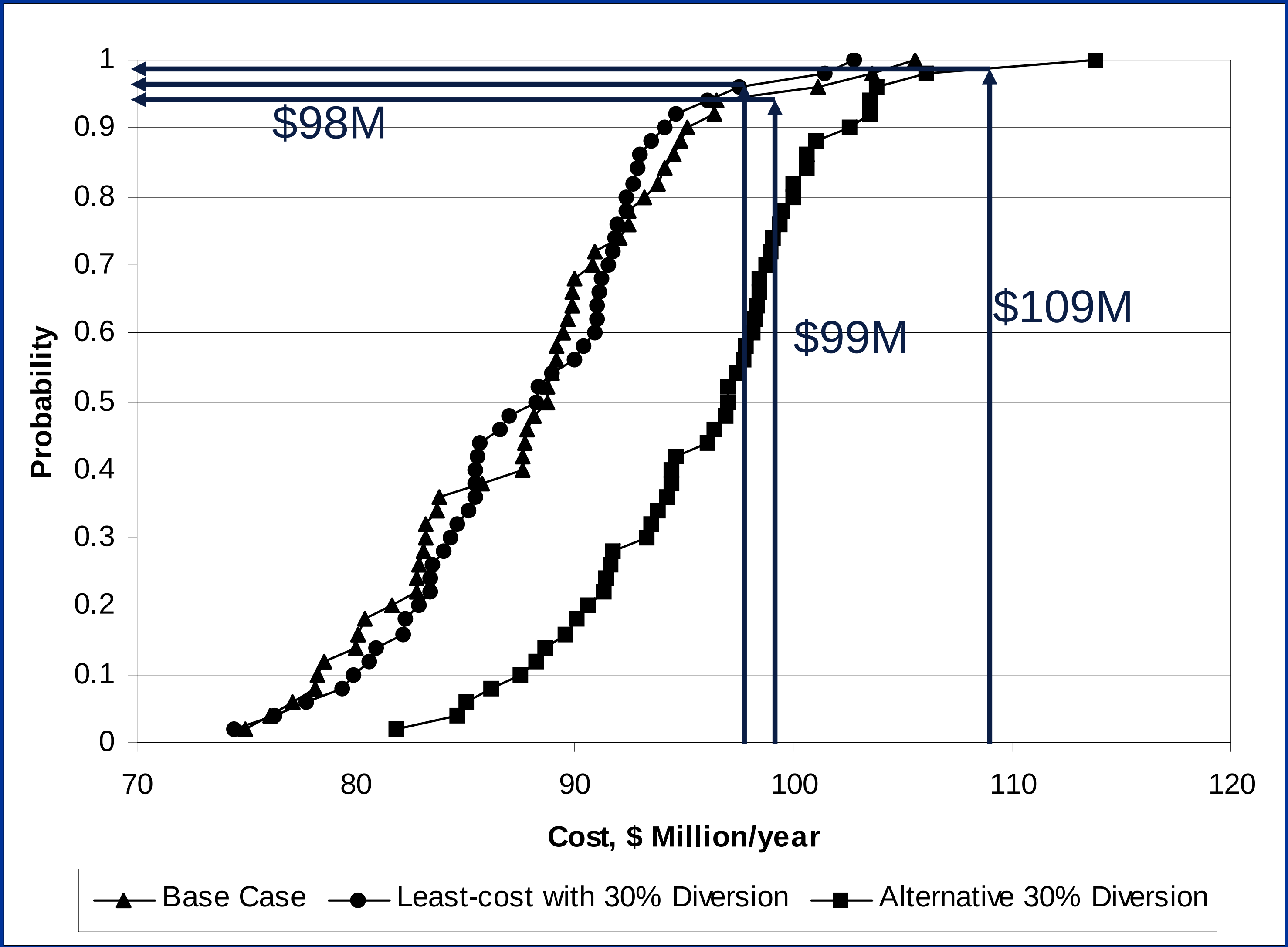
- Objectives
  - Integrate uncertainty propagation procedures
  - Characterize and compare uncertainty in cost and LCI emissions estimates

# Illustrative Results

- The procedure was applied to the cost-effective 30% statewide diversion case
- The least-cost and two alternatives were analyzed

# Uncertainty in Cost of Strategies for 30% Statewide Diversion

*[curbside recycling + yard waste composting + combustion]*



# Summary

- Developed new procedures to use the model for a complex statewide analysis
- Demonstrated modeling to generate alternatives and uncertainty analysis
- Quantified tradeoffs among cost, diversion, emissions
- Provided counter-intuitive and creative results

# The Answer Is ……

- Humans must still make decisions
  - Consider combustion, mixed waste MRF
  - Can we vary solid waste management by county, or even neighborhood?
    - Use model to document cost implications of this decision
  - What are the appropriate cost and emissions targets?
  - Detailed engineering analysis

# Reference

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